Alternative protein-rich ingredients for Australian pigs and laying hens

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by Dr Elham (Ellie) Assadi Soumeh

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Foreword

This project was conducted to identify alternative protein sources that can be practically incorporated into pig and layer rations, to provide a balanced diet especially regarding protein and amino acids, at an economical cost to producers. The overarching aim of this project was to provide the Australian pork and egg industries with an understanding of the available options for practical feed formulations to improve sustainability and reduce the carbon footprint of pork and egg production, and to reduce the reliance on imported soybean meal as the main protein source for Australian poultry and pigs.

Through the course of this project, a wide range of alternative protein-rich ingredients that are produced sustainably and/or locally were identified, and the existing literature was reviewed and summarised with respect to the nutritional characteristics of each ingredient; global and Australian production volumes; nutritive value including potential antinutritional factors and existence of toxins; animal (laying hens and pigs) physiological response to the dietary inclusion of each studied ingredient; carbon footprint and sustainability of the production. The alternative protein-rich ingredients are divided into six different categories including oil-seed meals; legumes or pulses; plant by-product protein sources; animal by-products/insect protein sources; aquatic protein sources; and other sources and based on the available literature. The optimum inclusion level of each ingredient was highlighted. Viable alternative ingredients were then selected based on their availability throughout the year and production volumes, as well as novel emerging ingredients, which demonstrate a great potential for future sustainable farming and circular economy, were introduced. The report provides essential information to the feed industry to generate a framework to adjust the feed formulation practices using locally and sustainably produced ingredients while maintaining performance.

This project was funded from industry revenue, which is matched by funds provided by the Australian Government.

This report is an addition to Australian Eggs Limited's range of peer reviewed research publications and an output of our R&D program, which aims to support improved efficiency, sustainability, product quality, education, and technology transfer in the Australian egg industry.

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About the Authors

Dr Elham (Ellie) Assadi Soumeh is a senior lecturer in Animal Science and Production within the School of Agriculture and Food Sustainability, the University of Queensland. Her background is in monogastric animal nutrition – poultry and swine. Her PhD research was about branched-chain amino acid requirements and metabolism in pig post-weaning, and characterisation of the metabolic profile of high performing pigs when they were fed with optimum dietary branched-chain amino acid levels. The focus was to identify discriminating metabolites in blood or urine, which could be linked to high growth performance. After conducting her PhD in Aarhus University in Denmark and prior to joining UQ, Dr Soumeh worked in the animal feed industry (Cargill BV, Netherlands) for two years. During this time, Dr Soumeh was involved in different customer-focused research portfolios within the area of monogastric animal nutrition and production, e.g. nutrient requirements and metabolism, gut health, nutritional strategies and management. Dr Soumeh has completed a BSc in Animal Science, an MSc in Animal Nutrition, and a PhD in Animal Nutrition and Physiology. The scientific outcomes have been published in high-impact journals and/or presented in conferences and symposiums around the world.

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Abbreviations

AA	Amino acids
ADFI	Average daily feed intake
AAFCO	Association of American Feed Control Officials (US)
ADF	Acid detergent fibre
AME	Apparent metabolisable energy
ASA	Australian Sunflower Association
BDG	Brewer's dried grains
BSFL	Black soldier fly larvae
BW	Body weight
CF	Carbon footprint
CGF	Corn gluten feed
CO_2	Carbon dioxide
CP	Crude protein
CV	Coefficient of variation
DDGS	Distiller's dried grains with solubles
DE	Digestible energy
DM	Dry matter
EM	Egg mass
EP	Egg production
EU	European Union
FAO	Food and Agriculture Organization
g	Gram
FB	Faba bean
GAIN	Global Agricultural Information Network
FFB	Fresh unit bunches (fresh fruit bunches)
GHG	Greenhouse gas
h	Hour
GWP	Global warming potential
Kcal	Kilocalories
LCA	Life cycle assessment
LW	Live weight
Lys	Lysine
MBM	Meat and bone meal
ME	Metabolisable energy
Met	Methionine
MJ/kg	Megajoules per kilogram
MP	Microbial protein
NDF	Neutral detergent fibre
NE	Net energy
NIRS	Near Infrared Spectroscopy
NSP	Non-starch polysaccharides
POL	Point of lay
PUFA	Polyunsaturated fatty acid
SBM	Soybean meal
SCP	Single-cell protein
TNF	Tumour necrosis factor
US	United States of America
USDA	United States Department of Agriculture

WBG	Wet brewers' grains
Wk	Week

Executive Summary

Introduction/brief background

Rapid expansion of poultry production, shortage of conventional feed ingredients, and the price inflation of feedstuff have emerged as major barriers to the long-term sustainability development of the poultry industry. The Australian chicken and pork industries annually import 1.2 million tonnes of soybean meal for use in feeds to satisfy the protein and amino acid requirements of the animals/birds. This soybean meal comes with an emission profile of 1.87–3.03 t CO_2-eq per tonne and is a major contributor to the greenhouse gas (GHG) emissions profile of Australian eggs, chicken meat and pork products, with about 40–60% of all contributed emissions relating to the feed source. There are multiple alternative ingredients that can replace soybean meal in laying hen and pig diets, however, lack of up-to-date knowledge often causes the opportunity to be lost.

This project specifically aimed at a systematic literature review and industry consultation to collect information regarding the potential alternative ingredients that can replace soybean meal fully or partially, regarding:

- global and Australian production quantities
- general characteristics
- nutrient composition and digestibility
- antinutritional factors and processing requirements (extraction methods, quality)
- production performance of pigs and laying hens when fed with the alternative ingredients
- sustainability of production, carbon footprint and life cycle assessments.

Overview of the desktop review

Alternative ingredients that can supply protein/amino acids for pigs and laying hens were divided into six categories including:

1. Oilseed meals: canola meal; sunflower meal; sesame meal; coconut meal; peanut meal; palm kernel meal; cottonseed meal.
2. Legumes and pulses: beans; peas; chickpea; guar meal.
3. Plant by-products: DDGS; gluten meal; lupins.
4. Animal by-products/insect meal: hatchery waste; slaughterhouse waste; insect meals.
5. Aquaculture protein sources: microalgae; duckweed; seaweed.
6. Other sources: protein-rich food wastage; single-cell protein.

Overview of the approach

This systematic approach acquired and gathered the information on alternative protein-rich ingredients to fill in the knowledge gap, which is required prior to conducting animal trials. In this review we have listed the most viable alternative ingredients that can replace soybean meal in laying hens and pig diets. The next step is to propose a framework for animal trials (*in vivo*) where the alternative ingredients will be benchmarked against soybean meal and the amino acid and protein digestibility coefficients and optimum inclusion rates will be updated. Finally, a roadmap will be developed for the feed industry to implement changes.

Overall Conclusions

Over the course of this study, we reviewed over 25 alternative ingredients including traditional feedstuffs that are used sparingly in feed formulations, such as canola meal, sunflower meal, cottonseed meal and coconut meal, and novel ingredients such as microalgae, duckweed and insect meal. The nutrient profile, antinutritional factors, nutritive value, and optimum inclusion rates of each alternative ingredient were summarised, and the maximum inclusion rate with no detrimental effects on production performance was stated. The study determined that certain alternative ingredients possess the capacity to effectively substitute soybean meal in laying hen/pig diets, with no adverse effects on eggs and pork production, egg weight or quality, pork quality, or fatty acid content, provided that the diets are formulated according to the concentration of digestible amino acids and maintain the correct amino acid-to-energy ratio.

Our literature review concluded that canola meal, lupins (or lupin kernel meal to be further investigated), and sunflower meal are among the most viable alternative ingredients that can potentially replace the soybean meal in the diet, where the diet is balanced for digestible amino acids following the ideal protein profile for laying hens. This requires crystalline amino acid (such as lysine and methionine) supplementation.

In addition, our literature review concluded that insect meals such as black soldier fly larvae are emerging novel alternative ingredients that can replace 25–50% of the soybean meal in a correctly formulated balanced diet for laying hens. The beauty of using insect meal lies in the circular economy resulting from its growth on waste streams. This can reduce the carbon footprint of egg production to a great extent and improve the sustainability of the production system. However, the technology of BSFL farming needs to be optimised and the production costs should be reduced in order to successfully include it in least-cost feed formulations.

It needs to be stated that, when it comes to practical formulation of rations, the combination of alternative ingredients may have different additive effects on production performance than the inclusion of solo alternative ingredients. For example, canola meal may replace soybean meal in laying hens' diet, however, the combination of canola meal and sunflower meal increases the fibre content and may become high in antinutritional factors originating from both the meals and therefore generate a limitation on the inclusion of combined canola and sunflower meal.

Based on the data acquired in this report, new and up-to-date research is required to revisit and re-evaluate the alternative ingredients, estimate their amino acids digestibility, study production performance of hens and pigs when fed with alternative ingredients replacing soybean meal at different inclusion rates, study egg quality, pork quality, and the health status of animals/birds. New studies should consider total digestible amino acids in ratio to energy content in feed formulation practices.

1 Soybean meal in animal farming

1.1 Sustainable animal farming

Sustainable agriculture combines the three key objectives of healthy environment, equitable social and economic conditions, and financial gain to achieve balance in social, environmental and economic outcomes. In line with these objectives, livestock farmers in turn not only strive to exercise compassion in raising their animals but seek to improve their produce and earn a livelihood for themselves and their family while simultaneously building their soil, sequestering carbon and trying to lessen greenhouse gas (GHG) impacts (Godde et al., 2021).

Situated squarely within the increasingly strained environment, the agricultural sector, in particular the livestock industry, has recently become a global focus of environmental concern, largely because of the previously unrecognised magnitude of the interface between the two. While the cultivated land within the livestock sector does contribute to the ecoservices provided by the agricultural industry at large by virtue of the nutrient up and down cycling that occurs within this domain, the sector does still, however, negatively impact the environment with its extensive GHG emissions. Gerber et al. (2013) claim that the livestock industry strongly impacts climate change by virtue of its 7.1 gigatons of CO_2-eq annually, which equates to 14.5% of human-induced GHG emissions.

As their feed is the biggest source of the above impacts, the efficiency with which animals convert it into other food products suitable for human consumption determines the energy expended and greenhouse gases expelled when producing livestock outputs.

Wiedemann et al. (2012) using the Life Cycle Assessment (LCA) tool, which is used globally for estimating the environmental cost of producing different outputs, suggest that of all the animals producing meat for human consumption, poultry are the most sustainable as, in comparison to grazing animals, they produce little methane so have a low environmental footprint.

Abiding by current farming systems for rearing pigs and poultry, in terms of meeting the ideal climatic conditions for their wellbeing and the necessary nutrient profiles of individual animals at each stage of their development, ensures the optimisation of growth and feed efficiency. The energy requirements for maintaining body temperature, and sourcing water and feed are thus reduced.

Apart from the above, to strengthen the sustainability of pig and poultry production, it is important to consider the type of feed they are given and how it is produced. Typically, they are fed grains and pulses, for instance corn and soybeans, and in raising crops such as these, the soil-building methods of no-till, crop rotation and cover cropping can help in the sequestration of carbon in the soil, thereby reducing the amount of CO_2 emitting into the atmosphere (reduced carbon footprint). Additionally, pigs and poultry can be fed fruit pulp, cull crops or similar by-products to implement nutrient cycling. Insects fed on crop residue can also comprise part of a sustainable diet for pigs and poultry.

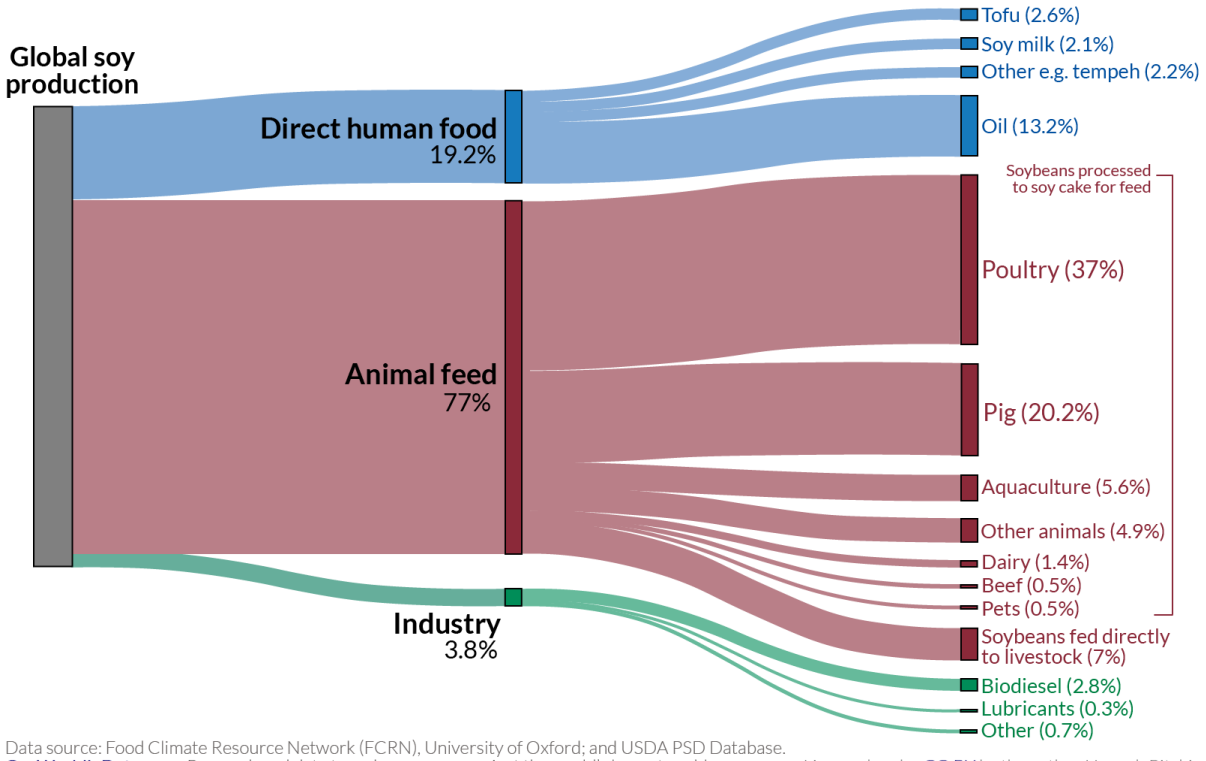
With pigs and poultry, nutrient cycling through feed, manure and soil is a natural phenomenon. The manure fertilises the feed crops, which is particularly efficient in circumstances where the feed crops and animals are raised on the same farm, meaning that pig and poultry production can in fact be carbon neutral, fossil fuel use can be reduced and GHG production minimised. If the feed, energy, and water used to produce pig and poultry products are used efficiently, GHG emissions will be reduced (Gerber et al. 2013) and so the pig and poultry industry will be well on the way to supporting the United Nations Sustainable Development goals of ending hunger, increasing economic prosperity, and promoting social justice.

1.2 Soybean meal: the main source of protein

As expounded by Carter et al. (2004), Glycine max (L.) Merrill, sub family Fabaceae, or soybean, originally from China, was domesticated for food more than five hundred years ago. Oil is removed from the seed by crushing, pressing or solvent extraction for use mainly in food, but it also has industrial uses as oil, soap or biodiesel (Glencross & Carter 2007). A side product of the oil removal process, soybean meal, results from the residue of the seed oil extraction process. It is most often solvent-extracted (44% CP, as-fed basis) and dehulled, solvent-extracted (48% CP, as-fed basis). It is then heated to rid it of the solvent, and toasted to a prescribed temperature (Jiang et al. 2018). It consists of protein, carbohydrates (sucrose, oligosaccharides, and fibrous components), minerals and vitamins and, being rich in phosphorus, is important for the growth and bone integrity of pigs and poultry (Sotak-Peper et al. 2016). As it is heat-treated during production for denaturing its trypsin inhibitors, it does not interfere with protein digestion (Mourtzinis et al. 2017). However, because of its organic nature (phytate), the phosphorus is only moderately available to nonruminants, with pigs and poultry able to access only some through inclusion of dietary phytase as a supplement to their feed. Soybean meal is a good source of energy and it contains large quantities of essential amino acid (approximately 45% of the total amino acid), with methionine as the most limiting amino acid (De-Coca-Sinova et al. 2010).

Of all the protein supplements used for livestock, soybean meal is the most common and, along with legumes, it comprises 15–30% of their diet. Soybean is used for protein extensively beyond that and because of its outstanding amino acid composition, palatability, and digestibility, it constitutes approximately 69% of all animal feed protein sources.

Even though soybean meal accounts for two-thirds of global protein feedstuff output, its chemical composition is varied, and depends on factors such as the latitude of its planting, length of daylight, weather, and other environmental conditions at harvest time (Sotak-Peper et al. 2016). Figure 1 presents soybean use as food, directly in human food, feed (animal feed), or industry/fuel.



Data source: Food Climate Resource Network (FCRN), University of Oxford; and USDA PSD Database.
OurWorldinData.org – Research and data to make progress against the world's largest problems.
Licensed under CC-BY by the author Hannah Ritchie.

Figure 1 Soybean use as food, feed or fuel

The tight control of the sophisticated facilities used to process soybean meal to ensure consistent quality of the product both compositionally and in terms of its physical properties, serve to guarantee the consistency and quality of the protein for the feed formulator. This uniformity allows nutritionists to know that they are providing the key nutrients essential to the least-cost feed formulations (Mourtzinis et al. 2017).

Even though soybean meal is the most popular product, other products of soybean are also used in livestock diets, including full-fat soybeans, soy protein concentrate (SPC), soy protein isolate (SPI) soybean oil, and soybean hulls (Glencross & Carter 2007).

1.3 World's soybean production

The greatest provision of protein in livestock feed globally is derived from soybeans, with approximately 77% of the global crop being processed into meal (for animal feed) and oil (mainly for human consumption). While 7% of soybeans themselves are directly used as human food, particularly in Asia, the rest is used as biodiesel production, and other soybean products such as soy flour (Guo et al. 2021).

Soybeans are cultivated in around 100 countries, with the most important of these being the United States, South America, Europe, China, India, and additional Asian countries (Westcott & Hansen 2016).

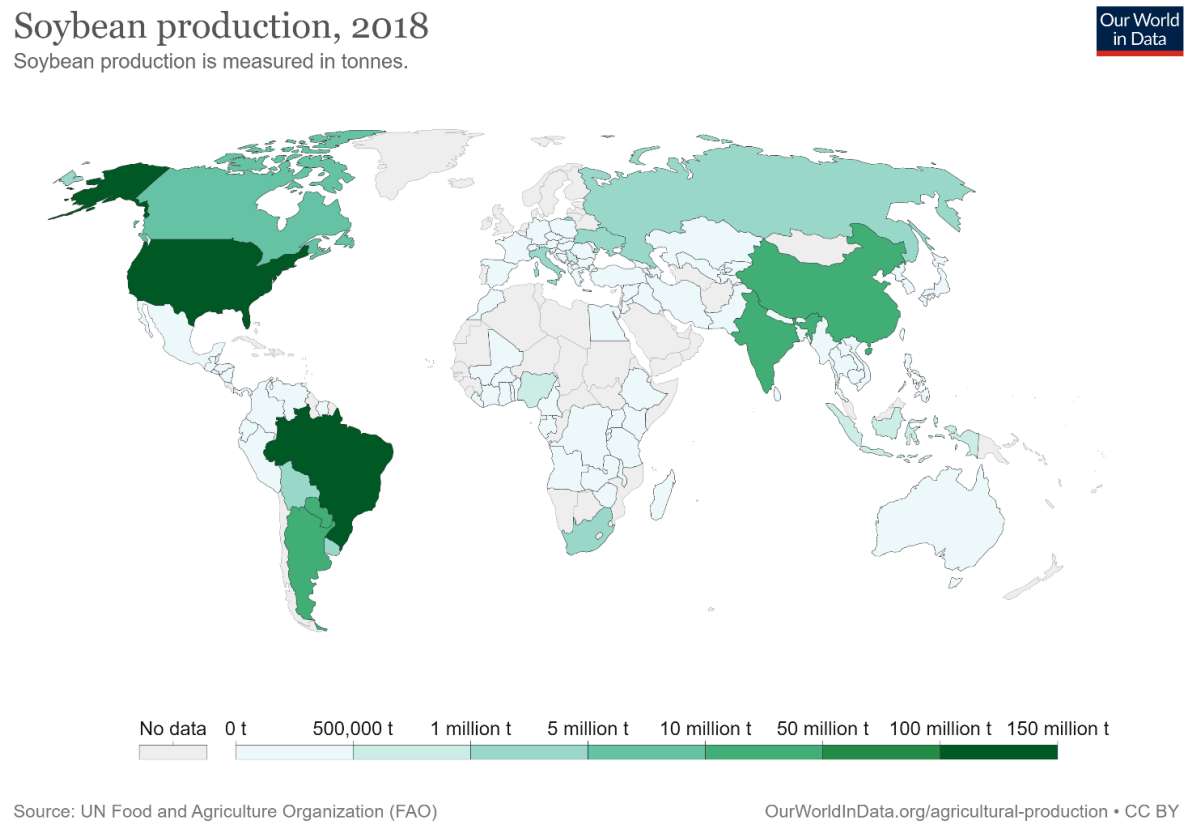


Figure 2 Soy production map worldwide (tonnes)

Kim and Lee (2017) found that the production of soybean for the period 1968 to 2018, grew inexorably over that time both for the area harvested for soybean, and the average crop yield. Their work has been supported by De Maria et al. (2020) who claim there was an 8.4-fold increase in soybean production over the previous 50 years, while the average crop yield grew to nearly twice that of 2000

over the same time frame, and the global surface devoted to soybean cultivation also increased: from 1968's 28.8 million hectares (ha) to nearly 125 million in 2018, that is by a factor of 4.3.

Extensification (soybean cultivation area expansion) and intensification (crop yield increase arising from both genetic and production improvements) combined, seem to be the source of the exponential increase in global soybean production levels (Westcott & Hansen, 2016).

Soybean production globally is currently very concentrated with nearly 90% of the global crop having been produced by five countries: Brazil, the US, Argentina, India and China (Figure 2; 2018). It should be noted that the US share of production has declined to some extent. Among these countries, Brazil appears to be the main soybean player in the world (Zortea et al. 2018), as it has the largest cultivated area (36.9 million hectares), the highest production (128.5 million tonnes), and is the leading exporter (Brito et al. 2021). Over the last decades, soybean production has continued to rise because of its use as an essential source of protein for the growing demand for animal feed and human food globally (Castanheira & Freire 2013; Brito et al. 2021). For example, US soybean production for 2021 totalled a record-high 109 million tonnes (4.44 billion bushels), a 5% increase from 2020 (United States Department of Agriculture 2022b). Brazil, for 2022–23 marketing year, forecasts soybean planted area at 42.5 million hectares (ha), and production at 144 million metric tonnes (United States Department of Agriculture 2022a).

Such remarkable increase in soybean production, reflects soybean the increase it its consumption. The Foreign Agriculture Service of the USDA data indicated that China, the US, Argentina, Brazil and the EU were the five biggest consumers, accounting for around 80% of the 2019 soybean global consumption. In 1999 China consumed less than half of the soybeans utilised by the US, despite a much greater population (4.5 times the US population; American Soybean Association 2018).

It was by 2009 that China had become the largest consumer of soybeans globally and surpassed the US, and in 2019 30% of global soybean production was consumed in China. At the same time, the consumption of soybean oil has also been on the increase, with India and China mainly responsible for this, being fourth and first, respectively in terms of global ratings for consuming it. Jointly, they utilise almost a third of the soybean oil traded internationally. China's internal production of soybean oil today is approximately 14% of its requirements, assuming it currently uses around five times more soybean than in 1999 (Guo et al. 2021).

1.4 Carbon footprint of soybean production

The soybean's impact on climate change is largely dependent on where it is grown and where eventually shipped. Even though policy efforts may be directed at ensuring soybean production in the most GHG-efficient regions, they often ignore the GHG emissions embedded in the agricultural inputs. From an ecological sustainability perspective, rising figures of soybean production are worrisome as significant GHG emissions may result from land use change due to the expansion and cultivation of soybean (Castanheira & Freire 2013). Research showed that ecological problems, such as excessive water usage, soil erosion and deforestation, are deeply associated with soy production (Jia et al. 2020). For instance, the GHG emissions in the Amazon, Brazil, mainly come from deforestation and land use conflict rather than fossil fuel use (Jia et al. 2020). Many reasons exist to explain why, in practice, soybean crop production and the soybean animal feed trade are among the chief sources of GHG emissions:

a) Deforestation because of soybean plantations occurs in many countries, such as in the rainforest areas of Brazil. The change from natural forested area to arable land for use in supporting global population increases is a key, and probably the most significant, contributor to global climate change, since arable land binds much less CO_2 than the original forest

ecosystems. When trees are cut down, they release carbon into the atmosphere rather than store it for eons; thus, deforestation increases the carbon footprint of any product cultivated on the cleared, arable land of ex-forests.

b) Because of the large amounts of feed that livestock eat, massive areas of arable land, and tons of fertiliser, water and other resources must be used to produce sufficient quantities of soybeans. This is evident in monogastric farming, where 60% of the carbon footprint emanates from feed, and mainly from its soybean meal component.
c) Acid-neutralising lime, synthetic fertilisers, pesticides and herbicides are all used in large quantities in soybean cultivation.
d) Hexane, an extremely flammable, non-bio renewable solvent, is usually used to extract soybean meal; it is regulated as a hazardous air pollutant (Sun et al. 2021).

A carbon footprint is the total amount of GHG (carbon dioxide, methane and nitrous oxide) caused by a product, expressed as carbon dioxide equivalents (CO_2e or CO_2-eq) (Gil 2020). As soil can store carbon, thereby reducing carbon dioxide concentrations in the atmosphere, agriculture can do more than merely reduce GHG emissions. It can foster carbon sequestration, which can offset GHG emission impacts (Tamburini et al. 2020). As organic matter constitutes most of the sequestered carbon, all practices and tools that increase soil organic matter along with maintaining soil stability and keeping vegetation on the ground, can help sequester carbon (Wang, Wang, Han et al. 2021).

Hydrogen coupled CO_2 fixation, or the process by which nitrogen fixation releases H_2 into the soil system and so promotes chemoautotrophic carbon fixation by soil microbes (Lu et al. 2020), is one explanation for the increased carbon storage in soil that comes with sequestration, though the mechanism is largely unclear. It is difficult to estimate agricultural activity contributions to GHG emissions compared to the benefits to be derived from carbon storage in agricultural processes, especially for soybeans and other legume crops.

One methodology used to estimate carbon footprints and environmental impacts embedded in all stages of a product's life, is Life Cycle Assessment (or Analysis) (LCA). It analyses a product's entire life cycle and can account for many impact categories. In doing this, it considers all relevant phases of the product life, including its use of land, water, transport routes, manufacturing processes, disposal and in addition, it considers the acidification of the ocean (Esteves et al. 2016).

Carbon foot printing is the name of the life cycle assessment process at the individual product level, as such assessment particularly focuses on the product's generation of GHG emissions, or product carbon footprint (PCF). A carbon footprint analysis is a subset of a complete life cycle assessment of a product, activity or process and is always based on internationally recognised standards (ISO 14040/44, ISO 14067, PAS 2050, GHG Product Life Cycle Standard). A CO_2 balance at the product level (product carbon footprint) results from an application of the LCA methodology that focuses specifically on GHG emissions (Matsuura et al. 2017).

Briefly, some LCA benefits are:

a) Emissions overview of individual services and products.
b) Optimisation potential identified within operations and life cycles.
c) Products or services compared in terms of eco-friendliness or impact on the environment.
d) Environmental-friendly or climate-neutral product developed by recording the GHG emissions and creating carbon foot printing with the appropriate offsetting options.
e) Provision of the basis for communicating the product or service's ecological performance, based on facts.

Thus, the comprehensive, product–specific carbon footprints are paramount for successful climate change mitigation (Kookos et al. 2019).

Life Cycle Assessment (LCA) studies on soybean (Greenhut et al. 2013) may reflect how this commodity impacts the environment from cradle-to-grave (production, transportation and distribution) (Brito et al. 2021). In Latin American case studies, Castanheira and Freire (2013) observed a large disparity in soybean carbon footprint (CF) ranging from 0.1 to 17.8 kg CO_2-eq/kg of soybean depending on original land use and soil/crop management. The highest GHG emissions were calculated for a humid tropical region where the rainforest is transformed into soybean cultivation. Without considering the land use conversion, CF varies from 0.3–0.6 kg CO_2eq/kg of soybean (Castanheira & Freire 2013). Another case study in China – the fourth largest soy-producing country – found that the soybean of China had an average carbon footprint of 222 kg CO_2-eq/ha, and 0.10 kg CO_2-eq /kg of product (Cheng et al. 2015). In a study, Brito et al. (2021) showed that the soybean production system (agricultural phase) is the hotspot that has the greatest contribution of CF (ranging from 29.6% to 95.4%) in different impact categories.

Apart from production system, different studies found that soybean transportation can significantly contribute to the GHG balance as the soy supply chain involves a much-extended transportation distance to meet international demand (Castanheira & Freire 2013; Jia et al. 2020). For example, 42% of the soybean produced in Brazil and 25% in Argentina was exported for processing in other countries. Apparently, road transport and long-distance transoceanic transport might increase GHG emissions affecting the environment (Prudêncio da Silva et al. 2010; Castanheira & Freire 2013). Castanheira and Freire (2013) found that transportation contributes between 47% and 60% to the total GHG emissions depending on farming systems and other issues.

1.5 Soybean international trade and price change

Of all segments of global agricultural trade, soybean is the largest and most concentrated. Major soybean trade routes traverse the Pacific Ocean triangularly between China, Brazil, and the US (Gale et al. 2019), meaning that the soybean industry and its related commercial flows converge around these three countries; but it must be remembered that more than 170 countries internationally trade soybean (Banaszkiewicz 2011).

In the last two decades, China's soybean production has remained quite constant, though its consumption levels rose at the same time. This has allowed foreign exporters to close the gap, with Brazil and the US leading the way with their combined approximate 80% of the world's soybeans production (Guo et al. 2021). With its increasing wealth, China, along with global developing economies, is expected to increase its meat consumption, which will benefit the soybean market, via the use of soybeans as livestock feed and as a healthy protein-rich human food choice.

It is anticipated that Brazil and the US, the two leading soybean cultivators, will produce 139 million tonnes and 120.8 million tonnes respectively, of soybean in 2021-22. In 2020, the value of US soybean international sales reached a record of US$25.7 billion, up nearly 40 per cent (US$7 billion) by value and up 23 per cent (11.9 million tonnes) by volume from the previous year. Brazil also exported significant quantities of whole soybeans to Europe, and further volumes to Asia, the Middle East and elsewhere in the world (Dhoubhadel et al. 2023).

Looking at the other side of the picture, it is expected that soybean consumption will climb further in 2021–22. Market analysts predict China, thought to be the primary driver of the swelling oilseed trade, will buy a record 103.8 million tonnes of soybeans over 2021–22, that is, about 60% of the global trade (Shaik & Addey 2020). As a result of its steady rise over recent years, the global soybean market is

expected to reach a record 173.4 million tonnes in 2021–22 (Shaik & Addey 2020). Further, Transparency Market Research believes the value of this market will grow from US$146.23 billion in 2017, to US$215.746 billion in 2025 – unless consumer health preferences change, which could spell bad news for soybeans (Shea et al. 2020).

Together with recent unfavourable South American weather conditions and tight ending stocks, robust demand from China has seen increases in global soybean prices. Consequently, Brazilian soybean prices have doubled for the past decade (https://www.indexmundi.com/commodities), while US future prices may rise to $7 year on year. Future price and supply may be affected by changing trends in climate change, which in turn affect soybean crop production. Because of the COVID-19 pandemic, the shipping industry has also undergone dramatic changes, and these too have caused serious disruptions for soybean exporters world-wide (Abraham et al. 2020).

1.6 Australian soybean industry

Constituting an important part of Australia's $2.5 billion oilseed industry, soybean production is not only important to Australian farmers, but it's also an important contributor to regional economies, as businesses associated with the industry include input suppliers, service providers, soybean processing facilities and soy food manufacturers, all regionally based. The sustainability and profitability of farming systems also benefit from soybean cultivation, as it is a rotation crop that improves soil fertility and works as a disease breaker (Stirling et al. 2007).

Soybeans have adapted to broad areas of Australia, from northern Queensland to the Darling Downs and its inland river valleys, down to the NSW coastal hinterland and coastal belt areas, and to the inland cropping areas of southern NSW and Victoria. They are additionally grown in Western Australia's northern irrigation areas. Their successful growth demands adequate summer rainfall, which restricts their growing areas to those that naturally receive such rainfall, or to areas under irrigation (Willis 2003).

Although Australia is a relatively small player in the soybean industry, in terms of both production and consumption, its status is growing in both areas. With the prevalent dry conditions of 2002–03, Australia had one of the smallest soybean crops on record, with plantings severely restricted because of the weather. However, in 2020, 44.06 thousand tonnes of soybeans were produced in Australia, and the forecast is that production by 2030 will reach almost 44.1 thousand tonnes (https://www.statista.com/statistics/631832/australia-volume-soybean-crop/).

Compared with the animal industries' requirements of 1 million tonnes of soybean meal annually (2021), Australia's typical annual 30–40 thousand tonnes of soybean meal production is minor. Because of this serious shortfall, Australia is relegated to be a net importer of soybean meal (Figure 3), importing more than 1 million tonnes of it annually from nations such as Argentina, Brazil and the US to meet the intensive livestock industry requirements (Milan et al. 2025).

Most soybean grown in Australia is harvested for grain, and there are three main divisions under which it is marketed: the oilseed crushing sector, the full-fat meal, and the human consumption sector. The major one of these is the oilseed crushing division in which crushed soybean is processed into vegetable oils, which are further processed into table oils, margarine and soybean meal as animal feed. The oil from the soybean can also be used for industrial applications such as biodiesel (González-Orozco et al. 2012).

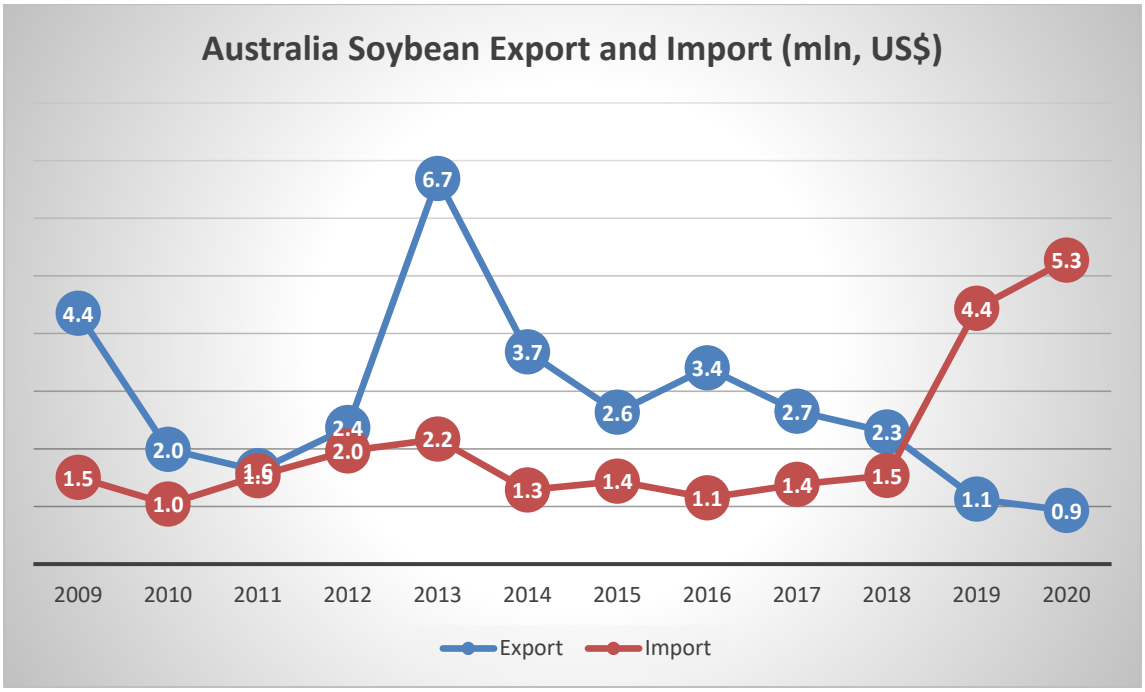


Figure 3 Australia soybean export and import

While almost 50% of the crop was crushed for oil and meal, up until the late 1990s, a further 25% went into full-fat meal for intensive raising of livestock. At the same time, around 20% of the crop went into the human consumption market, with the remaining 5% being retained as planting seed.

Over the last ten years, this has changed: the crush and full-fat sectors have declined, while the domestic consumption of edible beans has increased, as has the export market. The higher returns from the culinary markets have driven this shift, and they have been facilitated by the availability of new soybean varieties aimed at the higher quality product that the growing markets require.

The north coast of New South Wales is the largest soybean producing area in Australia, other major regions being some inland sections of northern New South Wales, the southern Queensland coast, the Riverina, the north-west of Western Australia, and the Northern Territory. Sizeable challenges are thus presented to the soybean industry in its efforts to develop Australian varieties, with the wide latitude range of the growing areas (12° to 36° south), the different lengths of daylight in each, and the differences in district temperatures, disease prevalence, and environments (Yang & James 2014).

Soy Australia represents the soybean industry and was formed with the aid of:

- Australian Oilseeds Federation (AOF)
- Northern Australian Soybean Industry Association (NASIA)
- North Coast Oilseed Growers Association (NCOGA)
- Riverina Soybean Growers Association (RSGA).

Solvent extracted soybean meal is the main product of interest in the animal feed industry and is both produced in Australia and imported from the US. Additional to that, there is also same industry interest in full-fat soybean meal for animal feed. Australia produces around 20 thousand tonnes of full-fat soybean, annually.

1.7 Alternative protein-rich ingredient to soybean meal

Pigs and poultry receive compound feed, in which the major and most common protein ingredient is soybean meal, which provides the necessary amino acids for the growth and production (Walugembe et al. 2015).

Characteristics of soybean meal include its extreme palatability, significant protein content and good balance of amino acids including lysine, tryptophan, threonine and isoleucine, but low crude fibre content, which is less than 3% for the meal from dehulled soybeans. Recently, however, there has been some change in that the animal feed industry is actively seeking alternatives to soybean and its meal because of its fluctuating prices, which can be quite high (Van Zanten et al. 2016). Additionally, there are the sustainability issues with soybean production because of its association with natural grassland destruction and deforestation in parts of the world. These factors directly affect small-scale farmers in soybean producing areas (Zu Ermgassen et al. 2020).

Of concern, is the fact that most US soybean is from genetically modified seed. In addition, the phytoestrogen in soybeans is concerning, as they imitate the way estrogen, the female hormone, behaves (Gatta et al. 2013). As a result, the soybean allergies are becoming more common in people, especially children (Savage et al. 2010) and consumers increasingly seek alternatives to soybean and are looking for soybean-free choices in their diets (Lourenço et al. 2019). High soil erosion rates for land under soybean cultivation and unsustainable water use via irrigation are further problems faced by soybean farmers, along with the use of agrochemicals and fertilisers that they use to improve the efficiency of their farming methodology. The chemicals used are heavy pollutants of rivers, lakes, and estuary waters globally.

As a result of the above problems, soybean-free diets have become more popular, while consumers have become increasingly ethical in their food choices and supportive of sustainable production systems, yet, as Banaszkiewicz (2011) points out, the effects of the soybean-free diets on an animal's growth performance and product quality are far from clear.

Alternatives to soybean meal in livestock diets need to be assessed in terms of local production volume, sustainability, transport distances, requirements for further processing, cost, nutrient composition and quality, digestibility, and palatability for pigs and poultry. Exploration is needed of local, low-cost potential alternative protein sources for livestock feed, especially if such sources have little or no direct value as food for humans.

With all the above in mind, it is obvious that alternative livestock protein, especially that which may be of some nutritional benefit for humans, should be sought and sourced locally and as inexpensively as possible. It is also of importance that such food be of sound pedigree in terms of climate effect and environmental impact. Thus, in the long-term, the aim is to replace imported livestock feed with Australian-cultivated protein alternatives. That said, the cost of the protein ingredient and subsequent mixed diet for livestock production performance is a key, and least-cost feed formulation for determination of the value of each source of protein is vital. Table 1 lists all the alternative ingredients produced in Australia and their production volumes (ACE Livestock Consulting Pty Ltd).

Table 1 Production volume of protein-rich ingredients in different Australian States

	Australian production							
Production (kt)	**2021-22**	**2020-21**	**2019-20**	**2018-19**	**2017-18**	**2016-17**	**2015-16**	**Average**
Chickpeas	1004	733	235	205	998	2004	875	865
Faba beans	520	510	313	233	416	484	301	397
Field peas	261	294	210	160	317	415	205	266
Lentils	656	634	526	359	543	680	182	511
Lupins	808	774	591	799	714	1031	652	767
Canola	5732	4524	2299	2366	3893	4313	2775	3700
Soybeans	26.6	26.9	11	9.2	13.6	17.3	19.2	17.7
NSW production								
Chickpeas	440	374	24.4	22.2	407	792	489	364
Faba beans	88	110	14.6	7.9	63.3	78	143	72
Field peas	45.1	61	18	18.5	46.4	85	72.5	49.5
Lentils	9.5	9.8	2.8	3.4	1.3	10	2.9	5.7
Lupins	122	130	23.6	23.8	46.4	663	111	160
Canola	1600	1395	206	263	893	1248	937	935
Soybeans	28.9	31.2	8.3	5.8	17.2	23.8	20	19.3
Queensland production								
Chickpeas	527	275	162	118	467	1150	371	439
Faba beans	64.8	42	8	4.6	4.8	14.6	11	21
Field peas								
Lentils	1.3	0.1	0.2	0.1	0.2	0.5	0.4	0.4
Lupins	1.1	0.1						0.6
Canola	4	1.2	0.9	0.3	0.3		2.8	1.6
Soybeans	10.7	11.5	8.8	7.5	10.2	6.8	8.3	9.1
South Australian production								
Chickpeas	11	11	18.1	26.6	38.4	27	7.1	20
Faba beans	190	185	121	128	132	160	84.4	143
Field peas	85	105	89.9	53.1	137	175	82.1	104
Lentils	350	300	234	213	274	470	137	283
Lupins	45	50	41.3	37.2	82.3	100	52.8	58
Canola	375	375	241	243	335	382	219	310
Soybeans								
Tasmanian production								
Lupins		0.5	2	0.4	0.9	0.1		0.8
Canola	2.5	2.6	1.7	2.7	3.5	2.9	2	2.6
Victorian production								
Chickpeas	40	67.5	25.5	24.4	78.3	28	3.5	38
Faba beans	162	160	159	67.2	196	220	57.3	146
Field peas	71	82.5	85.2	42.8	91.4	100	20.6	71
Lentils	275	306	268	128	261	200	39.9	211
Lupins	39	43.7	39.1	24.4	52.2	60	31.1	41
Canola	1000	1100	731	511	938	633	287	743
Soybeans	1.1	1	0.2	1.8	1.5	0.7	1.1	1.1
Western Australian production								

Chickpeas	6	5	5.1	14.3	7.5	7	3.9	7
Faba beans	15	12.5	10.4	26.1	20	11	4	14
Field peas	60	45	44.3	45.1	42.3	55	29.3	46
Lentils	20	18	20.8	14.8	6	0	1.4	12
Lupins	600	550	485	713	532	805	457	592
Canola	2750	1650	1117	1346	1724	2048	1328	1709
Soybeans								

(Source: ACE Livestock Consulting Pty Ltd 2022)

2 Oilseed meals as protein sources

2.1 Canola meal/rapeseed meal

Canola seeds, or rapeseed are the seeds of the oilseed rape plant (Brassica napus L. and interspecific crosses of Brassica napus with other Brassica species including Brassica rapa L. and the brown mustard Brassica juncea (L.) Czern). After soybean oil and palm oil, canola seeds are the third-largest source of vegetable oil and third largest oilseed meal (after soybean meal and cottonseed meal). They belong to the family Brassicaceae, which also includes cabbage, mustard, turnips, radishes, and cauliflower, and are the most extensively grown agricultural species. There are many different canola seed varieties available (Snowdon 2006). The major uses of modern canola seed types with low levels of antinutritional factors (erucic acid and glucosinolates) include edible oil, biofuel, industrial oil, and lubricants. Oilseed rape plants can be sown in the autumn, or the spring for winter and spring varieties, respectively. Canola plants grow steadily during the whole growing season. The cycle of growth starts with the seed, which is followed by leaves, branches, flowers, pods, and seeds. The variety, fertility, moisture, soil conditions, temperature, day length, and sunlight have an impact on how long each phase or stage of growth lasts.

Canola seed is grown all over the world, however, it is believed to have originated from Europe. It is mostly cultivated in temperate areas and also grown at high elevations. In geographical areas where the winter is mild such as Europe and Asia, it is mainly cultivated as a winter crop. In Canada, northern Europe and Australia, spring varieties are more suitable (Snowdon 2006). Canola seed crop is prone to heat stress in very hot weathers. It is a good alternative crop to soybean in soils where soybean cultivation is not very successful. The optimum climate conditions for canola seed cultivation are an annual rainfall between 300 and 2800 mm and an optimum temperature of 20°C (between 12 and 30°C). It responds well to nitrogen and phosphorous fertiliser. Oilseed canola is frost-resistant and can stand -4°C at all stages of growth. It is relatively tolerant to soil salinity, but sensitive to aluminium and manganese toxicity in acid soils.

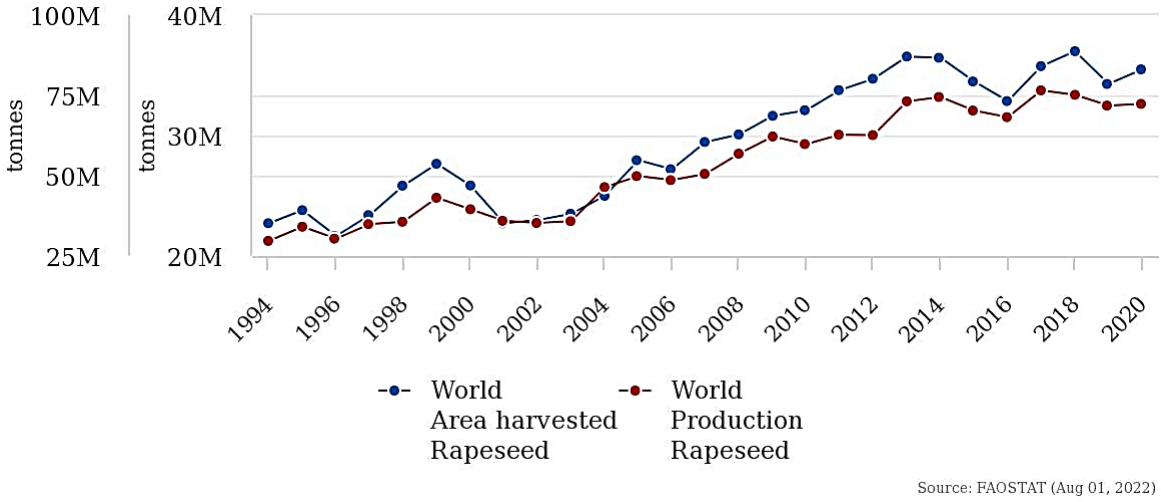
About 40–45% of the canola seed is oil. Every 23 kg of canola seed makes 10 L of canola oil. Canola oil is made at a processing facility by slightly heating and then crushing the seed. Then the oil is extracted using hexane solvent, which is recovered at the end of processing. At the final stage, canola oil is refined using water precipitation and organic acids to remove free fatty acids and gums, filtration to remove colour, and deodorising through steam distillation. The oil might be bleached to have a lighter colour. Mechanical oil extraction or cold-pressed canola oil is limited.

Canola oil has low saturated fats and a substantial amount of mono-unsaturated fatty acids, with roughly a 2:1 mono- to polyunsaturated fats ratio, being a healthy choice for human consumption. It has been reported that canola oil consumption may reduce the risk of coronary heart disease, resulting from its significant content of unsaturated fats. Canola seed oil extraction yields about 55–60% meal when fully extracted by crushing followed by solvent extraction. The main steps of the process include seed cleaning, seed preconditioning, rolling and flaking, cooking and pressing to mechanically remove a portion of the oil, solvent extraction (hexane) of the press-cake to remove the remaining oil, and toasting (Gaber et al. 2018). One of the key elements influencing the quality of rapeseed meal is temperature. Canola seed meal that has been solvent-extracted shouldn't have more than 2% to 3% oil in it.

2.1.1 Canola and meal production globally and in Australia

Oilseed canola has been grown for its oil in Europe since the 13th century. Until petroleum replaced it in the middle of the 19th century, it was a significant source of lamp fuel. Due to the presence of erucic acid, which has a bitter taste and was later discovered to have negative health effects when consumed in excessive doses, canola oil previously had a bad image as a food. The presence of glucosinolates, as an antinutritional factor with detrimental effects on animal performance, further restricted the use of canola meal as an animal feed.

Since 1960–1970s, canola oil became a significant source of food-grade oil for human consumption after the development of low-erucic varieties (called "0"), and low-erucic plus low-glucosinolate varieties (called "00"), as well as canola meal becoming a major protein ingredient for livestock feed. The double zero varieties were introduced commercially in the mid-1970s in Canada and in the late 1980s in France. The majority of cultivars developed now for edible oil, biofuel, industrial oil, and lubricants are double zero variants. Additionally, high-erucic variants are produced for particular industrial uses (Snowdon 2006). Figure 4 presents global rapeseed production from 1994 to 2020.



Source: FAOSTAT (Aug 01, 2022)

Figure 4 Global canola/rapeseed production 1994–2020

The amount of canola meal produced globally in 2018 was 38.8 million tonnes, which was slightly lower than in 2015-2016 (39.1 million tonnes). (USDA 2016). In 2018, the European Union produced the most canola meal (12.8 million tonnes), followed by China (9.6 million tonnes), Canada (5.3 million tonnes), and India (4.0 million tonnes). European Union, China, North America (the US and Canada), and India were the top consumers of canola meal (IndexMundi 2019; Oil World 2015).

The global production of canola is estimated at 70 million tonnes. After soybeans, oil palm, and cotton seeds, it is the fourth-largest producer of oil seeds (FAO 2014). The top canola producers are Canada (19.5 million tonnes), European Union (16.29 million tonnes, with Germany 6 million tonnes, France 4.5 million tonnes), China (14.05 million tonnes), India (8.5 million tonnes), with Australia (5 million tonnes), Poland, Ukraine, the UK, and the Czech Republic rounding out the top ten (Figure 5, by region). Canada produces 20 per cent of the world's canola and is by far the largest exporter, accounting for more than 70% of the export trade.

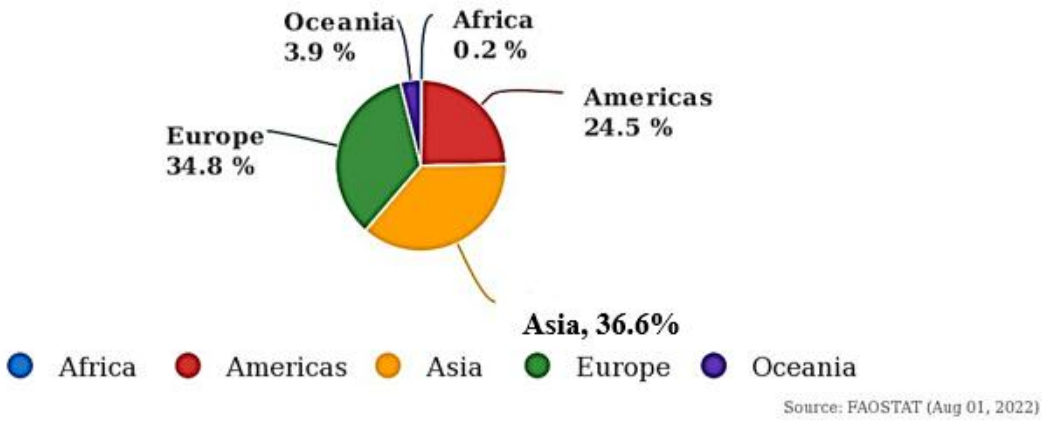


Figure 5 Production share of canola seed by region 1994–2020

Australia has produced about 5–6 million tonnes oilseed crops each year, with canola and cottonseed accounting for over 90 per cent of the total oilseed production. Western Australia (WA) is the major canola-growing state in Australia, producing about 40% of the nation's annual production. The majority of the canola produced in Western Australia is exported, which generates about $0.6 billion revenue for the state.

Australian Oilseed Federation Crop Report (Figure 6) shows that the total production volume and gross production value of canola to reach 5.238 million tonnes and $5.2 billion dollars in 2021–2022, almost four times higher than 2018–2019 and 2019–2020. Domestic prices are still quite high due to the limited foreign supply brought on by the drought in Canada in 2023, the continued high demand for biofuel production in the US and Europe, and Ukraine's failure to meet global demand. Ukraine was the world's top exporter of sunflower meal and oil, the third-largest exporter of canola, and ranked the seventh in soybean export globally.

Canola 2022/23

	2020/21 Final		May 2022 Estimate	
	Harvested Area (hectares)	Production (tonnes)	Sown Area (hectares)	Production (tonnes)
NSW	700,000	1,637,000	825,000	1,360,000
Vic	500,000	1,144,000	525,000	865,000
SA	230,000	418,000	270,000	378,000
WA	1,540,000	3,130,000	1,700,000	2,635,000
Total	**2,970,000**	**6,329,000**	**3,320,000**	**5,238,000**

Source: Industry Estimates, GIWA; NSW DPI, DEDJTR (Vic)

Figure 6 Projection of canola production in Australia 2022–2023

2.1.2 General characteristics

Canola seeds are a good source of protein and lipids with approximately 21% crude protein (17–24% of DM), which is higher than sunflower seeds (17%), but lower than soybeans (40%) and linseeds (24%) and are comparable to cottonseeds (22%). They contain a high oil content of 46% (40–50% DM), which is significantly greater than that of linseeds (37%), soybeans (21%), and cottonseeds (20%), and only slightly lower than that of sunflower seeds (48%). Canola seeds have far less fibre than any other

oilseeds, (crude fibre 10% DM, neutral detergent fibre (NDF) 21% DM, and acid detergent fibre (ADF) 15% DM) with the exception of soybeans (crude fibre 6% DM).

Canola meal is relatively rich in fibre (10%) and removing the hulls reduces the fibre content while increasing the protein content of the meal, which improves the nutritive value of the meal for pigs and poultry. However, due to some factors such as increased processing costs, removal of a fraction of oil with the hulls and the limited market for hulls, dehulling of the canola is not a common large-scale practice. In saying that, during recent years there has been an interest to identify protein alternatives to replace soybean meal in livestock feed, and with the advent of new tools and techniques, dehulling is being investigated again. In a recent methodology developed for the EU "Feed-a-Gene" project, the meal obtained after crushing is subjected to tail-end fractionation. The meal is then divided into a high-protein fraction and a low-protein portion using a plantsifter (Bach Knudsen 2018).

Table 2 Chemical composition of low erucic, low glucosinolates canola seed

Main analysis	Unit	Avg	SD	Min	Max	Nb
Dry matter	% as fed	92.3	1.1	87.3	94.9	3844
Crude protein	% DM	20.9	1.2	17.5	24.6	3630
Crude fibre	% DM	10.1	2.2	5.8	15.7	2035
NDF	% DM	20.4	4.6	13.2	30.5	78
ADF	% DM	14.4	3.2	9.1	21.4	76
Lignin	% DM	6.3	1.3	4.5	10.2	78
Ether extract	% DM	46.0	2.1	39.8	51.0	1598
Ash	% DM	4.3	0.2	3.7	5.0	1683
Starch (polarimetry)	% DM	3.7	0.9	2.7	5.7	9
Total sugars	% DM	5.5	0.7	4.8	7.1	10
Gross energy	MJ/kg DM	28.8	0.7	27.7	30.6	14

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Canola oil is rich in polyunsaturated fatty acids (60% C18:1 oleic acid, 21% C18:2 linoleic acid and 10% C18:3 linolenic acid), which makes it valuable for human and animal diets (Blair 2011). Outcomes of a study in Australia, showed that there are significant differences between the fatty acid profile of the residual oil expeller and solvent-extracted meals. The oleic acid content was 5% less in solvent-extracted meal than expeller meal (54 vs. 59%) and the linoleic acid was 3% higher (25 vs. 22%) (Spragg et al. 2007).

Table 3 Fatty acid profile of low erucic, low glucosinolates canola seed

Fatty acids	Unit	Avg	SD	Min	Max	Nb
Stearic acid C18:0	% Fatty acids	1.7	0.5	1.3	3.3	13
Oleic acid C18:1	% Fatty acids	59.9	2.1	53.5	61.7	13
Linoleic acid C18:2	% fatty acids	20.6	0.6	19.4	21.8	27
Linolenic acid C18:3	% fatty acids	10.1	0.8	8.9	11.6	13

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

2.1.3 Nutritive value for animal feed

Canola meal is a protein-rich ingredients (35–44% of DM), which is comparable to soybean meal and can be used as a substitute for it in livestock feed. Canola has slightly lower lysine than soybean meal (5.5% vs. 6.3% of the crude protein) but sulphur-containing amino acids are in greater quantity than soybean meal (sum of methionine + cysteine: 4.3% vs. 3% of the crude protein in soybean meal). Canola seeds are small and contain about 18–21% oil, and the meal after oil extraction has approximately 30% hulls. The fibre content of the canola meal (10–18%) is higher than that of soybean meal (6–10%), however, the fibre content of canola meal is less than other oil meals such as sunflower meal. One component that restricts its use for animal feed is its lignin content, which is 10% of DM vs. less than 1% in soybean meal.

Solvent extracted meal has about 0.5 – 1% oil left in it, which is a great source of energy (Newkirk 2009), however, low lysine content together with high fibre limits the use of canola meal for pigs and poultry. Previous studies have reported that when canola meal is used as the only source protein for pigs and poultry, the growth performance is impaired. However, the inclusion of crystalline amino acids was not commercially feasible due to the high costs or unavailability. Currently crystalline amino acids are produced much more cheaply, and all the indispensable amino acids and some of dispensable ones are all available commercially at a reasonable price, which is changing the trends in the raw material selections for animal feed industry.

Table 4 Chemical composition of canola meal "00" – solvent extracted

Main analysis	Unit	Avg	SD	Min	Max	Nb
Dry matter	% as fed	89	0.9	84.3	94.5	7005
Crude protein	% DM	38.1	1.3	32.6	44.8	7056
Crude fibre	% DM	14.3	1.2	8.6	18.1	6136
Neutral detergent fibre	% DM	31.6	3.5	20.5	41.6	241
Acid detergent fibre	% DM	20.7	1.6	16.8	26.6	239
Lignin	% DM	9.7	1.2	7.1	13.8	285
Ether extract	% DM	2.4	0.7	0.3	5.7	5758
Ash	% DM	7.6	0.4	6.5	10.4	1164
Insoluble ash	% DM	0.3				
Starch (polarimetry)	% DM	6.3	1.6	0.6	8.1	99
Starch (enzymatic)	% DM	1.6		1.3	1.8	2
Total sugars	% DM	10.5	0.9	8.2	13.6	80
Gross energy	MJ/kg DM	19.3	0.4	18.3	20	28

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Mechanical oil extraction generates a meal with variable but much higher oil content (7–15%% of DM), which is a great source of energy for animals, and due to the lack of heat processing during the cold-pressed oil removal process, the lysine content is higher, indicating less heat damage. However, in cold-pressed meal, myrosinase was not, or less, deactivated than in solvent-extracted meal.

Another study reported a lower glucosinolate content in cold-pressed canola meal, which was below the tolerance levels for pigs. Dehulling (removing hulls before oil extraction) reduces the fibre content and increases the amino acid digestibility in pigs and has been reported to improve the nutritive value of the canola meal. Extruding has been also reported to increase availability of protein to the pig's

digestive enzymes, improved digestibility of most amino acids, and reduced hindgut fermentation of protein.

Table 5 Mineral composition of canola meal "00" – solvent extracted

Minerals	Unit	Avg	SD	Min	Max	Nb
Calcium	g/kg DM	8.6	1	5.1	11.3	433
Phosphorus	g/kg DM	12.7	1	10.2	20.8	511
Potassium	g/kg DM	14.1				
Sodium	g/kg DM	0.29				
Chlorine	g/kg DM	0.7				
Magnesium	g/kg DM	4.6		3.1	5.4	4
Sulfur	g/kg DM	8.3				1
Manganese	mg/kg DM	68	11	49	86	10
Zinc	mg/kg DM	78	25	56	142	18
Copper	mg/kg DM	9	7	2	25	17
Iron	mg/kg DM	183	36	110	202	5
Selenium	mg/kg DM	1				

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Table 6 presents the amino acid content of solvent-extracted canola meal (double zero variety). When compared to soybean meal, canola meal has a comparable (similar or slightly different) concentration of alanine, glutamic acid, glycine, histidine, isoleucine, serine, threonine, tryptophan and valine.

Table 6 Amino acid profile of canola meal "00" – solvent extracted

Amino acids	Unit	Avg	SD	Min	Max	Nb
Alanine	% Protein	4.3	0.1	3.8	4.6	77
Arginine	% Protein	5.8	0.3	5	6.4	129
Aspartic acid	% Protein	7.1	0.3	6.2	8.1	78
Cystine	% Protein	2.4	0.1	1.8	2.6	130
Glutamic acid	% Protein	17	0.9	14.9	21.1	78
Glycine	% Protein	5	0.2	4.4	5.3	77
Histidine	% Protein	2.7	0.08	2.4	2.9	130
Isoleucine	% Protein	4	0.08	3.7	4.3	130
Leucine	% Protein	6.8	0.1	6.6	7.5	130
Lysine	% Protein	5.3	0.3	3.8	6.2	247
Methionine	% Protein	2	0.07	1.8	2.2	127
Methionine+cystine	% Protein	4.4	0.1	4	4.7	129
Phenylalanine	% Protein	3.9	0.1	3.4	4.3	130
Phenylalanine+tyrosine	% Protein	6.7	0.2	6.2	7.5	56
Proline	% Protein	6	0.3	5.3	7	68
Serine	% Protein	4.4	0.2	3.9	4.9	77
Threonine	% Protein	4.3	0.2	3.8	4.8	83
Tryptophan	% Protein	1.2	0.1	1.1	1.7	65
Tyrosine	% Protein	2.8	0.2	2.3	3.4	64
Valine	% Protein	5.1	0.1	4.7	5.5	129

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Canola has slightly higher concentrations of cystine, methionine, methionine + cystine, and proline (% of protein) when compared to soybean meal. The concentrations of arginine, aspartic acid, leucine, lysine, phenylalanine, and tyrosine in canola meal are lower than that of soybean meal (% of protein). The Australian canola meal produced in Western Australia is locally produced canola meal has been reported in an old paper (Mullan et al. 2000) and presented in Table 7. The lysine content of the Australian Canola meal is much more comparable with that of soybean meal. Valine, threonine, proline and methionine concentrations are greater in Australian canola meal compared to soybean meal.

Canola meal is a common feed ingredient for all classes of ruminant livestock, as a source of protein and energy. Canola meal was considered of significantly lower value than soybean meal due to its lower protein content, higher fibre and higher protein degradability, however, several meta-analyses concluded that both the energy and the protein value of canola meal were higher than previously thought. Recent unpublished work from the University of Queensland shows that canola meal combined with other protein rich ingredients and crystalline amino acids can fully replace soybean meal in reduced crude protein diets in broiler chicken feed.

Table 7 Chemical and amino acid composition of Australian canola meal

Chemical Composition	Unit	No. of Samples	Mean	Min	Max	CV (%)
Dry Matter	g/kg DM	8	941	935	953	9.6
Crude protein	g/kg DM	8	327	297	359	6.9
Ether extract	g/kg DM	8	96	82	112	10.0
Crude fibre	g/kg DM	8	136	113	153	10.6
Ash	g/kg DM	8	55	52	60	4.7
Total Glucosinolate	(mmol/kg – oil-free DM)	8	10.5	8.0	13.2	22.3
Amino acids						
Alanine	g/kg DM – (%of CP)	5	14.1 (4.6)	13.5	15.0	4.5
Arginine	g/kg DM – (%of CP)	5	19.5 (6.4)	17.3	21.7	9.3
Aspartic acid	g/kg DM – (%of CP)	5	22.7 (7.4)	20.6	24.9	8.1
Cystine	g/kg DM – (%of CP)	5	7.8 (2.6)	7.4	8.6	6.2
Glutamic acid	g/kg DM – (%of CP)	5	55.1 (18.0)	51.4	60.5	6.9
Glycine	g/kg DM – (%of CP)	5	15.8 (5.2)	14.8	17.1	6.0
Histidine	g/kg DM – (%of CP)	5	8.5 (2.8)	8.0	8.9	5.2
Isoleucine	g/kg DM – (%of CP)	5	12.0 (3.9)	11.4	12.8	4.8
Leucine	g/kg DM – (%of CP)	5	22.2 (7.3)	20.5	24.3	7.2
Lysine	g/kg DM – (%of CP)	5	18.7 (6.1)	17.2	20.0	6.2
Methionine	g/kg DM – (%of CP)	5	6.7 (2.2)	6.3	7.1	4.8
Phenylalanine	g/kg DM – (%of CP)	5	12.5 (4.1)	11.8	13.6	6.7
Proline	g/kg DM – (%of CP)	5	20.2 (6.6)	17.6	21.7	7.9
Serine	g/kg DM – (%of CP)	5	14.8 (4.8)	13.9	15.8	5.4
Threonine	g/kg DM – (%of CP)	5	14.8 (4.8)	13.6	15.9	6.1
Tyrosine	g/kg DM – (%of CP)	5	10.2 (3.3)	9.2	11.0	6.9
Valine	g/kg DM – (%of CP)	5	15.4 (5.0)	14.1	16.7	6.8

(Source: Mullan et al. 2000)

2.1.4 Antinutritional factors – nutritional limitations

Erucic acid

Canola seed used to contain a significant amount of erucic acid (cis 13-docosenoic acid, 22:1n-9), up to 50% in initial varieties. Early research with rats, ducklings, chickens, and pigs showed that erucic acid has a bitter taste, has detrimental effects on heart health, and impairs animal performance. As a result, low-erucic acid varieties ("0") were created in the 1970s, and by 2005, the majority of canola oil produced worldwide contained less than 2% erucic acid (Snowdon 2006; Przybylski et al. 2005). The erucic acid level of foods is currently regulated: in Canada, canola oil must have an erucic acid content of less than 2% (CCC 2014); In the EU, the fat content of the foods must have less than 5% erucic acid, and it should be below 1% for infant formulas.

Although it has been proved that erucic acid results in myocardial lipidosis in pigs and rats, a recent literature review found that this lipidosis regresses after animals are fed with erucic acid-free diet (EFSA 2016). In pigs, a level of 700 mg/kg body weight (BW) per day did not result in any adverse effects. For dairy cows, a reduction in feed intake and milk yield was reported at an intake of 0.4 g erucic acid/kg BW per day from canola meal. The lowest observed adverse effect level of 0.02 g/kg BW per day was defined for poultry, when maximum inclusion rates are applied. As there is a linear increase between the level of the erucic acid in animal feed and the erucic acid in food from animal origin, the dietary erucic acid level remains as a concern.

Erucic acid has a niche industrial use in producing erucamide, which is an additive in polyethylene and polypropylene manufacture; and a surfactant, and behenic acid (Snowdon 2006).

Glucosinolates

Glucosinolates are a family of sulphur-rich glucosides that exist in Brassicaceae plants. The bitter taste of the glucosinolates is caused by the end-products of hydrolysis of glucosinolates including isothiocyanates and other sulphur-containing compounds. This pungent taste is the flavour of mustard oil which is often enjoyable for humans but has a low palatability in livestock and reduces feed intake (A). Metabolically, glucosinolates interfere with iodine metabolism, and cause disorders in the liver, kidneys, and thyroid glands in monogastric animals. Consequently, growth is impaired, and mortality can increase, especially in laying hens, due to haemorrhagic liver syndrome. As stated before, since the 1970s, double zero varieties of canola were developed where the glucosinolates are very low. Based on the Canadian food regulations, canola oil must contain less than 30 µmoles of glucosinolates per gram of dried oil-free canola meal. Further breeding programs have resulted in a steady decrease in the glucosinolate levels in canola (less than 10 µmole vs. 120 µmole in non-“00” varieties). Canadian canola meal has on average 3.9 µmole of glucosinolates, where the French one is about 10 µmole/g.

Tannins

Tannins are phenolic compounds that bind with proteins, reducing their digestibility and availability to animals (Bell 1993). The majority of the tannins in canola seeds are found in the seed coat (Lipsa et al. 2012). Pigs were found to digest yellow hulled seeds quite well, but black hulled seeds were almost indigestible, which was argued to be related to the higher lignin and tannin levels in darker seeds. The “000” varieties are reported to have less tannins. Current breeding programs include reducing the thickness of the seed coat, and hence the tannin amount. Therefore, the dehulled light-coloured canola meal has lower tannin content.

Choline and Sinapine

Canola seeds are rich in choline and sinapine, two compounds that function as precursors to trimethylamine. Feeding canola meal to laying hens that produce brown-shelled eggs and lack the trimethylamine-degrading enzyme, resulted in eggs with a fishy flavour and smell. Therefore, the inclusion of canola meal for this breed of layers should be restricted (Honkatukia et al., 2005).

2.1.5 Canola meal in the laying hen diet

Canola meal is a potential alternative protein ingredient to soybean meal and is fed to all types of poultry throughout the world. Canola meal can be a cost-effective alternative to other proteins in poultry diets. The nutritive value of canola meal for poultry is lower than that of soybean meal and therefore low inclusion levels of canola meal e.g. 4–10% was initially recommended in laying hen diets.

Early studies using diets formulated based on crude protein demonstrated a decrease in egg weight when canola meal was used in place of soybean meal. The canola meal-based diet had a lower lysine content, which was overlooked when the diets were formulated only on the basis of crude protein (Kaminska 2003). In a study by Novak et al. (2004), the lysine deficiency in canola meal-based diets was argued as the cause of reduction in egg weight. The researchers increased the egg weight (from 59.0 g to 60.2 g) by increasing the lysine content of the diet from 860 mg/day to 959 mg/day in canola meal-based diets.

In old studies, the inclusion of canola meal (initial varieties) at higher than 10% inclusion rate was associated with liver haemorrhage mortality, which was linked to the glucosinolate levels (Butler et al. 1982; Campbell & Slominski 1991). The double zero “00” varieties of canola meal have a very low level of glucosinolate as a result of breeding and hence, new studies show excellent performance of laying hens when canola meal is included at a much higher rate. According to the research done by Oryschak and Beltranena (2013), canola meal can be incorporated in a layer diet at an inclusion rate of 20% without having negative impacts on egg production, egg quality, or egg fatty acid content. In the mentioned study, egg weight and lay percentage were maintained for the duration of the 36-week long study. No fishy odour or liver-haemorrhages were detected during the study.

Similarly, Rogiewicz et al. (2015) demonstrated that canola meal can be used in laying hens’ diets at 15–20% inclusion rate with no detrimental effects on lay performance. In another study, laying hens were fed with diets containing 0 (control: soybean meal), 8, 16, and 24% of canola meal replacing soybean meal in the control diet, from 33 to 49 weeks of age. Feed intake, egg production, egg weight, and body weight were not affected by the canola meal inclusion rates (Groski et al. 2015).

In a recent study by Savary et al. (2017), canola meal replaced soybean meal at two inclusion rates of 10 or 20%. The trial was conducted in 4 experimental phases including 30–41 weeks of age; 42–49 weeks of age; 50–61 weeks of age; and 62–78 weeks of age. The egg production, feed conversion ratio, egg quality parameters, and mortality were not affected by canola meal inclusion for the four phases and the entire experiment.

In general, when given diets high in canola meal that are balanced for total digestible amino acids (in ratio to lysine), birds will maintain optimum feed intake levels. Compared to soybean meal, canola meal has lower energy value for poultry, but energy levels of a diet can be easily adjusted through diet formulation practices. The standardised ileal digestibility (SID) of amino acids from canola meal are reported after extensive research has been done recently (Table 8). Canola meal provides excellent value in diets when the emphasis in formulation is placed on amino acid balance. Care must be taken to formulate diets on a digestible amino acid in ratio to lysine and ideal protein profile basis to ensure performance is optimal when canola meal is included in diets for laying hens.

Table 8 Standardised ileal digestibility of amino acids in solvent extracted canola meal for laying hens

Indispensable amino acid	Layers
Arginine	88.0
Histidine	83.0
Isoleucine	77.5
Leucine	80.5
Lysine	81.0
Methionine	88.5
Phenylalanine	81.0
Threonine	71.5
Tryptophan	77.5
Valine	78.0
Dispensable amino acid	
Alanine	79.0
Aspartate + Asparagine	76.0
Cysteine	79.0
Glutamate + Glutamine	87.0
Glycine	76.0
Proline	-
Serin	72.0
Tyrosine	78.0

(Source: Saki et al. 2017b; Huang et al. 2006)

These latest findings suggest that, as long as the diets are formulated based on the concentration of the total digestible amino acids, canola meal can be fed effectively at high inclusion levels in laying hen diets up to 24% without having a negative impact on egg production, egg weight, egg quality, or fatty acid content.

2.1.6 Canola meal in the pig diet

With all the progress in feed formulation, the widespread adoption of more accurate feed evaluation systems, the commercial availability of crystalline amino acids, and greater knowledge of nutritional composition of canola meal, and pig requirements, nowadays, canola meal can be easily added to pig diets at increased inclusion rates. Table 9 presents the standardised ileal digestibility of amino acids in high protein canola meal (CM-HP), conventional canola meal (CM-CV), and canola meal processed at high or low temperatures (CM-HT and CM-LT, respectively) for growing pigs.

Similar to the scenarios in poultry industry, canola meal inclusion in pig feed was problematic due to several factors potentially reducing feed intake such as glucosinolates, tannins, sinapine, fibre, and mineral balance. Glucosinolates have a bitter taste and certainly represented a major negative impact on pig feed intake when canola meal was included in the feed. After the “00” variety of canola meal was developed in Canada, the glucosinolate level was greatly reduced, and the new varieties have a neutral taste.

Table 9 Standardised ileal digestibility of amino acids of different sources of canola meal[1] for growing pigs

Indispensable amino acid	CM-HP	CM-CV	CM-HT	CM-LT
Arginine	82.0	84.8	84.5	84.1
Histidine	80.8	80.7	80.6	78.2
Isoleucine	74.4	75.3	74.6	72.4
Leucine	76.2	77.3	75.9	76.2
Lysine	76.1	71.8	71.6	64.3
Methionine	83.0	82.3	81.6	82.6
Phenylalanine	75.8	77.8	76.2	76.7
Threonine	69.4	71.0	68.6	69.5
Tryptophan	84.9	84.0	80.7	85.7
Valine	72.0	72.8	72.0	69.2
Dispensable amino acid				
Alanine	75.5	76.9	75.2	73.4
Aspartate + Asparagine	71.1	70.6	68.9	67.3
Cysteine	74.9	77.8	75.1	68.1
Glutamate + Glutamine	82.6	83.8	83.1	82.0
Glycine	74.9	78.0	77.3	74.7
Proline	102.7	104.6	110.4	103.0
Serin	71.5	72.9	69.9	72.9
Tyrosine	75.6	77.8	76.4	76.0

[1] High protein canola meal (CM-HP), conventional canola meal (CM-CV), and canola meal processed at high or low temperatures (CM-HT and CM-LT, respectively).
(Source: Based on unpublished research by T. Maison and H. H. Stein https://nutrition.ansci.illinois.edu/node/653)

Several studies have reported successful inclusion of canola meal in pig diets replacing soybean meal with no detrimental effects of feed intake or growth performance. Hayer et al. (2018) replaced 20% of the soybean meal with canola meal (solvent extracted or subjected to low, medium, or high extruder intensity) and no negative impact on feed intake, weight gain, or feed conversion ratio was reported. The high intensity extruder further reduced glucosinolates, however, this did not result in any better performance in pigs. Table 10 shows the standardised ileal digestibility of amino acids in canola meal fed to sows.

A double choice study was conducted by Landero et al. (2018), where weaned pigs were given soybean meal and canola meal. Although there was a strong preference for soybean meal, however, 20% inclusion of canola meal, when no choice was given, did not affect feed intake or growth performance of pigs.

Low inclusion of the canola meal in pigs feed is still being practised in the industry, however, research findings are constantly disproving such restrictions. The poor pig performance when fed with canola meal-based diets may lie in improper feed evaluation for digestible nutrients especially amino acids, and/or incorrect feed formulation practices.

Current data show that if diets are properly formulated and amino acids are balanced for total digestible amino acids in ratio to lysine, high levels of canola meal can be included in pig diets. The nutritional value of canola meal is being further researched, and the only constraint might be the available energy content, especially when measured as net energy. The fibre content of canola meal is the limiting factor regarding energy content. Diet formulation based on the net energy content allows for higher inclusions of canola meal in pig diets. Ultimately, the recommended inclusion rate of canola meal in well-formulated diets will depend on the relationship between its cost and nutrient profile.

Table 10 Standardised ileal digestibility of amino acids in canola meal fed to sows[1]

Indispensable amino acid	Mid-gestation	Late-gestation	Lactation
Arginine	88.4	89.8	94.2
Histidine	92.6	93.1	95.8
Isoleucine	86.7	86.6	88.9
Leucine	88.7	88.7	90.5
Lysine	86.8	86.7	89.9
Methionine	90.9	92.0	95.1
Phenylalanine	88.0	88.7	89.9
Threonine	84.0	84.0	83.8
Tryptophan	89.1	89.8	93.8
Valine	84.7	84.9	89.3
Dispensable amino acid			
Alanine	85.6	85.7	86.7
Aspartic acid	84.8	85.3	83.9
Cysteine	86.3	86.5	88.5
Glutamic acid	92.6	93.1	93.6
Glycine	91.3	91.3	91.6
Proline	102.5	100.7	99.1
Serin	91.7	91.7	86.7
Tyrosine	85.6	86.0	88.3

[1] CM = canola meal containing diet at 31.3% inclusion and as the only source of AA.
(Source: Velayudhan et al. 2019)

The energy values are published by NRC (2012), and some other studies that are presented in Table 11. A more recent study conducted by Kim et al. (2018) reported that the Net Energy values ranged from 1960 to 2233 kcal/kg as fed.

Table 11 Energy values for solvent extracted canola meal, as fed basis

Reference	Digestible energy	Metabolisable energy	Net energy
Kim et al. 2018	3,180	2,925	2,099
Le et al. 2017	2,605	2,409	1,765
Liu et al. 2016	2,630	2,303	1,769[1]
Berrocoso et al. 2015	3,084	2,922	1,928[1]
Heo et al. 2014	2,901	2,692	1,850
Liu et al. 2014	2,883	2,681	1,769[1]
Liu et al. 2014	2,972	2,724	2,724[1]
NRC 2012	3,154	2,903	1,821

[1] Calculated as ME x 0.66 (Source: Kil et al. 2013).

To improve the energy availability in diets containing canola meal, enzyme supplementation might be effective. Multi-carbohydrase exogenous enzymes can help animas digest the non-starch polysaccharides of canola meal and boost the energy content of the diet. Multi-carbohydrase cocktail improved total tract digestibility of protein when canola meal was included at 20% and 25% of the diet replacing soybean meal. This improvement, however, was not reflected in improved growth performance in weaned pigs (Sanjayan et al. 2014). The outcomes of enzyme supplementation are however, varied and not consistent, with better results in *in vitro* experiments but not much improvement in pig growth performance.

Similar to poultry, pig diets should be formulated based on the digestible amino acids (which is a common practice in the industry now). Recent studies have shown that amino acids should be formulated based on true, or standardised amino acid digestibility coefficients in pig diets (Stein et al. 2007). The standardised amino acid digestibility coefficients correct for both indigestible fractions of the feed ingredients, as well as endogenous losses related to the animals' digestive processes.

Earlier feeding studies with young pigs reported that inclusion of canola meal in starter diet at more than 5% rate impairs growth performance (Bourdon & Aumaître 1990; Lee & Hill 1983), However, studies conducted in the past 10 years demonstrated that up to 20% inclusion of canola meal in weaned pigs' diet (body weight about 8 kg), had no negative impact on growth performance (Landero et al. 2011).

Sanjayan et al. (2014) fed weaned pigs (initial body weight 7.26 kg) with 25% of canola meal inclusion with highly acceptable growth performance after a week of feeding trial. To determine if the grain source included in the canola meal-based diet might make a difference, Mejicanos et al. (2017) fed piglets (starting weight 6.7 kg) with 20% soybean meal compared to 20% canola meal and either wheat or corn as the primary grain. Performance of pigs with canola meal diets was similar to that of soybean meal diets. The main difference in these three studies, compared to the earlier work, is that researchers formulated diets based on net energy content and standardised ileal digestible amino acids.

In another study conducted by Parr et al. (2015) soybean meal was replaced gradually with canola meal at increasing inclusion rates of 10, 20, 30, and 40%. The growth performance was increased linearly in response to increasing canola meal inclusion in the diet, proving that if the diets are formulated properly, pigs can bed fed with 40% of canola meal in their diet without compromising their growth performance.

Recently, Smit et al. (2018) compared solvent extracted canola meal to expeller soybean meal and found that the diet containing expeller soybean meal produced higher rates of gain and gain to feed ratio. The grower diet, which contained 25% canola meal, was quickly introduced to the pigs, and for a short time afterwards, their feed intake was lowered, according to the authors. Feed consumption did increase but gains and the feed to gain ratio remained notably different. It could be important to make the modifications gradually if pigs are to be switched to very high inclusion rates of canola meal.

A study with gestating and lactating sows, showed that replacing 50 or 100% of soybean meal in the diet, starting from day 7 of gestation through to weaning, improves piglet survival greatly, however, the weaning to oestrus interval was slightly higher with the highest canola meal diet than with the control diet (Liu et al. 2018).

Table 12 summarises the outcomes of the studies from the last 10 years with successfully including canola meal in the pig's diet either in starter or in grow-finish phases.

Table 12 Summary of studies with successful inclusion of canola meal in pigs' diet

Reference		Canola Meal	Control	P-value
Smit et al. 2018[1] (Grow-finish)	Inclusion %	25/20	15/12.5	
	ADG, g	988	1025	0.001
	Gain/feed	0.361	0.373	0.001
Mejicanos et al. 2017 (Starter)	Inclusion %	20	20	
	ADG, g	408	408	0459
	Gain/feed	0.61	0.59	0.024
Wang et al. 2017 (Starter)	Inclusion %	20	20	
	ADG, g	664	660	0.457
	Gain/feed	0.66	0.65	0.047
Parr et al. 2015 (Starter)	Inclusion %	40	28	
	ADG, g	570	560	0.951
	Gain/feed	0.68	0.59	0.001
Sanjayan et al. 2015 (Starter)	Inclusion %	15	20	
	ADG, g	453	452	0.979
	Gain/feed	0.60	0.60	0.714
Little et al. 2015 (Grow-finish)	Inclusion %	27.3/23.2	21.0/18.0	
	ADG, g	940	930	0.70
	Gain/feed	0.360	0.370	0.02
Kim et al. 2015 (Grow-finish)	Inclusion %	11.3	27.3	
	ADG, g	700	725	0.102
	Gain/feed	0.46	0.44	0.196
Landero et al. 2011 (Starter)	Inclusion %	20	20	
	ADG, g	493	488	0.592
	Gain/feed	0.70	0.73	0.087

[1] The control diet was based on expeller soybean meal.

Based on recent studies, it appears that canola meal can be included in the diet at 20–25% with no negative impacts on growth performance, if the diets are properly formulated based on net energy content and standardised ileal digestible amino acid coefficients.

2.1.7 Carbon footprint and sustainability of canola meal production

From a carbon footprint perspective, the question is how good this canola surge is for the environment due to carbon emissions in different phases (Figure 7). A study found that the production of one tonne of canola in Western Canada was projected to emit 475–580 kg CO_2eq (disregarding LUC- and LMC-induced emissions), changing on soil zones. Based on weighted averages considering cultivation area and yields, the GHG emissions of one tonne of canola produced in Western Canada were 525 kg CO_2eq (MacWilliam et al. 2016). A previous study, Gan et al. (2011) found that one tonne of canola emitted 800 kg CO_2eq averaging 1105 kg CO_2eq ha−1 across the Canadian semiarid prairie represented by the Brown and Dark Brown soil zone.

In an Australian study, Eady (2017) showed that the GHG emissions from cradle-to-farm gate for canola production, were 468 kg CO_2-eq/tonne canola seed harvested at a national level. Once changed to a dry matter (DM) basis, by correcting for moisture content, the emissions were 0.497 tonne CO_2-eq/tonne canola seed DM. Other studies in Iran, (Soltani et al. 2014; Kazemi et al. 2016) reported that canola production results in GHG emission of 1028.1 kg CO_2-eq ha−1 and 556 kg CO_2-eq t-1 to the atmosphere. Kazemi et al. (2016) mentioned that the rate is a bit higher than other countries, as Iran is mostly dependent on non-renewable sources for energy needed for production.

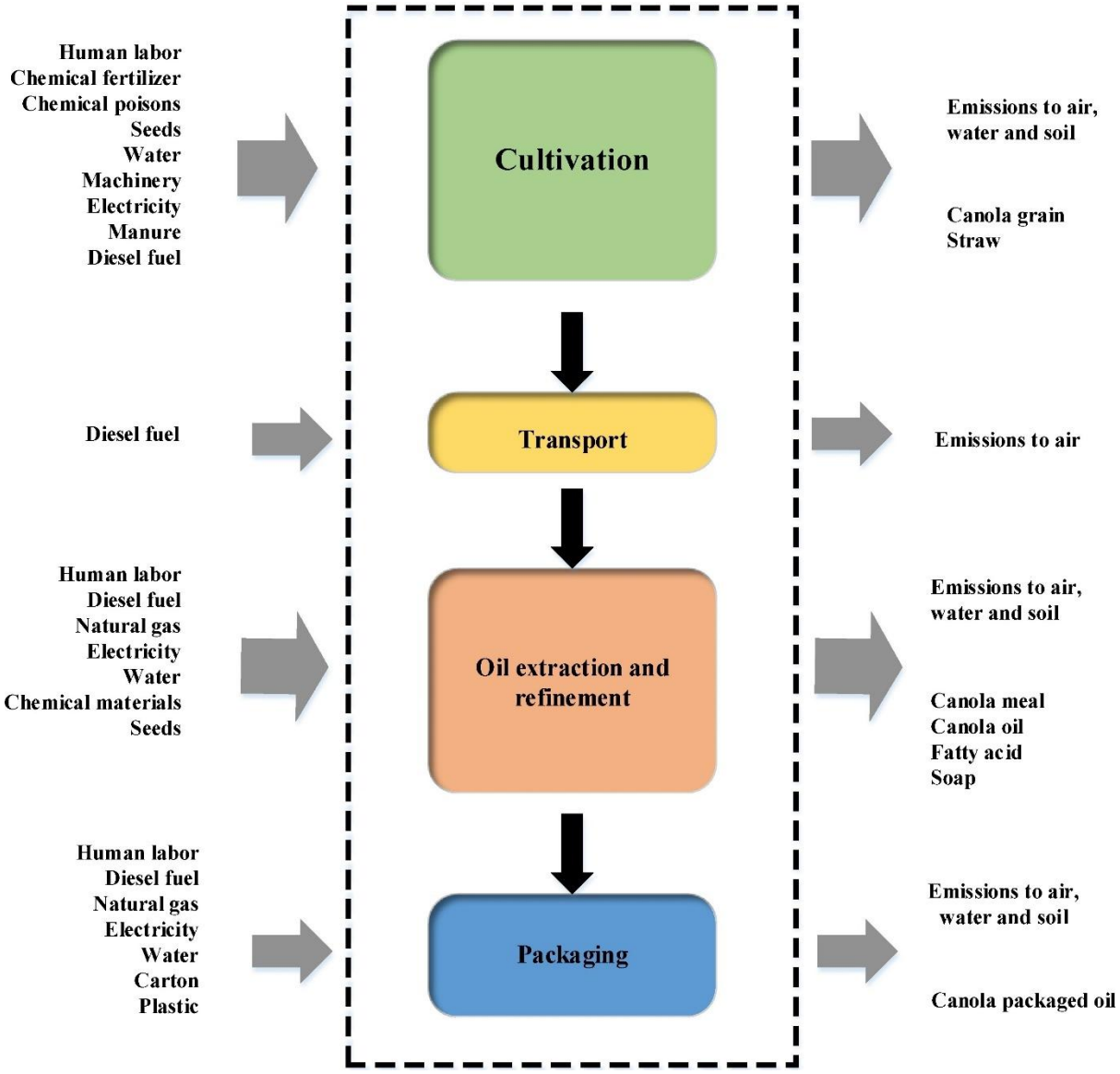


Figure 7 System boundary and main phases in production of packaged canola edible oil

In a life cycle assessment study of canola production (from cradle to farm gate), Mousavi-Avval et al. (2017) investigated the field emissions of fertilisers, and reported that they contribute more than 90% to global warming impact during cultivation. In a similar LCA study (from farm to the end of packaging stage of canola oil), Khanali et al. (2018) reported that canola farm activities contribute more than 78% to carbon emission, while only 3% is emitted at the transport stage (Figure 8).

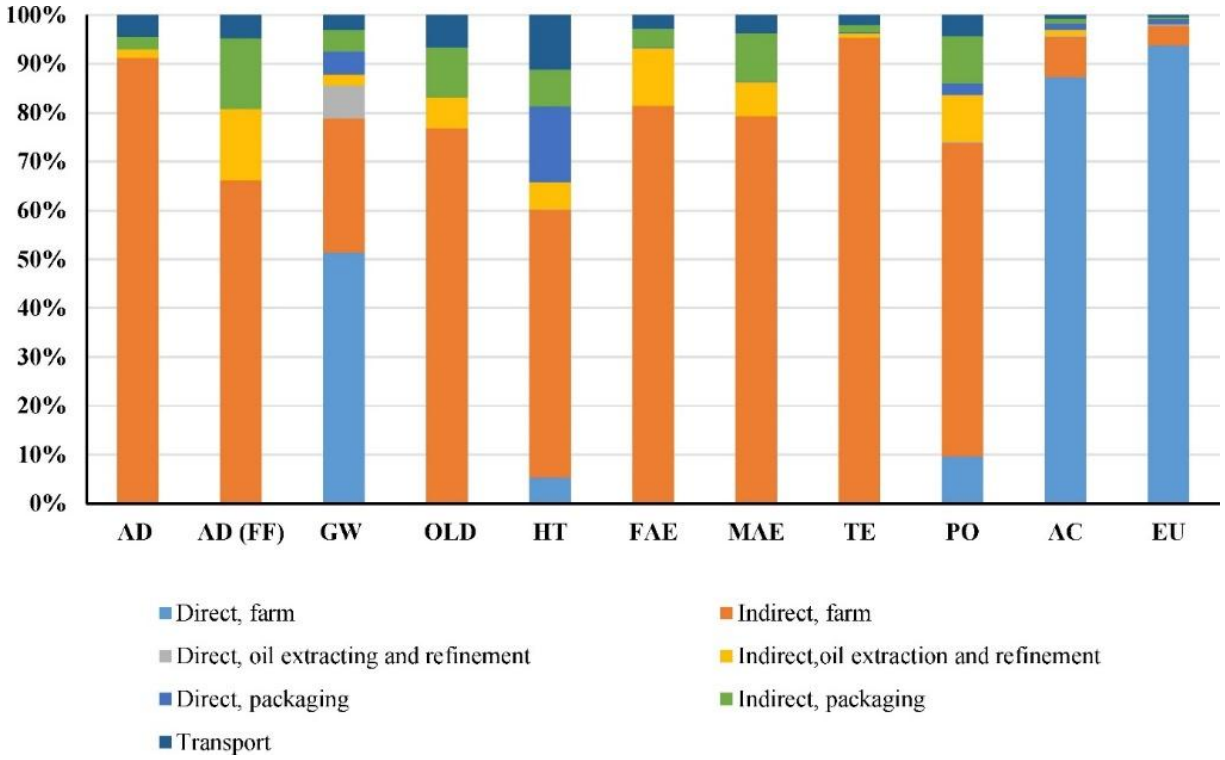


Figure 8 Categories of environmental impact in canola edible oil production for entire life cycle

AD: Abiotic Depletion; AD (FF): Abiotic Depletion (fossil fuels); GW: Global Warming; OLD: Ozone Layer Depletion; HT: Human Toxicity; FAE: Fresh Water Aquatic Ecotoxicity; MAE: Marine Aquatic Ecotoxicity; TE: Terrestrial Ecotoxicity; PO: Photochemical Oxidation; AC: Acidification; EU: Eutrophication.

Interestingly, canola production does have a brighter side as well. Canola oil is recognised as a healthy option in the kitchen but it is also used across a diverse range of non-edible products, such as biofuel feedstock, cosmetics, sunscreen, toothpaste, and industrial lubricants (Figure 9).. While converting canola to biodiesel, GHG emissions can be decreased by 5–26% and 8–41% when canola meal substitutes animal feed and crude glycerine reinstates synthetic glycerine (Mahbub et al. 2019). Again, when canola is cultivated in the mixed farming setup, amongst the crops, estimates of emissions from cereal grains, canola and lupins averaged 202 kg CO_2-eq/tonne, 222 kg CO_2-eq/tonne and 510 kg CO_2-eq/tonne respectively (Eady et al. 2012).

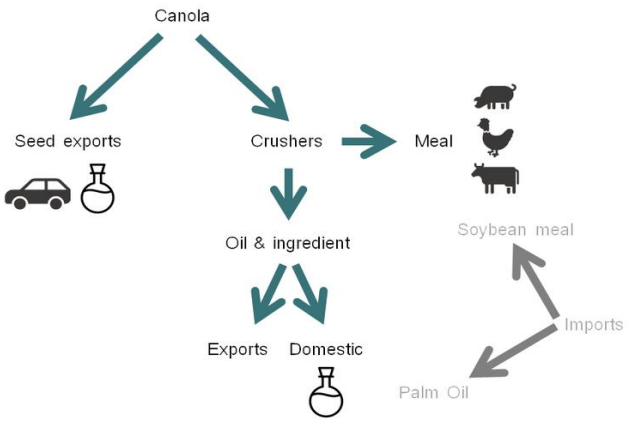


Figure 9 Use of canola in different paths

2.2 Cottonseed meal

Cottonseed oil, extracted from the seeds of the cotton, is a commercially valuable product. The high-protein meal left after oil extraction serves as a nutritious feed for farmed animals.
Being native to Northwest India and Pakistan, cotton, of the genus Gossypium, is today widely grown in both mild and tropical areas. Historically, the people of ancient China and India used cottonseed oil as a medicine. In 1833, the first cottonseed-oil mill was up and operational, but in the mid-century, cottonseed was mainly used for the planting of cotton, with seed excess to requirements regarded as a pollutant and problematic for health. Today, cottonseed has three uses: to produce oil, to plant further crops, and to feed animals.

Ginning is the process of removing the cotton from the bolls. The short cellulose fibres remaining on the seed, linters, are used in the manufacture of coarse yarns and cellulose products.

The cotton seed comprises approximately half the weight of the picked cotton and in general is used for oil extraction. One tonne of cotton seed produces approximately: oil (200 kg), cotton seed meal (500 kg) and hulls (300 kg). The cottonseed oil fatty acid profile comprises generally 70% unsaturated fatty acids (18% monounsaturated, and 52% polyunsaturated), and 26% saturated fatty acids. When fully hydrogenated, the oil is 94% saturated fat and 2% unsaturated fatty acids (1.5% monounsaturated, and 0.5% polyunsaturated).

Cottonseed oil does not need hydrogenation to the extent of other polyunsaturated oils to achieve similar results, according to industry sources, and is used in the manufacture of soap, emulsifiers, cosmetics, pharmaceuticals, rubber, paint, waterproofing agents and candles.

While making the oil, the cotton seed is crushed to remove any fibre or linter remnants, then hulled and polished so their soft, high-protein content can be released. From the production of the cottonseed oil, that is, following the pressing of the dehulled seed and the extraction of the solvent (hexane), comes the cottonseed meal.

The ground hulls are added to the extracted seeds in varying amounts to modify the protein content of the meal. That hexane used in the oil extraction process receives much criticism because it contaminates the environment and impacts health (neuropathy) and safety (spontaneous ignition of cottonseed flakes following oil extraction; O'Brien et al. 2005). As a result, other solvents have been assessed as potential replacements, with ethanol showing the most valuable properties (Saxena et al. 2011).

The edible cottonseed oil results from the removal of certain constituents in the initial dark-coloured cottonseed oil. On successful filtration, the oil is first refined under an alkaline solution treatment that reacts with its free fatty acids before forming soap that settles out. The oil is then centrifuged from the soap and washed with water to remove any further particles of soap.

2.2.1 Cottonseed and meal production globally and in Australia

Because of its high availability, low cost, high protein content (26–54%), dependent on the processing method used, its amino acid profile, cottonseed meal is a ready source of plant protein in tropical and subtropical regions (Mandal et al. 2020).

Global cottonseed production can potentially provide protein requirements for half a billion people and many billions of other animals. More than 50 million tonnes of cottonseed are produced globally each year, but less than 1% of that total is used to plant cotton. Much of it is crushed to extract oil.

The United States has continued as the largest consumer, but cottonseed is mainly used in the countries where cotton oil is produced in quantity – India, China, Mexico, Egypt, Pakistan and Brazil. These countries account for almost 80% of the world production and consume 75% of this production as feed (FAO 2011).

Of the approximately 5 million tonnes of oilseed crops produced annually in Australia, cottonseed accounts for a third. Australian cottonseed production in 2018–19 was 1.10 million tonnes, but the monogastric animal feed industry's inclusion of it at high dietary levels has been limited.

Cottonseed consumption in 2018–19 was 0.85 million tonnes, 24 per cent less than that of the previous year, which was mainly due to the prevalent hot and dry conditions of the time, but also to loss of production because of pesticide drift. Most of the cottonseed produced by cotton gins in Queensland and NSW, Australia's main cotton-producing states, is consumed by its feedlot sector. Over recent years, new gins have been constructed in the south of NSW, which has increased the provision of cottonseed to beef feedlots in that area (USDA GAIN Report Number: AS1807, 2018). Note that the cost of ginning a bale of cotton was around A$65 in early 2018, while around A$520 was the price for cotton bales in the same year (USDA GAIN Report Number: AS1807, 2018).

Australian cottonseed exports in 2018–19, including to Japan (crushed and cattle feed), Korea (crushed), China (crushed) and the United States (dairy feed) were 300 thousand tonnes. Australia usually exports cottonseed to these countries, with trade direction varying on occasion, in accordance with price parity and the value of the Australian dollar.

In the same year (2018–19), Australian cottonseed meal production was 318 thousand tonnes from a crush total of 700 thousand tonnes, of which only 10 thousand tonnes was exported from Australia. In the same year, Australian cottonseed oil production was 15% below that of the previous year, at 117 thousand tonnes, due to a lower seed extraction rate during that period. Providing a significant return to growers and processors, cottonseed oil is a higher value product than cottonseed meal. Even so, in 2018–19 Australian cottonseed oil consumption was down 7 per cent on that of the previous year, at 130 thousand tonnes. Despite that slump, cottonseed oil for human consumption is increasingly popular, and the Australian food service sector uses it for deep frying in its restaurant and fast-food industries because of its relatively high smoke point. Hydrogenation is not required for cottonseed oil either, so it is lower in cholesterol than most other oils and it lacks in trans-fat content. A further advantage lies in the fact that cottonseed oil reportedly has a high antioxidant content and can be kept for a relatively long time (USDA GAIN Report Number: AS1807, 2018).

In dry seasons when pasture is less available, cottonseed meal demand rises. Habitually, feedlots have been the biggest consumers of cottonseed meal and recent expansion in that industry has further increased their feed demand. The areas where beef feedlots are to be found in both southern Queensland and northern NSW mark the locations where the cotton industry and its processing facilities have been constructed in those states. Currently, around one million cattle are accommodated in feedlots around Australia, and invariably these are located near areas of cotton production, especially in Queensland and northern NSW (USDA GAIN Report Number: AS1807, 2018). Australia's two major cottonseed crushing facilities are in Hay and Narrabri in NSW.

2.2.2 General characteristics

Gossypium hirsutum (around 95% of cultivated cotton), *G. barbadense*, *G. arboreum* and *G. herbaceum* together (the last three representing about 5%) are the four cultivated cotton species (Stetina et al. 2014).

Their mature brown ovoid seeds weigh about 0.1 grams, consisting of 60% cotyledon, 32% coat and

8% embryonic root and shoot, by weight. These figures represent 20% protein, 20% oil and 3.5% starch. Fibres grow from the seed coat to form a boll of cotton lint, the boll being a protective fruit when the plant is grown commercially. For the unit weight of fibre, about 1.6 units of seeds are produced (Wang, Wang, Li et al., 2021)

Cottonseed meal is revealed to consist of 90% dry matter, and a chemical composition of 40% crude protein (DM basis), 25% NDF (DM basis), 15% ADF (DM basis) and 10% fat (oil) (DM basis), although there can be variations in the composition depending on the raw ingredients and seasonal conditions. As reported by different authors, 26 to 50% of cottonseed meal consists of crude protein (DM basis) (Mishra et al. 2015).

Cottonseed meal has low calcium (0.15–0.25%) and high total phosphorus (0.95–1.71%), i.e. the ratio of calcium to phosphorous is 1:6 when compared to soybean meal, which contains a 1:2 ratio of calcium to phosphorus: 0.36% calcium and 0.66% total phosphorus. Also, when compared to soybean meal, cottonseed meal has low lysine (1.76–2.13% vs. 2.69%), threonine (1.24–1.58% vs. 1.72%) and comparable methionine (0.48–0.78% vs. 0.62%) (Thirumalaisamy et al. 2016).

When too wet, cottonseed meal is susceptible to mould development and when too dry, to dust explosion. Between 5 and 11% moisture content is ideal, and this needs to be monitored and maintained. The temperature for storage would ideally be between 5 and 25°C. A high risk of ignition arises in tropical areas, where the temperature of cottonseed meal can rise above 55°C. Tight closure, and CO_2 injections into the storage containers help control the temperature (Bellaloui et al. 2015). Additionally, cottonseed meal has a nitrogen, phosphorus, and potassium ratio of 6-0-4. Its nutrients make it a perfect nitrogen fertiliser, with the meal improving soil texture, helping to build the humic acid needed for healthy plant growth (Bellaloui et al. 2015).

Cottonseed oil is trans-fat-free, is high in polyunsaturated fats and, contributing to its long shelf life, it has high levels of antioxidants (vitamin E). As it does not impart flavour to food, and is lower in cholesterol than many other oils, it can be used for some margarines and salad dressings and for many commercially fried products, for example potato chips and other snack foods for the domestic market.

2.2.3 Nutritive value for animal feed

Generally, cottonseed meal is marketed for ruminants as a crude protein meal comparable to soybean meal. Although it is the cottonseed meal that is currently used in cattle feed, cottonseed cake (compressed, ground, or pelletized cottonseed meal), can be utilised in several agricultural and industrial applications, demonstrated through the bio methanation potential of cottonseed cake in anaerobic digestion, using mixed consortia (Tanksley 2017). The method of extraction, the proportion of husk and lint, and the degree of decortication determine the nutritional value of cottonseed meal. Its protein concentration varies with processing type and is lowest for prepress solvent extracted cottonseed meal (41.6% of DM), intermediate for mechanically extracted cottonseed meal (45.8% of DM) and highest for direct (49.0% of DM) or expander solvent extracted cottonseed meal (48.4% of DM).

Table 13 Chemical composition of cottonseed meal obtained after dehulling and solvent extraction

Main analysis	Unit	Avg	SD	Min	Max	Nb
Dry matter	% as fed	90.9	1.5	87.5	94.4	230
Crude protein	% DM	47.3	2.9	40.1	54.4	251
Crude fibre	% DM	12.9	1.8	7.5	16.4	224
NDF	% DM	27.0	4.5	15.8	35.3	58
ADF	% DM	17.8	2.8	10.5	22.2	55
Lignin	% DM	6.1	0.9	3.4	7.2	55
Ether extract	% DM	3.0	1.6	0.4	6.5	152
Ash	% DM	7.4	0.6	5.9	8.7	204
Starch (polarimetry)	% DM	3.3	1.7	1.7	6.9	15
Total sugars	% DM	5.2	0.9	4.1	6.9	13
Gross energy	MJ/kg DM	20.0	1.0	19.0	22.2	41

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

The decorticated cottonseed meal contains 41% CP and 78% total digestible nutrients (TDN). The crude fibre content ranges from 2–2.7% in glandless and 7.9–16.0% in decorticated to 26.9% in un-decorticated form. Ether extract content varies from 4.2–11.3% in expeller and 0.9–2.9% in solvent-extracted meals.

Compared to other oil seed cakes, cottonseed cake is relatively high in phosphorus. The amino acid quality of cottonseed meal is lower than SBM owing to its lower concentrations of lysine (4.13 versus 6.29% of CP, respectively). As well as the naturally occurring lower concentrations of lysine, some lysine is bound to gossypol (a phenolic antinutrient), its high gossypol content during detoxification further reducing available lysine concentrations (Lim & Lee 2009).

Cottonseed meal, being less digestible than soybean and having a variable amount of non-starch polysaccharides (NSP), can adversely affect consumption and cause physiological changes that alter nutrient use especially in monogastric animals including pigs and poultry. This NSP is resistant to hydrolysis in the digestive tract of monogastric animals, thereby presenting two problems: reducing the energy content of the feed available to the animal and interfering with the use of other nutrients which are bond or encapsulated with the NSP fraction and therefore become unavailable to the animal.

The mean digestibility coefficient of essential amino acid in cottonseed meal is 67 per cent, which is lower than for SBM (91.67%). The digestibility coefficients of three critical amino acids for broilers including lysine, methionine and threonine, were found to be 65, 72 and 64 per cent in cottonseed meals, and the corresponding values for SBM were 93, 94 and 88 per cent (Mandal et al. 2004) . Similarly, Salas et al. (2013) reported the mean digestibility of the essential amino acid of cottonseed meal to be 72.03 per cent and the digestibility for each of lysine, methionine and threonine to be 64.6, 76.6 and 74.9 per cent, respectively.

Table 14 Mineral and amino acid composition of cottonseed meal

Minerals	Unit	Avg	SD	Min	Max	Nb
Calcium	g/kg DM	2.1	0.6	1.3	3.9	72
Phosphorus	g/kg DM	13.1	2.2	7.0	17.2	70
Potassium	g/kg DM	16.4	2.6	9.2	20.8	37
Sodium	g/kg DM	0.9	1.2	0.3	3.9	14
Magnesium	g/kg DM	6.0	1.4	3.0	7.8	36
Manganese	mg/kg DM	23	6	18	43	17
Zinc	mg/kg DM	44	31	19	101	17
Copper	mg/kg DM	117	85	15	198	17
Iron	mg/kg DM	170	52	81	317	14
Amino acids	**Unit**	**Avg**	**SD**	**Min**	**Max**	**Nb**
Alanine	% protein	4.4	0.3	3.9	4.8	27
Arginine	% protein	11.0	0.5	9.8	12.0	29
Aspartic acid	% protein	9.2	0.4	8.6	9.8	28
Cystine	% protein	1.7	0.5	0.5	2.3	12
Glutamic acid	% protein	19.0	0.7	17.9	20.8	26
Glycine	% protein	4.1	0.1	3.8	4.3	28
Histidine	% protein	2.9	0.3	2.3	3.6	15
Isoleucine	% protein	3.1	0.3	2.8	4.0	34
Leucine	% protein	5.6	0.3	5.1	6.3	34
Lysine	% protein	4.0	0.3	3.2	4.8	38
Methionine	% protein	1.4	0.2	1.1	1.8	32
Phenylalanine	% protein	5.2	0.2	4.6	5.7	32
Proline	% protein	3.6	0.5	3.0	4.6	8
Serine	% protein	4.2	0.3	3.7	4.8	25
Threonine	% protein	3.1	0.2	2.9	3.5	32
Tryptophan	% protein	1.2	0.2	1.0	1.5	5
Tyrosine	% protein	2.7	0.4	1.8	3.1	9
Valine	% protein	4.7	0.3	4.2	5.2	32

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia)

In another study, it was confirmed that although nitrogen retention was reduced (0.939 vs. 1.036 g/bird/day) when cottonseed meal was used at a 10 per cent level replacing soybean meal, its dry matter digestibility was comparable (Thirumalaisamy et al. 2016). However, Elangovan et al. (2006) reported that the nitrogen retention and dry matter digestibility coefficient of a diet containing cottonseed meal at the 10 per cent level was comparable to a cottonseed meal free diet. Also, cottonseed has high fibre content, relatively low protein digestibility (Zaboli et al. 2011) and poor protein quality (Zotte et al. 2013).

Whole cottonseed being high in fat, protein and fibre, it can be fed to cattle, sheep and other ruminants. The quantity of cottonseed that can be incorporated in pig and poultry diets is dependent on the levels of gossypol and cyclopropenoids present in the meal. They can be fed diets containing up to 0.01% free gossypol with safety and no fear of gossypol toxicity (Zeng et al. 2014).

2.2.4 Antinutritional factors – nutritional limitations

Gossypol and the cyclopropenoid fatty acids are the most important antinutritional factors contained in cottonseed oil (Zeng et al. 2014). Gossypol is the major toxin found in whole cottonseed and cottonseed meal. Produced in high concentrations in seeds of cotton plant (genus Gossypium), it is a yellow, polyphenolic pigment. Being toxic, it imparts insect resistance to cotton, meaning that low-gossypol varieties are subject to substantial insect damage. Its toxic effect accumulates in monogastric and ruminant animals. Free gossypol is toxic and chemically reactive.

There is variation in the gossypol content of whole cottonseed and cottonseed meal in accordance with the species of cotton, environmental conditions during the growing season, and the method of oil extraction. The gossypol exists in two forms: the free, toxicologically active form and the inactive, protein-bound form (Jithender et al. 2019). Total and free gossypol content of cottonseed meal varies between 1.16–1.52 and 0.024–0.82 per cent, respectively (Salas et al. 2013) and is found exclusively in discrete bodies called 'pigment glands', which are dispersed in leaves, stems, roots and seeds. Solvent extracted cottonseed meal has a higher level (0.1–0.5%) of free gossypol compared to that which has been mechanically extracted (0.02–0.05%) or extracted pre-press with solvent (0.02–0.07%) or when expanders were utilised in the solvent process (0.06–0.1%) (Thakur et al. 2019).

When free gossypol covalently binds to amino acids, especially lysine, it becomes the non-toxic, bound gossypol. To facilitate oil extraction for salad oil, margarine, and shortening use, the seeds are sliced into flakes during processing. Any remaining cottonseed flakes, along with some free gossypol, are ground into cottonseed meal for livestock protein feed. Gossypol poisoning occurs only rarely and is traceable to situations when the gossypol concentrations in the feed were unknown, or the recommended safe levels were exceeded.

Cottonseed meal lysine availability is lower because the free gossypol combines with the lysine in meal processing, resulting in bound gossypol. Of 15 gossypol pigments, the yellow one is the predominant, naturally occurring one, and is chemically 1, 1', 6-6', 7-7' hexahydroxy-5-5'-diisopropyl-3-3'-dimethyl (2,2'-binapthalene)-8-8' dicarboxaldehyde (Kadam et al. 2021).

In unprocessed seed, free gossypol exists only in the toxic, unbound form and it is easily absorbed in the gut of monogastric animals. Mature ruminants are less susceptible to gossypol toxicity because they have a detoxification mechanism in the rumen. It is here that free gossypol combines with soluble protein, mostly to the epsilon amino group of lysine, which is resistant to the proteolytic enzymes secreted in the lower gut (Thirumalaisamy et al. 2016). Gossypol has a partly reversible anti-fertility effect in male animals. The reduced oxygen-carrying capacity of blood and the haemolytic effect on erythrocytes partially account for death from gossypol toxicity which exerts its toxic effect on animals by uncoupling respiratory linked oxidative phosphorylation. Gossypol mainly affects the heart and liver, although the reproductive tract, abomasum, and kidneys are also affected. Further effects from intakes of high free gossypol include obvious clinical intoxication, insidious impact on reproduction, interference with normal *in vitro* development of embryos and synthesis of progesterone by luteal cells (Thakur & Kumar 2017).

Pigs and poultry have known susceptibility to gossypol toxicity. Pig feed is not permitted to contain greater than 0.01 per cent or 100 ppm of gossypol. Cattle and sheep can manage higher levels of free gossypol as the gossypol binds to proteins in their rumen, but young calves and lambs are typically susceptible to gossypol toxicosis (Batonon-Alavo et al. 2015) despite being ruminants, because their rumen is not fully functional and is unable to bind as much free gossypol as an adult's can (Soetan & Oyewole 2009). The binding of gossypol is also dependent on the number of available proteins.

Different extraction techniques significantly affect the amount of free gossypol in the meal. The older screw-press method used heat, which increased the protein binding, thus converting greater amounts of free gossypol (toxic form) to the bound form (non-toxic). Solvent extraction is widely used now because of its better oil extraction ability. However, since heat is not used, the amount of free gossypol in the meal is almost ten times higher than in the meal processed by the screw press method, which can be significant if much gossypol is in the seed. This change in solvent extraction methodology may account for the increase in gossypol toxicity over recent years.

Increased recognition of the above undesirable factors, coupled with progress in processing techniques, has improved oil extraction methods, which has resulted in low-gossypol cottonseed meal (He et al. 2015). The more refined technology, with no heating at high temperature, greatly reduces husk and maintains maximum nutrient density during oil extraction. Meanwhile, after oil extraction, the integrated degossypolisation in the solvent processes highly decreases free gossypol levels in cottonseed meal.

Several studies have focused on the reduction of gossypol in cotton waste, including cottonseed cake (Savitha et al. 2019) and on using single or mixed microbial cultures to enhance the waste. Mageshwaran and Parvez (2016) optimised a solid-state fermentation process to reduce free and bound gossypol from cottonseed meal. Sterilised cottonseed meal with 80% initial moisture, along with inoculation of fungus Pleurotus flabellatus strain M-1, incubated for 48 hours at 30°C, resulted in reduction of bound (53.3%) and free gossypol (70.0%). Apart from gossypol, aflatoxin contamination of cottonseed meal can be problematic in some areas of the World (Thakur et al. 2019).

In cases where cottonseed or cottonseed meal is bought in bulk, it is worthwhile testing before using it as feed. Depending on the level of free gossypol, the cottonseed could be utilised to the best advantage of the livestock.

2.2.5 Cottonseed meal in the laying hen diet

Gilani et al. (2013) reported that cottonseed meal inclusion in laying hen diets has been linked to lower egg production, lowered feed efficacy, and egg yolk discoloration mostly due to free gossypol content, although He et al. (2015) proposed that such negative effects may instead be attributed to the excessive arginine concentration in low gossypol cottonseed meals. Cottonseed meal contains low levels of available lysine (Mushtaq et al. 2009), however, this issue can be resolved by supplementing more synthetic lysine (Hassanabadi et al. 2009).

Table 15 Cottonseed meal metabolisable energy value for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max	Nb
AMEn broiler	MJ/kg DM	10.6	2.4	8.9	13.3	3

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Another study reported no differences in laying performance or egg yolk discoloration when hens were fed 100 g/kg low gossypol cottonseed meal diets containing 20 or 59 mg/kg free gossypol (Nagalakshmi et al. 2007). An old study by Fletcher et al. (1953) reported that during five-month delayed preservation, 80% of the eggs were discoloured when layers were fed a cottonseed meal diet

with 30 mg/kg free gossypol. The egg production rate was unaffected when layers were fed a 100 g/kg cottonseed meal diet (61 mg/kg free gossypol), but it decreased when 150 g/kg cottonseed meal was included in the diet (101.5 mg/kg free gossypol) (Reid et al. 1987).

Table 16 presents the standardised ileal digestibility of cottonseed meal for laying hens (compared to soybean meal).

Table 16 Standardised ileal digestibility of amino acids of soybean meal, conventional cottonseed meal, and low-gossypol cottonseed meal in laying hens

Indispensable amino acid	Soybean meal	Cottonseed meal	Cottonseed meal (low gossypol)
Arginine	89.02	86.95	89.54
Histidine	85.04	77.31	80.69
Isoleucine	83.78	68.65	75.04
Leucine	83.88	71.84	77.56
Lysine	85.35	64.12	70.06
Methionine	83.56	69.20	76.33
Met+Cys	76.95	70.56	76.97
Phenylalanine	84.97	80.06	83.92
Threonine	78.69	64.58	71.86
Tryptophan	84.24	74.36	79.11
Valine	81.88	72.00	76.89
Dispensable amino acid			
Alanine	82.53	68.72	76.36
Aspartic acid	83.26	74.14	81.16
Cysteine	68.61	70.20	79.07
Glutamic acid	87.84	83.29	87.94
Glycine	79.83	68.41	76.37
Proline	83.92	71.04	80.43
Serin	82.17	71.16	79.14

(Source: Qui et al. 2023)

According to Panigrahi et al. (1989), the number of eggs was not reduced unless the cottonseed meal inclusion rate reached 300 g/kg (containing 225 mg/kg free gossypol). However, subsequent research discovered no yolk discolouration in fresh eggs by layers fed a cottonseed meal diet containing 262 mg/kg free gossypol (Panigrahi & Hammonds 1990).

Previous studies have reported that egg yolks from hens given diets containing cottonseed meal or oil can develop mottling and discolouration and look waxy with a semi-solid appearance when stored at a low temperature (Phelps, 1966; Kemmerer et al. 1962; Qi et al. 2017). Average daily feed intake and egg production were unaffected when laying hens were fed a diet containing 144 mg/kg or 179 mg/kg free gossypol (Davis et al. 2002; Yang 2003).

He et al. (2015) conducted a trial to study the effects of feeding low-gossypol cottonseed meal at 50, 98.3, 144.2, or 189 g/kg inclusion rates replacing soybean meal at 25%, 50%, 75%, 100%, respectively. They reported no significant differences on egg production or feed conversion ratio among all groups, but feed intake and egg weight were significantly decreased in the 189 g/kg low-gossypol cottonseed meal group in weeks 46 to 51. A significant decrease was not observed in shell strength, shell thickness, and yolk colour in all periods, but Haugh unit, albumen height, and egg white protein content were reduced in 189 g/kg low-gossypol cottonseed meal group in weeks 46 to 51. A dietary inclusion rate of 98.3 g/kg was recommended with optimum FCR and without adverse effect on egg production, quality, and health of layers (He et al. 2015).

Wang et al. (2020) also investigated different inclusion levels of cottonseed meal (19.5, 67.5, 115.5, and 163.5 g/kg with free gossypol level was 20, 70, 120, 170 mg/kg, respectively) in laying hen diets and found no negative impacts of higher dietary free gossypol on laying performance, egg production and organ indexes among all groups. In their study, the ileum Tumour necrosis factor-alpha (TNF-α) was increased linearly with increasing free gossypol and the liver damage was aggravated. They concluded that free gossypol above 70 mg/kg can destroy intestinal immunity and liver tissue. The Haugh unit is an essential statistic for figuring out the crude protein and quality of eggs.

The chemical interaction between gossypol and ferric iron (Fe+3) formed by yolk proteins may result in yolk discolouration (Kemmerer et al. 1966). The impact was more pronounced in eggs that were stored (Phelps 1966). In an experiment, yolk discolouration was not found in hens fed a diet containing 170 mg/kg free gossypol. Other articles reported similar results and neither yolk colour, nor eggshell thickness or strength were negatively affected in hens fed a cottonseed meal containing 100–170 mg/kg free gossypol (He et al. 2015; Wang et al. 2020). Wang (2016) reported that yolk discolouration was not recorded from hens fed a diet containing 400 mg/kg free gossypol during four weeks of the experimental period.

In an investigation by Zhu et al. (2018), gossypol exhibited no discernible impact on the liver, spleen, or kidney index. A well-known immunological protein called secretory IgA (slgA), which keeps germs away from establishing the mucosa and piercing the epithelium (Martin et al. 2017). Birds fed a meal containing 120 mg/kg free gossypol had significantly lower levels of sIgA in the jejunum and ileum mucosa. The TNF level rose by 16–27% in the ileum mucosa of chickens fed a diet containing 70–170 mg/kg FG (Wang et al. 2020).

The TNF is a well-known pro-inflammatory cytokine that significantly influences activated macrophages' ability to kill tumours. The sensitivity of birds to cottonseed meal or free gossypol may be varied by various species or ages of layers, however, over 70 mg/kg of free gossypol seems to cause an inflammatory response, liver damage and a destroyed mucosal immune system.

It seems that inclusion rate of 10% low-gossypol cottonseed meal in laying hens' diet is safe.

2.2.6 Cottonseed meal in the pig diet

Cottonseed meal's value in pig nutrition is constrained by its high fibre concentration (110–130 g/kg), varied protein content (average 410 g/kg), lower amino acid content and bioavailability, and the presence of gossypol (Adeniji & Azeez 2008).

The European Union's directive 2002/32 (2002L0032 – EN – 26.02.2013 – 017.001) states that the maximum free gossypol concentration levels for cottonseed are 5,000 ppm and 1,200 ppm for cottonseed meal or cake, respectively, and that the ultimate free gossypol quantities for complete feeding material are 20 ppm for laying hens and piglets, 60 ppm for rabbits and pigs, 100 ppm for chickens (Gadelha et al. 2014).

Pigs, similarly, to poultry, are more susceptible to free gossypol toxicity than grazing livestock (Zhang et al. 2007; Xiaokang et al. 2019) and reduce their feed intake and body growth when fed with high gossypol levels and experience a higher mortality rate (Yu et al. 1996).

Batterham and Shenstone (1971) investigated an inclusion rate of 100 g/kg of locally produced cottonseed meal in the diet of developing pigs and found no evidence of gossypol toxicity. Baustad (1974) reported that feeding 160 g/kg cottonseed meal and soybean meal to growing pigs resulted in a better feed efficiency and faster development than feeding soybean meal alone.

Table 17 Cottonseed meal nutritive value for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max	Nb
Energy digestibility, growing pig	%	69.8	4.2	56.0	69.8	3
DE growing pig	MJ/kg DM	14.0	0.7	11.0	14.0	4
MEn growing pig	MJ/kg DM	12.7		10.0	12.7	2
NE growing pig	MJ/kg DM	7.6				
Nitrogen digestibility, growing pig	%	73.8	5.1	68.0	80.0	5

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia)

According to Ikurior and Fetuga (1988), up to 200 g/kg cottonseed meal together with soybean meal can be included in the weaner-grower pigs' diet. According to Balogun et al. (1990), weaner and growing pigs can be fed undecorticated cottonseed meal at 100 g/kg. Pigs may exhibit reduced weight gain, anorexia, respiratory discomfort, cardiac inefficiency, coughing, and exercise intolerance. Fluid accumulation in the bodily cavities, edema and congestion in the liver, lung, and spleen, and cardiac hypertrophy with deteriorated muscle fibre were all found at necropsy (Gadelha et al. 2014); nevertheless, the polyphenol present in free gossypol in concentrations less than 100 ppm has no negative impact on pigs (Adeniji & Azeez 2008).

Table 18 Standardised ileal digestibility of amino acids of multiple sources of cottonseed meals in pigs[1]

Indispensable amino acid	Mean
Crude Protein	70.93
Arginine	91.17
Histidine	81.24
Isoleucine	78.04
Leucine	79.44
Lysine	68.26
Methionine	87.80
Phenylalanine	85.59
Threonine	74.81
Tryptophan	84.78
Valine	79.63
Dispensable amino acid	
Alanine	74.87
Aspartic acid	81.40
Cysteine	68.61
Glutamic acid	85.67
Glycine	77.04
Proline	84.20
Serin	78.89
Tyrosine	81.95

[1] Mean value of the multiple sources is presented.
(Source: Ma et al. 2019)

Pigs fed higher concentration of free gossypol (more than 146 ppm) had lower feed intake and body weight (Fombad & Bryant 2004), while pigs at even higher levels (over 400 ppm) of gossypol struggled

to breathe, developed purple noses and ears, and occasional sudden deaths (Fombad & Bryant 2004).

Lana (2000) reported that cottonseed meal is deficient in lysine, tryptophan, vitamin D, and vitamin A; although it has a high phosphorus concentration, pigs can tolerate it very well. In a study, pigs fed an equal mix of cottonseed meal and soybean meal had a slightly higher growth rate than those on a soybean meal-only control diet (Fombad & Bryant 2004). Pigs fed diets containing 225 or 300 g/kg cottonseed meal showed decreased live weight gain and feed efficiency, and reduced voluntary feed intake (Fombad & Bryant 2004). Additionally, Rincon et al. (1978) discovered that supplementing pig diet with cottonseed meal at doses greater than 160 g/kg lowered feed intake and inhibited growth.

Cellulose, lignin, and hemicellulose comprise a large portion of the crude fibre in cottonseed meal, (Silva et al. 2021). Diets high in fibre dilutes the energy content of the feed for monogastric animals since the gastrointestinal enzymes are unsuitable for breaking down fibrous components in diets (Bedford & Schulze 1998). In some other studies, the live weight gain of pigs decreased as the density of cottonseed meal in diets increased, possibly as a result of the reduced voluntary food intake as well as diluted energy content due to the higher crude fibre content (67.6 g/kg compared to 43.0 g/kg for soybean meal) (Fombad & Bryant 2004). When free gossypol was added to pigs' diet, their daily growth and feed intake were decreased. Pigs administered toxic doses of gossypol may appear normal for a few weeks to a year before starting to gasp for air and dying within 2–6 days, with severe anaemia and other issues (Florou-Paneri et al. 2014).

In an investigation conducted by Fombad and Bryant (2004), no fatalities occurred even with free gossypol levels as high as 355 mg/kg. Gossypol bioaccumulation in pig organs was correlated with feed quantities and ingestion time. It has been reported that feeding pigs a diet containing 240 mg/kg gossypol for 15 weeks caused reduced haematocrit and haemoglobin levels and some indications of toxicity from prolonged free gossypol, which led to increased weights of organs such as the heart, liver, and kidneys with higher levels of cottonseed meal in the diets (Florou-Paneri et al. 2014).

According to Paiano et al. (2003), cottonseed meals can be included in the pig’s diet for up to 10% without having negative impact on the growth performance during the grow-finishing phase, if the total amino acids requirement is met. Cottonseed meal inclusion in diets increases the hardness of the fat in the carcass, which is reported as having higher melting points and lower iodine levels. It has been argued that the increased hardness of fat deposits is attributed to the increased concentration of saturated (palmitic and stearic) to unsaturated (palmitoleic and oleic) fatty acids when pigs are fed with cottonseed meal (Fombad & Bryant 2004).

A trial was conducted by da Silva et al. (2021) to evaluate the digestibility of diets containing increasing levels of cottonseed meal with enzymatic complex, and the performance and the economic viability of pigs in the finishing phase. Experimental diets included 0, 5, 10, and 15% cottonseed meal plus enzyme complex. The results showed that cottonseed meal inclusion and enzyme complex in the diets reduced the digestibility of the dietary components, however, no effects on the performance were observed, concluding that depending on the price and the availability of cottonseed meal, it can be included in the grow-finish pig’s diet up to 15%. Qin et al. (2015) conducted a trial with two sources of dietary proteins (cottonseed meal, CSM vs. soybean meal, SBM) and two levels of CP (12 % vs. 14 %, as-fed basis) and reported that growth, carcass characteristics and meat quality were not affected by dietary protein source nor crude protein level except that average daily feed intake was increased by cottonseed meal diets. Similar data were found by Paiano et al. (2014) who also did not find any effect on the performance of the animals during the growth phase when they included cottonseed meal (CP 42%). However, they observed an increase in daily feed intake and an increase in the feed conversion ratio as the level of inclusion of cottonseed meal in pigs in the finishing phase increased. They argued that the lower amino acid digestibility of cottonseed meal might be the reason for reduced feed efficiency, despite considering the total amino acids for the feed formulation of the diets.

Based on the available reports, it seems that 10% and 15% low-gossypol cottonseed meal can be included in young and grow-finish pig's diet, respectively.

2.2.7 Carbon footprint and sustainability of cottonseed production

Wang et al. (2015) reported that the yields of cottonseed from central pivot irrigation for industrial production purpose is 3030 kg·ha−1 and field production GHG emission is 884 carbon equivalents per hectare The GHG emission is 0.19 kg carbon equivalents per kg of cottonseed production. From 1000 kg of cottonseed, 160 kg cottonseed oil, 455 kg cottonseed meal, 270 kg husks, and 83.5 kg linters can be derived. Around 46% of GHG emission related to cottonseed can be assigned to cottonseed meal, then GHG emission is 0.19 kg carbon equivalents per kg of cottonseed meal produced (Wang et al. 2015).

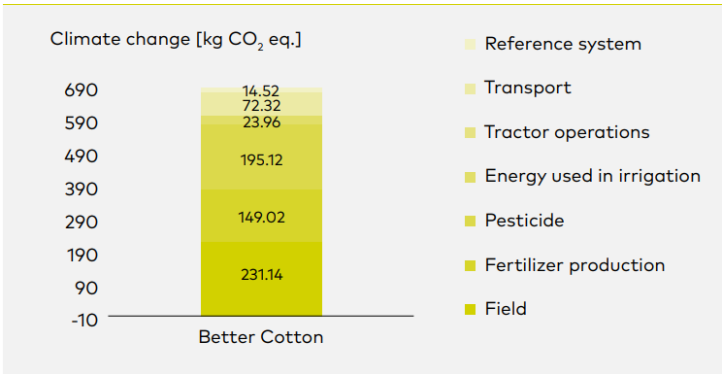


Figure 10 GHG emission for 1 metric ton of cottonseed at the farm gate

In another study related to refined cottonseed oil (CSO) CF in US, Prado et al. (2021) estimated emission to be approximately 1.1 kg CO_2-eq kg-1 CSO. Figure 10 shows GHG emissions for 1 metric ton of cottonseed at the farm gate (C&A Foundation 2018) and Figure 11 shows that around 68% of the emission comes from cotton production (Prado et al. 2021).

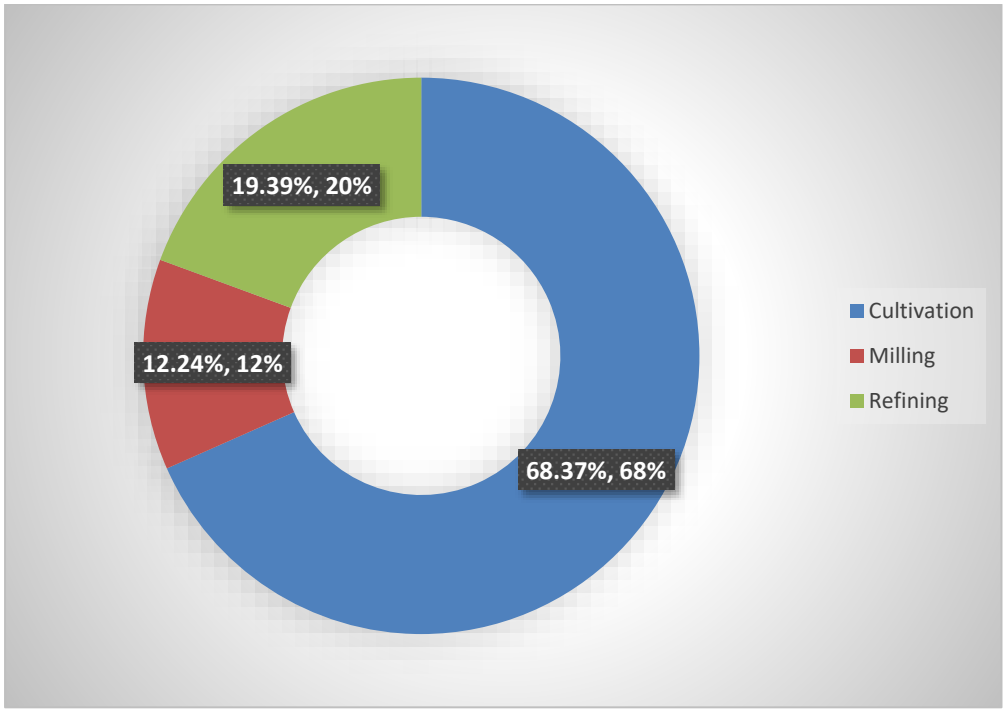


Figure 11 GHG emissions for refined cottonseed oil (US)

An LCA study found that the climate change impact of cotton lint on a cradle-to-gate basis was 1.601 kg CO_2-eq per kg of cotton lint. Production was identified as the 'hot spot' within the emissions profile (46% of emissions), as shown in Figure 12 (Hedayati et al. 2019).

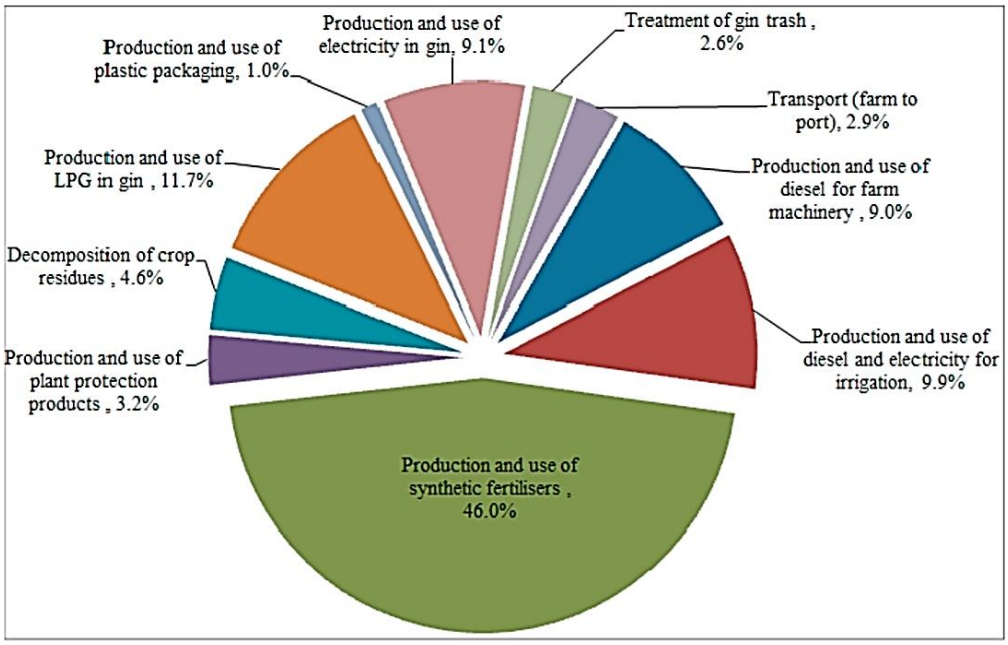


Figure 12 GHG emission profile for cotton lint at port

2.3 Linseed meal (flaxseed meal)

Linseed (or flaxseed) derives from the flax plant, a small one that can grow to around 60 centimetres in height. Flax (Linum usitatissimum L.) has a long history and is generally considered as a dual-purpose crop plant because of its main two products, the textile fibre and the nutrient-rich seed (Kang et al. 2021).

It has been cultivated globally, but it can be traced back to Egypt where it was probably first grown, right at the dawn of civilisation. Around 200 species of Linum are known, and it is cultivated in more than 50 countries. Canada is the major linseed producer, followed by China, the United States and India (Rubilar et al. 2010).

Linseed, rich in fat, protein and dietary fibre, has been consumed for centuries for its good flavour and nutritional properties, containing 40% oil, 30% fibre, 20% protein, 4% ash and 6% moisture. However, the composition of the linseed varies according to species and method of analysis (Hashempour-Baltork et al. 2018).

By-products are derived from the linseed plant, which also provides seedcakes (linseed expeller), fibres and shives. Recent developments in analytical methodology have enabled the determination of several valuable compounds in these by-products, thus making them more appealing to industry. Apart from lignocellulose biomass, which is mainly used as part of polymer composites or in liquid/gas fuel production, phenylpropanoids and terpenoids are the major constituents contributing to the by-product bioactive properties of the linseed plant (Waszkowiak et al. 2016). Antibacterial, antifungal, anticancer, and anti-inflammatory activities are attributed to these compounds. Findings about them have led to the diversification of linseed plant application (Kang et al. 2021).

It must be pointed out that linseed seedcakes are a rich source of secoisolariciresinol diglucoside (SDG), and the beneficial role of this compound in human health is also worth noting. Several reports confirm the role of SDG in protection against different kinds of cancer (Flower et al. 2014).

Linseed is typically processed by cold pressing to obtain linseed oil suitable for human consumption, but also by solvent extraction to obtain industrial linseed oil. Linseed meal is the by-product of linseed processing for oil (Goyal et al. 2014). Linseed oil has a very healthy fatty-acid profile, with low levels (approximately 9%) of saturated fat, moderate levels (18%) of monounsaturated fat, and high concentrations (73%) of polyunsaturated fatty acids (PUFAs). The PUFA content comprises approximately 16% omega-6 fatty acids, mainly as linoleic acid (LA), and 57% alpha-linolenic acid (ALA C18:3n-3), an omega-3 fatty acid. The amount of pigment present determines seed coat colour, which can be changed through the normal practices of plant breeding. Flax oil (linseed oil) is the richest natural food source of omega-3 essential fatty acids. (Czyż et al. 2021).

After the oil is extracted, a large quantity of linseed cake remains. The meal is mainly used as cattle feed, and it is very good manure (Dixit et al. 2012). Linseed meal is used normally for ground un-extracted seed (35%), ground linseed cake (10% oil) and linseed meal (3%) from a solvent plant. Rich oil content can affect the texture and flavour of the meat and butter obtained from cattle consuming linseed (Dixit et al. 2012).

2.3.1 Linseed and meal production globally and in Australia

Nowadays, the linseed plant is mostly grown for seed production, as its nutty-tasting seeds can be eaten on their own or crushed and cold-pressed to release linseed oil. In 2016, total global linseed production was 8.7 million tons. This statistic indicates the value of linseed exports worldwide in 2020.

Canada was then the leading global exporter of linseed, which had an export value of around 254 million US dollars (Balamurugan et al. 2021).

Though world production of linseed has fluctuated substantially in recent years, it is tending to decrease. According to FAO statistics, linseed production has declined over the last decade almost everywhere in the world. Depending on the country, there was a 10–60% drop in production, perhaps in association with linseed's lower than most other grains' return to farmers (e.g. wheat and corn) or oilseeds (e.g. rapeseed). At the same time, however, in Eastern Europe especially in the Russian Federation, Ukraine, and Belarus, a significant increase (more than 2.5-fold during the last five years) in linseed production was achieved (Taherkhani et al. 2018).

Linseed is also grown in the US (USDA program 2015) and the EU, currently. The EU's implementation of direct payments is aimed at increasing productivity, stabilising farmers' income, and securing crop diversification along with availability of goods for the market.

Australia produces 3–4 million tonnes of oilseeds annually, of which linseed production accounts for 36% of total production volumes. Currently, around 7,000 hectares of linseed are grown in Australia, producing between 10,000 and 11,000 tonnes of seed annually, with Tasmania producing 600 to 700 tonnes. Dryland systems generally produce 1 to 2 tonnes per hectare, while irrigated systems produce 2 to 3 tonnes per hectare.

In Victoria, linseed is currently mainly grown in the high rainfall areas of the southwest region, where average crop yield is approximately 1.25 tonnes per hectare. Most of it is sold and used as whole seed for bakery and confectionery products such as bread and muesli bars; but it is also for specialist stock feed.

Linseed and Linola™ are different seed types of the flax plant, Linum usitatissimum, which has been grown for oilseed for many years. Linola™ is a new crop in the flax group and was developed in Australia by plant breeders from CSIRO, Canberra. Linola is a registered trademark of CSIRO and the crop is patent protected. To grow Linola, a contract to do so must be arranged with the company holding the production and marketing rights at the time.

Linola plants are identical to linseed plants, but the seed is golden yellow instead of the usual brown of linseed. Linola oil is quite different from industrial linseed oil, being an edible polyunsaturated oil very similar to polyunsaturated sunflower oil. Linola™ production has been at a standstill in Victoria until recently, and currently no Linola oil is used in Australian food products. The crop has been widely grown in North and South America, and there are markets in Europe for Linola edible oils and margarine. All of the information about linseed growing can be applied to Linola growing. Only the varieties are different.

All Linola varieties are named after Australian lakes:

- Eyre (white-flowered, wilt susceptible) and Wallaga (blue-flowered, wilt resistant) were the two earliest Linola varieties, but they have been largely replaced by Argyle.
- Argyle is the most recently released wilt resistant Linola variety and it incorporates some beneficial characteristics from its Argentinian linseed parentage. It has excellent lodging resistance, which, together with its longer flowering period, gives it a yield advantage over Wallaga and makes it a suitable variety for autumn sowing. In spring-sown crops, its yield is usually close to that of Eyre and Wallaga.

Now that Linola can again be commercially grown in Australia it would be advisable to avoid growing both linseed and Linola on the one property or with one set of cropping and grain handling equipment.

There might well be a high risk of problems with quality, as differences in oil type, end-use and (usually) seed colour, signify that each is potentially a major contaminant of the other. The Australian industry embraces mono-unsaturated oils for margarine production over Linola's poly-unsaturated oil profile. Cold-pressed linseed oil is a growing and important use of linseed and is widely sold in Australia and overseas as an omega 3 health food.

2.3.2 General characteristics

Linseed is an important crop, and its mature seeds are a source of several important products for industrial purposes, such as oil, edible oil and fibre. Also being a medicinal plant, it is rich in oil, protein and dietary fibre (Crini et al. 2020).

Linseed contains 7.7% moisture and 3.3% ashes. Of the water-soluble components (0.05 μg/g fresh weight), vanillin has been identified as the most abundant (45%) phenolic compound in the linseed oil. The other identified components are non-hydrolysable (proanthocyanidins) and hydrolysable tannins
(5.4 and 3.0%, respectively), p-coumaric acid, ferulic acid, caffeic acid, coniferyl and syringic aldehyde (10, 16, 3, 9 and 7%, respectively) and small amounts of flavonoids, probably luteolin and kaempferol derivatives. Lipid-soluble secondary metabolites are highly (0.9 mg/g FW) represented in the oil. Among these components, γ-tocopherol (50%), plastochromanol-8 (44.5%), lutein (3%) and β carotene (1.5%) have been found in the oil from linseed (Zuk et al. 2012).

The linoleic acid concentration is in the range of 16 to 75% and alpha-linolenic acid varies from 1.7 to 59%. Genotype and environmental conditions significantly affect linseed properties (Cloutier et al. 2011).

Linseed is the richest known source of secoisolariciresinol diglycoside (SDG) (Prasad 1999), which is believed to be the plant precursor of enterolactone and enterodiol, referred to as the mammalian lignans with potent antioxidants (Martini et al. 2020), anti-cancer (Haseeb et al. 2019), antibacterial, antifungal and antiviral activity (Fadzir et al. 2018). As a result, it is suggested that SDG might protect fatty acids against oxidation during seed storage and industrial oil extraction (Soto-Cerda et al. 2014).

Linseeds have 534 calories per 100 grams of seed and are made up of 29% carbs, which means that they're low in net digestible carbs, making them a low-carb food (Thambugala et al. 2013). Linseed fibre content is composed of 20–40% soluble fibre (mucilage gums) and 60–80% insoluble fibre (cellulose and lignin) (Fadzir et al. 2018). Linseeds comprise 18% protein. Their amino acid profile is comparable to that of soybeans. Despite containing essential amino acids, they lack in the amino acid lysine. Still, linseeds are high in the amino acids arginine and glutamine, both of which are important for heart and immune system health (El-Bahr et al. 2021).

Linseeds contain 42% fat, with 1 tablespoon (10 grams) providing 4.3 grams. This fat content is composed of 73% polyunsaturated fatty acids, such as omega-6 fatty acids and the omega-3 fatty acid alpha-linolenic acid (ALA), and 27% monounsaturated and saturated fatty acids (Martins et al. 2018). Linseed oil is used for manufacturing paints, varnishes, inks, and soap (Członka et al. 2018). However, in recent times, linseed oil has become more popular as a functional food in the health food market because of its reported health benefits and disease preventive properties against coronary heart disease, cancer, neurological and hormonal disorders. The high content of omega-3 fatty acid makes linseed oil highly sensitive to heat, oxygen and light (Huang, Wang et al. 2018).

Linseeds are a good source of several vitamins and minerals:

- Thiamine or vitamin B1 is essential for normal metabolism and nerve function.

- Copper is vital for growth, development, and various bodily functions.
- Molybdenum is an essential trace mineral, abundant in seeds, grains, and legumes.
- Magnesium is an important mineral that has many functions in the human body.
- Phosphorus contributes to bone health and tissue maintenance.

In Canada, the oil content of linseeds varies up to 15% in individual farm samples (Duguid 2009). Also, the percentage of alpha-linolenic acid might increase (ca. 5%) in a cool environment (Kishawy et al. 2019).

2.3.3 Nutritive value for animal feed

Oil is extracted from the seed by either a mechanical or solvent process. The linseed meal is the finely ground residue (known as cake, chips, or flakes) remaining after the oil extraction. Linseed meal is a protein-rich feed containing about 30–39% protein in the DM. Cold-pressed meal contains slightly less protein than solvent-extracted meal (34 vs. 36% DM on average) but has more residual oil (6–15% vs. 2–6% DM). The oil is predominantly composed of polyunsaturated fatty acids (PUFA), C18:3 (54% of the fatty acids), C18:1 (19%) and C18:2 (15%) (. Linseed meal is moderately rich in fibre (crude fibre 8–14% DM). The protein profile of linseed meal is relatively poor in lysine (about 4% of the protein).

Although linseed is no longer commonly used in ruminant feeding, it is an ancient feedstuff that has been used since the nineteenth century in the form of crude seed or cake (Tudisco et al. 2019). Early in the twentieth century, linseed expeller cake was used particularly for beef fattening, not really for nutritional benefit, but for giving a shiny coat and tasty meat (Chiroque et al. 2018).

Table 19 Chemical composition of linseed meal after cold-press oil extraction

Main analysis	Unit	Avg	SD	Min	Max	Nb
Dry matter	% as fed	90.6	1.7	86.5	93.8	607
Crude protein	% DM	34.1	1.9	30.0	38.8	617
Crude fibre	% DM	10.5	1.5	7.7	14.1	554
NDF	% DM	25.4	3.3	17.2	32.7	29
ADF	% DM	15.3	0.8	13.5	16.1	24
Lignin	% DM	6.2	0.8	5.0	8.2	58
Ether extract	% DM	10.2	2.3	5.7	15.1	431
Ash	% DM	6.3	0.5	5.6	7.8	335
Total sugars	% DM	4.3	0.2	3.8	4.8	42
Gross energy	MJ/kg DM	20.7	1.9	19.8	24.5	14

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Significant use of linseed has been very recent and due to its richness in alpha-linolenic acid, it has been found to potentially allow an increase in omega-3 fatty acids in milk and meat. However, these products' increase in omega-3 fatty acids is limited because of the biohydrogenation of polyunsaturated fatty acids in the animals' rumen before absorption. In recent years, additional interest in linseed has developed because of its ability to significantly decrease ruminants' enteric methane production (Popova et al. 2019). Methane mitigation is a major means of decreasing

livestock greenhouse gas emissions.

The addition of linseed to livestock feed has focused on two main aims: the production of nutritionally enhanced human food products, and enhancing animals' health, productivity and performance (Facciolongo et al. 2018).

The production of omega-3-enriched eggs and meat is the main driver for using linseed as livestock and poultry feed. In Canada, a minimum of 300 mg of omega-3 fatty acid per serving must be achieved for the labelling of a product as a source of omega-3. Such labelling commands a premium price that health-conscious consumers are willing to pay. Omega-3-enriched chicken and pork products are also available to consumers (Chen, Cheong et al. 2019). Since linseed plant is grown in fields with high levels of selenium, linseed meal contains a higher selenium content than other feeds (Mech et al. 2021).

Since the early 1990s, linseed and linseed oil have been used extensively in poultry diets, mainly to fortify poultry meat and eggs with omega-3 PUFA. Considering the nutrient composition of linseed and linseed meal, these products can also substitute in part for laying hens' more traditional protein and energy sources.

Factors that often restrict linseed and linseed meal frequency in pigs and poultry diets include: (1) the high quantities of antinutritional compounds; (2) the poor digestibility of crude protein as well as other nutrients; (3) the inferior amino acid profile compared to that of canola and soybean meals; (4) lower availability of nitrogen-adjusted approximate metabolisable energy (AMEn); (5) the highly variable nutrient profile dependent on the area under cultivation, season and cultivar; and (6) lack of availability for animal consumption throughout the year (Watts et al. 2020).

Table 20 Minerals and amino acids composition of linseed meal

Minerals	Unit	Avg	SD	Min	Max	Nb
Calcium	g/kg DM	4.3	0.6	3.3	6.0	125
Phosphorus	g/kg DM	9.0	0.5	8.1	10.3	128
Potassium	g/kg DM	11.8	1.3	10.9	15.0	9
Sodium	g/kg DM	0.8	0.2	0.5	1.4	18
Magnesium	g/kg DM	5.5	0.4	5.1	6.4	10
Manganese	mg/kg DM	40	4	36	50	9
Zinc	mg/kg DM	68	5	62	78	9
Copper	mg/kg DM	19	1	18	22	8
Iron	mg/kg DM	175	85	131	366	7
Amino acids	**Unit**	**Avg**	**SD**	**Min**	**Max**	**Nb**
Alanine	% protein	4.7	0.1	4.4	4.9	11
Arginine	% protein	9.6	1.0	7.8	11.5	14
Aspartic acid	% protein	9.4	0.8	7.7	10.8	12
Cystine	% protein	1.8	0.3	1.3	2.3	13
Glutamic acid	% protein	20.4	1.7	18.7	25.4	12
Glycine	% protein	6.0	0.5	5.6	7.7	13
Histidine	% protein	2.5	0.4	1.9	3.5	14
Isoleucine	% protein	4.4	0.3	4.0	5.1	14
Leucine	% protein	6.0	0.4	5.1	6.9	14
Lysine	% protein	4.0	0.3	3.5	4.4	16
Methionine	% protein	1.9	0.2	1.5	2.4	14

Phenylalanine	% protein	4.8	0.3	4.3	5.4	14
Proline	% protein	4.2	0.2	4.0	4.4	3
Serine	% protein	4.8	0.3	4.3	5.7	12
Threonine	% protein	3.9	0.2	3.4	4.4	14
Tryptophan	% protein	1.6	0.2	1.4	1.8	4
Tyrosine	% protein	2.5	0.4	1.8	3.0	12
Valine	% protein	5.2	0.4	4.1	5.7	14

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia)

Linseeds are now used essentially in extruded mixtures of 50–70% linseeds and 30–50% other feed such as bran, to obtain a product that is easy to handle and easy to incorporate in concentrates.

2.3.4 Antinutritional factors – nutritional limitations

Linseed contains many antinutritional compounds that can adversely impact the production performance of monogastric animals. Some examples of these include mucins (mucilage), cyanogenic glycosides (linamarin, linustatin, and neolinustatin), linatine (pyridoxine antagonist), trypsin inhibitors, phytoestrogens and phytic acid. Trypsin inhibitors in linseed can decrease the effectiveness of proteolytic enzymes from the pancreas, which reduces the digestion of proteins and absorption of amino acids in the small intestine and, ultimately, production performance in monogastric animal species (Tesfaye et al. 2018).

Linseed mucins are non-starch polysaccharides (NSP) that mainly consist of fucose, galactose, xylose, arabinose, rhamnose, and galacturonic acid (Newkirk 2015). These NSP are indigestible by monogastric animals, are water-soluble, can absorb and hold large amounts of water, and increase digesta viscosity in the intestines of laying hens (Mangi et al. 2021). As a result, nutrient availability is reduced because of the laxative effect of NSP, the reduced rate of diffusion of endogenous enzymes and nutritional substrates, and decreased digestibility.

Linseed contains significant quantities of phytic acid (or phytate), which is an unavailable source of phosphorous for monogastric animals because they lack endogenous production of the phytase enzyme, notably in the early stages of life. The bioavailability of different minerals, trace elements, and some amino acids is also reduced by the phytate complexes, especially calcium, which leads to poor shell quality in laying hens (Mangi et al. 2021).

Linseeds contains linatine, a pyridoxine (vitamin B6) antagonist that interferes with the absorption of vitamin B6. Linseed-based diets can generate vitamin B6 deficiency symptoms in poultry, particularly in growing pullets, which can be solved by including an additional amount of vitamin B6 in linseed-based diets. Cyanogenic glycosides may produce prussic acid and hydrogen cyanide, though mostly in small quantities. Hydrogen cyanide, if absorbed in ample quantities from the colon of laying hens, can act to strongly inhibit respiration (Newkirk 2015). Linamarin is one of the major cyanogenic glycosides in linseed (10–30 mg/100 g of seed). Heat treatment during extrusion facilitates denaturation of β-glucosidase, the enzyme in linseed responsible for hydrogen cyanide formation from cyanogenic glycosides. If farm animals consume mature linseed that is not heat-treated, there are no noted observed deleterious effects from linamarin, however, it is concentrated in immature linseed and can lead to poor animal performance if not treated with heat (Moghadam et al. 2021).

The extrusion of linseed, which involves subjecting it to high temperature, moisture, and pressure under controlled conditions, can eliminate, to some extent, the antinutritional factors and improve the AMEn and crude protein digestibility of linseed meal (Gheorghe et al. 2019).

2.3.5 inseed meal in the laying hen diet

Linseed-based diets, if fed at too high a level, result in reductions in poultry performance due to the lower availability of AMEn and the poor digestibility of other nutrients.

Table 21 Linseed meal metabolisable energy value for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max	Nb
AMEn cockerel	MJ/kg DM	12.6	1.0	11.5	14.1	5

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Supplementation of linseed in laying hens' diets can increase jejunal digesta viscosity, which can lead to retention of nitrogen and reduction in the digestibility of amino acids, crude fat and fatty acids, and reduction in AMEn availability (Araujo et al. 2018). Because young pullets are most sensitive to the negative effect of increased digesta viscosity, it has been suggested that use of linseed in pullet diets be avoided (Newkirk 2015). It has also been reported that fibre-degrading enzymes that can specifically target linseed mucilage are not currently available; with the use of the available commercial cocktails of fibre-degrading enzymes, reduction in digesta viscosity and improvement in laying hen performance, is marginal (Huang, Wang et al. 2018).

Consuming linseed negatively impacted the body weight gain of young layers. From hatch to 18 weeks, pullets fed a diet containing 10% linseed gained significantly less weight than control-fed pullets, but not those fed a diet containing 5% or 7.5% linseed (Arshami et al. 2010). Similarly, Gonzalez-Esquerra and Leeson (2000) and Zajc et al. (2020) have reported a negative impact of including 10–20% linseed meal in a laying hen's diet. They argued that the antinutritional factors of linseed are responsible for reduced pullet development and body weight, possibly by raising digesta viscosity and inducing a laxative effect, causing poor nutrient digestion and absorption.

The diet's total energy significantly influences the amount of food consumed. Unsurprisingly, hens on a high-calorie diet consume less feed than those on a low-calorie diet because they eat to meet their energy needs. When actual or perceived metabolisable energy is considered, linseed-based diets have lower energy levels. To compensate for the reduced apparent metabolisable energy in the linseed-based meals compared with the control diet, which was meant to be isocaloric but higher in energy, hens consumed more feed (Novak & Scheideler. 2001). In another study, consuming linseed was strongly associated with less feed intake. In comparison to the control diet (10.82 MJ/kg of feed), linseed-based diet had a higher energy level (11.57 MJ/kg of feed), which was perhaps the reason for reduced feed intake (Kirubakaran et al. 2011).

Reduced feed intake associated with linseed consumption in another study was linked to the antinutritional chemicals that diminish palatability (Hayat et al. 2009). Ahmed et al. (2017) conducted a trial under high ambient temperatures and reported that hens reduce their feed intake due to oxidation of the PUFA in the linseed-based feeds, even though an antioxidant was included in the

experimental diets, however, the off-smell due to oxidation decreased palatability and resulted in a linear reduction in feed intake in a dose-dependent manner to increasing linseed inclusion rate.
Bean and Leeson (2003) conducted a 10-month study (one month defined as 28 days) with laying hens consuming a phased in and out linseed diet. Feed consumption declined during months 4 and 6, but then increased during month 9. The digestibility of crude protein was reduced by 30% in laying hens fed diets containing 10% linseed. It was believed that the declined feed consumption was caused by the cyanide present in the cyanogenetic glucoside (Ahmad et al. 2017).

Early research on laying hens suggested keeping linseed meal inclusion rate below 2.5% (Ewing 1997). Recent studies conducted in Germany, demonstrated that solvent-extracted linseed meal can be added to layer diets at a rate of 10% or 15% of the diet to fortify the egg yolk with linoleic acid (Jeroch et al. 2008;). It appears that a 10% inclusion rate is a suitable compromise between animal performance and egg quality (Halle et al. 2013).

In a different study, laying hens fed a meal containing 10% linseed had 30% less crude protein digestibility and 7.9% less AMEn availability than those fed a typical corn-soybean diet (Aziza et al. 2013). Due to the antinutritional components in linseed that result in reduced body weight throughout rearing, young hens going into lay may be more vulnerable to the detrimental effects of linseed than older chickens taking linseed for the first time (Arshami et al. 2010).

Table 22 Standardised ileal digestibility of amino acids of Linseed meal in laying hens

Indispensable amino acid	**Linseed meal**
Arginine	64.6
Histidine	56.5
Isoleucine	57.0
Leucine	60.4
Lysine	66.3
Methionine	66.7
Met+Cys	64.3
Phenylalanine	63.8
Threonine	47.4
Tryptophan	-
Valine	55.8
Dispensable amino acid	
Alanine	57.4
Aspartic acid	55.8
Cysteine	61.5
Glutamic acid	68.4
Glycine	58.9
Proline	67.0
Serin	55.0
Tyrosine	-

(Source: Blok & Dekker 2017)

Supplemental linseed has been shown to reduce egg production. Linseed cake at a 15% inclusion rate into young Lohman Brown hens for 24 weeks has reduced egg production, compared to a 5 or 10% inclusion rate (Halle & Schöne 2013). Similarly, feeding 22- and 38-week-old White Leghorn hens with 15% whole or ground linseed for 5 or 12 weeks resulted in a decrease in egg output compared to the control diet (Ahmad et al. 2013). Linseed meal may cause the yolk yellow colour to fade, which is probably due to the lack of fat-soluble pigments like xanthophyll and carotenoids, which has been

reported by Aziza et al. (2013) when 10% linseed meal is substituted for feed products high in pigments, such as yellow corn. The addition of the lutein pigment xanthophyll has restored the egg yolk colour when hens are fed a 10% linseed meal diet (Leeson et al. 2007). As linseed meal is abundant in omega-3 fatty acids, its inclusion in the feed can enrich meat and eggs with these fatty acids, but there is a risk that chicken products can taste like fish.

Inclusion of linseed meal or linseed oil (10%) reduces eggshell quality. Linseed's antinutrient components, such as phytic acid, may reduce bioavailable calcium that is absorbed and needed for shell calcification (Ahmad 2010). It has also been reported that linseed phytoestrogens can compete with natural oestrogen, possibly limiting intestinal calcium absorption and vitamin D3 activation, resulting in a decline in shell quality (Novak & Scheideler 2001).

Some investigations claim that including linseed meals at various life stages and amounts had no negative impact on the production performance of laying hens, however, has enriched egg yolk with omega-3 and -6 fatty acids. A recent study reported that adding 7.5–10% linseed to the diet significantly increased omega-3 fatty acids level in eggs compared to the control at eight weeks after the experiments. For the 10%, 7.5%, and control groups, the omega-3 fatty acid levels were 267, 232, and 64 mg/egg, respectively. Omega-6 to omega-3 ratios for the same groups were 2.33:1, 2.98:1, and 10.05:1, respectively. They reported no adverse effects from the addition of linseed to the diet on egg production, egg weight, or feed efficiency (Al-Nasser et al. 2021).

Similar to this study, Scheideler and Froning (1996), Lewis et al. (2000), and Bean and Leeson (2003) have reported fortification of egg yolk with omega-3 fatty acids when hens are fed with linseed in their diet. Novak and Scheideler (2001) demonstrated that the inclusion of linseed not only did not have any negative impact on egg production performance but also resulted in heavier eggs than the control group.

It seems that 5% linseed can be safely included in the laying hen diet, substituting soybean meal, with no adverse effects on egg production or feed intake, and positively enhancing the omega-3 fatty acid composition of egg yolk.

2.3.6 Linseed/linseed meal in pig diet

Similar to laying hens, linseed meal inclusion in pig feed can increase the n-3 PUFA contents and improve the n-6/n-3 PUFA ratio in pork (Czyz et al. 2021). Several studies have discovered that adding linseed to pig diets increased the levels of n-3 fatty acids, which is proven to have a beneficial impact on human health without altering organoleptic qualities, oxidation, or colour stability (Matthews et al. 2000; Riley et al. 2000; Kouba et al. 2003; Corino et al. 2008). Accordingly, Corino et al. (2008) found that when extruded linseed is fed to pigs, the n-3 PUFA content in the longissimus dorsi muscle and backfat is enhanced and the n-6:n-3 PUFA ratio is lowered. Similar outcomes were reported by Becková and Václavková (2010) and Leikus et al. (2018) where, when 13.4% ground linseed was added to the diet of pigs, their muscle tissue and backfat was enriched with linoleic and alpha-linolenic acids.

Increased n-3 tissue PUFA levels is associated with lowering the atherogenic and thrombogenic index, as well as altered physico-chemical properties of the muscle. Gilts and barrows are expected to respond differently to linseed supplementation because of their distinct capacity to store fat in the body depending on sex hormones. Barrows have a higher percentage of intramuscular fat than boars and gilts (Flachowsky et al. 2008). Okrouhlá et al. (2013) conducted a trial with 0 and 150 g/kg linseed supplementation to barrows and gilts, and evaluated performance, meat quality, and fatty acid profile of pigs. Linseed supplementation had no negative effects on performance, carcass value, or the physico-chemical indexes of pig meat quality while it improved the fatty acid ratios in both sexes.

Numerous studies have confirmed that the main effect of dietary linseed addition in different forms and doses is reflected in the fatty acid profile in the muscle of pigs (Enser et al. 2000; Kouba et al. 2003; Huang et al. 2008; and Guillevic et al. 2009).

Bell and Keith (1993) noticed significant drops in the average daily gain of growing pigs when feeding them graded levels of linseed meal (flaxseed meal) at 0 to 16%. This may possibly be attributed to a drop in digestible energy of the diets but also a shift in the amino acids supply. Linseed meal was substituted for soybean meal in their study and the experimental diets were adjusted for limited amount of digestible lysine, where the difference between the lysine content of the two is great. Pigs fed diets containing 30% linseed meal likewise showed slower growth rates, which Batterham et al. (1991) argued that a reduced digestible energy content might be the cause. On the other hand,

Table 23 Linseed meal nutritive value for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max	Nb
Energy digestibility, growing pig	%	76.0		62.0	76.0	2
DE growing pig	MJ/kg DM	15.7		12.3	15.7	2
MEn growing pig	MJ/kg DM	14.3		NA	NA	
NE growing pig	MJ/kg DM	9.5		NA	NA	
Nitrogen digestibility, growing pig	%	87.5		NA	NA	

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Eastwood et al. (2008) found that pigs fed increasing amounts of linseed meal (0 to 15%) could maintain steady growth rates if the diets are balanced for digestible energy and necessary digestible amino acids.

Table 24 Standardised ileal digestibility of amino acids of linseed meal in pigs

Indispensable amino acid	Linseed meal
Arginine	92.8
Histidine	78.1
Isoleucine	87.4
Leucine	84.2
Lysine	77.3
Methionine	84.9
Met+Cys	-
Phenylalanine	87.9
Threonine	69.6
Tryptophan	81.1
Valine	84.6
Dispensable amino acid	
Alanine	80.9
Aspartic acid	86.2
Cysteine	85.4
Glutamic acid	84.1
Glycine	73.2
Proline	-
Serin	80.6
Tyrosine	80.9

(Source: Wei et al. 2024)

Pregnant sows may benefit from linseed when included at a 4–5% rate (Bontempo & Jiang 2015). Linoleic acid (C18:2 n-6) is converted to arachidonic acid (C20:4n-6), which is the precursor of the PGF2α and α-linolenic acid (C18:3 n-3) is converted into eicosapentaenoic acid (C20:5n-3), which is used to form PGF3α.

It has been demonstrated that an increase in PGF3α and a decrease in PGF2α may help reduce embryonic mortality, which could contribute to improved reproductive performance of sows when fed with linseed or linseed meal (Van Kempen 2003; Maddock et al. 2005).

It seems that the presence of phyto-oestrogens (lignans) or cyanogenic compounds limits the inclusion of full-fat linseed or linseed meal in pig rations; rather, it is the low lysine content, the high mucilage content, and the low energy density.

Based on the literature and reports, it can be concluded that the growth rate of pigs can be reasonably maintained with diets containing up to 15% of linseed or linseed meal if the diet is well-balanced for digestible energy and lysine, where the pork products will be enriched with omega-3 fatty acid.

2.3.7 Carbon footprint and sustainability of linseed production

We found very limited studies for the carbon footprint of linseed production. A study mentioned that the cultivation of 1 ha of flax fibre contributes to stock 3.7 tonnes of CO_2 below-ground carbon (Gomez-Campos et al. 2021). Among the various crop species evaluated, linseed had the third largest emission after canola and wheat, which is 636 kg CO_2e ha−1 (Gan et al. 2011). The same study reports that the carbon footprints were 0.59 kg CO_2e for flaxseed based on the emissions released in the production of 1 kg of crop product. But to grow 1 kg of flaxseeds emits 1.8 kg of CO_2 (Baron 2021; HEALabel 2022a), which is equivalent to a car driving 6.75 kilometres (HEALabel 2022a).

2.4 Sesame meal

Sesame (*Sesamum indicum* L.) is a tropical and subtropical plant cultivated for its seeds, which produce roughly 50% of high-quality edible oil. The by-product of sesame oil extraction, sesame oil meal, is used as a feed additive. Dating back to as early as 1600 BC, sesame seeds are the oldest condiment known to man. Sesame (*Sesamum indicum* L.) is a self-pollinating annual plant having a straight, pubertal stem with branching, and is known as one of the most important oilseed crops. It is grown for its edible seed that grows in pods. Its flowers are light yellow, although the flowers also differ in colour, being purple or blue (Onsaard et al. 2010). It is widely cultivated in the tropical parts of Africa and Asia, and about 36 species are said to be existent (Hiremath et al. 2007). The original home of this crop is known to be Ethiopia (Nagendra Prasad et al. 2012). In the world, India ranks first in the production and area of sesame seeds, grown in different seasons covering practically all agro-ecological zones (Banerjee & Kole 2009). Potential health benefits of sesame include antioxidative, anticancer, anti-hypersensitive and anti-immunoregulatory actions (Reshma et al. 2010). The seeds are used to produce oil, paste, salads and various food formulations. Oil extracted from sesame is honoured as a rich food because of its high nutritive quality and stability (Ashri & Janick 2010). It has many uses, and it is markedly different from other vegetable oils due to its high nutritional and therapeutic values.

The unique flavour and its opposition to oxidative corrosion make sesame oil an outstanding salad oil. In addition to using sesame oil for cooking foods, it may be used for nutraceutical food (Elleuch et al. 2011). With an average of two-thirds of the world's sesame seeds being processed into oil and meal, the quality and variety of yield continue to improve and expand (Anilakumar et al. 2010). Sesame has been considered an ingredient in animal feed and human foods as a whole seed, oil, and meal (Hahm et al. 2009). A good quality meal contains about 40–50% high-quality protein especially rich in leucine, arginine and methionine, but low in lysine. Sesame seeds are pear-shaped, ovate, small (about 2.5–3 mm in length, 1.5 mm in width), slightly flattened and thinner at the helium. The weight of 1000 seeds is approximately 3 g. Light-coloured seeds yield better quality oil than dark colours but have lower oil content (Zhou et al. 2016).

2.4.1 Sesame seed and meal production globally and in Australia

Changing attitudes towards food, increasing wealth and consumer interest in health foods has driven market growth, with the global yield of sesame doubling between 2001 and 2014, an increase from 3 million tonnes to a peak of more than 6 million tonnes (Rahman et al. 2020).

The production of sesame has traditionally been dominated by African and Asian countries. Sesame is grown primarily in less developed tropical and subtropical areas of Asia, the Mediterranean, and South America (Girmay 2018).

The global market value of sesame was about US$6.5b in 2018, with some expecting the market to be worth US$17.7b by 2025 (Cision PR Newswire 2019), growing at 10% per annum, and is the eighth largest globally traded cereal crop by value (Coriolis 2021). The global demand for sesame was ranked as 'high' for overall attractiveness using a quantitative growth criteria score (Coriolis 2018). The world-leading sesame oil producers are Tanzania (33.3%), Myanmar (19.5%) and China (14.3%) (Rahman et al. 2020). Japan is the world's largest sesame importer. Sesame oil, particularly from roasted seed, is an important component of Japanese cooking, which is traditionally the principal use of the seed. China is the second-largest importer of sesame, mostly oil-grade. Other major importers are the United States, Canada, Netherlands, Turkey and France. The demand is driven by the variety of uses

for sesame, including its recognition as a healthy 'superfood' since it is a good source of vitamins, minerals, fibre, protein and fats (Rahman et al. 2019).

Sesame oil is widely used in pharmaceuticals and personal care products, including soaps, body wash and hair oils, and is expected to assist in driving growth in the future (Cision PR Newswire 2019).

Currently, Africa and India supply the most world trade (Coriolis 2021). In 2018, the average world price of sesame seed was US$1229/tonne in international markets. Sesame seeds that have been hulled have a higher price than unhulled seeds. Black sesame seed, which is a small minority of the total production, returns about 45% more than white sesame seed (Rahman et al. 2019). The reason for this is that white sesame is a bulk commodity used as a food condiment, while black sesame is used in higher-value markets for its oil, as a pharmaceutical component, and in value-added food products. These figures are only rough estimates of the situation as sesame is a smallholder crop and much of the harvest is consumed locally, without a record of the internal trade and domestic processing.

The Australian domestic consumption of sesame products is predicted to increase by 30% between 2016 (6,740 tonnes) and 2025 (10,000 tonnes). Currently, sesame is grown in Australia by a handful of growers. In 2019, just 525 hectares were planted to sesame (Rahman et al. 2019). Australia has been a net importer of sesame products since 1966 with domestic demand rising steadily. In 2020, Australia imported $57.25m worth of sesame and sesame products, comprising sesame seeds (A$19.75m, 7,000 t), sesame oil ($19.6m, 2,577 t) and tahini ($17.9m, 3,600 t) (Coriolis 2021), with the figure set to rise to nearly 20,000 tonnes by 2025.

An earlier report indicated that the industry was growing at 4.5% (20-year compound annual growth rate (CAGR); Coriolis 2018). This total tonnage of 13,177 t surpassed previous forecasts. This provides a significant opportunity for Australia to produce and market our sesame. Also, with projected demand for sesame expected to increase in China over the next three decades, together with Japan, these countries could be excellent market opportunities for Australian sesame. Further, Australia has free trade agreements in place with the major markets of China, Japan and the Republic of Korea (Rahman et al. 2019).

2.4.2 General characteristics

Sesame seed contains 40–50% oil, 20–25% protein, 20–25% carbohydrate and 5–6% ash (El Khier et al. 2008). Its meal chemical composition differs in line with the method of processing: mechanical or solvent extraction. Its dry matter (DM) content ranges from 83 to 96% while the content of CP, ash, ether extract, nitrogen-free extract (NFE), and crude fibre ranges from 23 to 46%, 7.5 to 17%, 1.4 to 27%, 25 to 32%, and 5 to 12%, respectively, as recorded by Mahmoud and Bendary (2014).

In the orient, sesame has been regarded as a health food for prevention of aging and increase in energy, while at the same time defending lipopolysaccharide-motivated oxidates, and constructively influencing the blood glucose, glycosylated haemoglobin, antioxidant levels and lipid peroxidation of diabetes. The sesame seed is not an excellent source of starch and approximately a quarter of the total fibre present in sesame is soluble. Mucilaginous gum comprises the main part of the soluble fibre and its composition ranges from 8–11 g per 100 g (Razavi et al. 2008).

Sesame seeds contain a group of phenylpropanoid compounds, lignans, which constitute an innate non-enzymatic antioxidant defence mechanism against the reactive oxygen species (Pathak et al. 2014). The seeds have a pleasant flavour and taste like nuts, while using them is simple and common to different products. They can be sprinkled over soups, salads, cereals or yoghurt. Baked products can be supplemented with whole sesame grains to achieve an attractive and appealing appearance

and improve the texture of the final product. The grinding of sesame before adding it to products can be most beneficial for health.

Sesame meal (45–55% protein value) is a significant source of protein for humans because of its sulphur-containing amino acids. Sesamolin comes from sesame seeds and inhibits leukemia cell development in humans (Lee et al. 2008). Eating whole sesame seed increases plasma γ-tocopherol and improves vitamin E action, which is thought to help prevent heart disease and cancer. The mineral composition of expeller sesame oil cake has been reported as 1.29% potassium, 0.8% magnesium, 107.5 ppm zinc, 51.61 ppm of manganese, and 100 ppm of iron (Yasothai 2014). This cake has also been found to contain 3.01 ppm thiamine, 3.87 ppm riboflavin, 13.44 ppm pyridoxine, 6.45 ppm pantothenic acid, 32.26 ppm niacin and 1651.6 ppm choline (Kulushtayeva et al. 2020).

Sesame seeds have a high polyunsaturated fatty acid content (Orsavova et al. 2015). It is also a rich source of tocopherols and lignans (notably sesamin and sesamolin) that provide exceptional oxidative stability compared to other edible oils (Yasothai 2014). Sesame oil contains about 40% oleic acid and 45% linoleic acid (Heuzé et al. 2016). Polyunsaturated fatty acids play essential roles in health and reproductive performance of male livestock, through modifying the fatty acid profile and maintenance of sperm membrane integrity (Van Tran et al. 2017).

Table 25 Fatty acids composition of sesame oil

Fatty acids	Unit	Avg	SD	Min	Max	Nb
Palmitic acid C16:0	% fatty acids	9.0	0.1	8.8	9.2	5
Stearic acid C18:0	% fatty acids	6.7	0.2	6.5	6.9	5
Oleic acid C18:1	% fatty acids	39.3	0.5	38.6	39.8	5
Linoleic acid C18:2	% fatty acids	44.5	0.6	44.0	45.2	5
Linolenic acid C18:3	% fatty acids	0.5	0.0	0.4	0.5	5

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

2.4.3 Nutritive value for animal feed

A protein-rich by-product of sesame oil extraction is sesame meal (or sesame cake), which, depending on how the oil was extracted, can be human food grade (from dehulled sesame seeds), or livestock feed grade (Obeidat et al. 2019). Sesame meal, consisting of 45% crude protein, 11.9% ether extract, and 11.9% ash is especially rich in leucine, arginine and methionine but is low in lysine, which means it is a good substitute for soybean meal.

Generally, the storing quality of sesame meal is greater than for other vegetable oil cakes, attributable to the presence of tocopherols, antioxidants like sesamol, sesaminol glucoside, and to the antioxidant precursor-like sesamin and sesamolin in the sesame seeds (Ono et al. 2020). Compared to soybean meal, sesame meal has lower levels of lysine, isoleucine, leucine, and valine, although it is an excellent source of sulphur-containing amino acids, e.g. methionine (Saleh 2020). Sesame meal does not contain any proteolytic enzyme inhibitors to hinder protein digestion, however, it has high phytate that chelates minerals and amino acids, forming insoluble and inaccessible fractions for animals. Adding exogenous phytase to the feed increases the digestibility of phosphorous and the fractions bond to the phytate, and it decreases nutrient loss through the faeces (Farrokhi et al. 2021).

While sesame meal is mildly laxative, it is a good source of several nutrients important for the functioning of the immune system. These include zinc, selenium, copper, iron, vitamin B6, and vitamin E, which all are involved in enhanced immune response (Farajbakhsh et al. 2019).

Table 26 Chemical composition of sesame meal after mechanical extraction oil extraction

Main analysis	Unit	Avg	SD	Min	Max	Nb
Dry matter	% as fed	92.8	1.7	88.7	95.9	48
Crude protein	% DM	44.9	5.0	32.1	53.4	54
Crude fibre	% DM	7.3	2.1	3.9	12.4	50
NDF	% DM	24.6	9.8	18.8	47.7	8
ADF	% DM	13.5	9.4	7.7	36.6	8
Lignin	% DM	1.7	0.2	1.5	2.1	7
Ether extract	% DM	11.3	3.7	5.2	19.6	41
Ash	% DM	11.9	2.2	8.1	16.7	43
Starch (polarimetry)	% DM	1.8	1.6	0.6	4.5	6
Total sugars	% DM	4.3	0.6	3.4	5.3	6
Gross energy	MJ/kg DM	20.6	0.9	18.7	22.0	9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Oxidation causes harmful deterioration of lipids, pigments, proteins and vitamins. Lipid oxidation affects meat colour, texture, taste and nutritional value, which leads to shallow profit margins as the meat often achieves only low prices. Additionally, egg production can decline, along with economic revenues, as a consequence of oxidative stress. High levels of natural antioxidants in sesame are considered of benefit to animal health and improve oxidation resistance.

Table 27 Minerals and amino acids composition of sesame meal

Minerals	Unit	Avg	SD	Min	Max	Nb
Calcium	g/kg DM	19.7	4.0	11.7	28.4	19
Phosphorus	g/kg DM	12.6	3.2	10.3	23.3	17
Potassium	g/kg DM	10.4	0.6	9.7	11.4	13
Sodium	g/kg DM	0.1	0.1	0.0	0.1	3
Magnesium	g/kg DM	5.9	0.7	4.1	6.6	12
Manganese	mg/kg DM	80	5	72	88	6
Zinc	mg/kg DM	126	8	114	136	6
Copper	mg/kg DM	44	1	43	46	6
Iron	mg/kg DM	1632	686	305	2055	6
Amino acids	**Unit**	**Avg**	**SD**	**Min**	**Max**	**Nb**
Alanine	% protein	4.6	0.3	4.3	5.1	8
Arginine	% protein	12.6	0.8	11.1	14.1	9
Aspartic acid	% protein	8.0	0.3	7.5	8.5	7
Cystine	% protein	2.2	0.2	1.9	2.5	8
Glutamic acid	% protein	18.1	1.0	16.3	19.6	8
Glycine	% protein	4.9	0.3	4.5	5.3	9
Histidine	% protein	2.8	0.2	2.5	3.1	8
Isoleucine	% protein	3.7	0.2	3.4	4.0	9
Leucine	% protein	6.6	0.3	6.3	7.5	9
Lysine	% protein	2.5	0.3	2.1	2.9	10
Methionine	% protein	2.7	0.2	2.3	3.1	10
Phenylalanine	% protein	4.5	0.1	4.3	4.7	9
Proline	% protein	3.5	0.2	3.1	3.9	7
Serine	% protein	4.5	0.2	4.2	4.7	8
Threonine	% protein	3.4	0.1	3.2	3.7	9
Tryptophan	% protein	1.3		1.1	1.4	2
Tyrosine	% protein	3.4	0.3	3.0	3.9	7
Valine	% protein	4.5	0.3	4.0	5.0	9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

2.4.4 Antinutritional factors – nutritional limitations

Nutrient digestibility can be affected by sesame seed antinutritional factors. Apart from having some lignans sesamolin, sesamin, pinoresinol, and lariciresinol (Jeon et al. 2016), sesame seed has high amounts of oxalate and phytic acid, which reduces the bioavailability of its phosphorous and calcium, although dehulling the seed reduces its oxalic acid content (Ghorbani et al. 2018; Yasothai 2014).

Decortication of seeds slightly reduces phytate levels (Yasothai 2014). The insoluble phytates present in sesame seed cakes form a complex with zinc, phosphorus and calcium, which is not absorbed. The protein digestibility is also negatively impacted through binding with carbohydrates and the inhibition of alpha-amylase activity in the digestive tract (Yasothai 2014; Ravindran, 1990).

The oxalate content of sesame is variable. Sesame seed contains 1 to 2% oxalic acid in the thin hull, and removing the hull reduces the bitterness of the meal (Pirie 1975). The total estimated oxalate in whole, dehusked, roasted, dehusked and roasted sesame seeds is 458.5, 278.7, 437.4 and 242.6 μg/g, respectively (Toma et al. 1979). The decortication of seeds nearly entirely removes the oxalates (Yasothai 2014). The oxalates in sesame oil cake give a darker colour and bitter taste to the meal (Okombo & Liebman 2010) and oxalic acid salts of calcium and magnesium are insoluble crystals, which are not absorbed (Sharma et al. 2021).

Another potential sesame meal antinutritional factor might be mycotoxins. Zhao et al. (2021) reported the presence of Fusarium toxins in sesame seeds, while Andargie et al. (2021) noted that trichothecene producing fungi was of low incidence compared to the same action undertaken by Aspergillus and Penicillium species in sesame oil cake.

Recently, sesame has been recognised as a major cause of allergic reactions in infants, young children and young women, which is surprising since its oil is widely utilised in the cosmetic and pharmaceutical industries because of its low antigenicity (Caminiti et al. 2006).

2.4.5 Sesame meal in the laying hen diet

As sesame meal has an impressive nutritional profile, it can be used for improved production. It has been proven that sesame meal in poultry feed ensures improved body weight, weight gain, feed intake and carcass weight. Such birds also reach sexual maturity earlier; hence, their productivity improves.

Table 28 Sesame meal metabolisable energy value for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max	Nb
AMEn cockerel	MJ/kg DM	11.4	0.2	11.2	11.6	5
AMEn broiler	MJ/kg DM	11.2		10.9	11.5	2

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Studies have shown that sesame meal is a suitable replacement for soybean meal in layer ratios where the replacement amount is 50% or less (Cheva-Isarakul & Tangtaweewipat 1993). A great lysine deficiency in sesame meal might introduce limitation of inclusion, as its lysine level of 2.7% is 50% less than that of soybean meal (Abdalla 1999). Sesame meal is an excellent source of fibre, though it has poor metabolisable energy for poultry and, unless dehulled, it contains a good level of methionine (3.2%) (Rezaeipour et al. 2016).

Sesame meal is a great source of nutrients and amino acids that can improve laying hen development and production in a commercial layer operation (Ahmed et al. 2020). In a trial, the effects of sesame seed meal at three inclusion rates (0, 10, and 20%) – with or without phytase and lysine supplementation – on performance, egg quality, blood biochemical and antioxidant status of laying hens were studied. Results showed that a 10% inclusion rate of sesame meal improved feed intake, however, 20% inclusion reduced feed intake. The addition of phytase to diets including sesame meal enhanced egg weight and mass and improved feed conversion ratio, although it had no effect on egg quality parameters, but did in terms of eggshell strength, which was substantially improved. Diet with a 20% sesame meal inclusion rate reduced blood low-density lipoprotein cholesterol, atherogenic index, total cholesterol, and egg yolk cholesterol (Baghban-kanani et al. 2019).

Table 29 Standardised ileal digestibility of amino acids of sesame meal in laying hens

Indispensable amino acid	Sesame meal
Arginine	87
Histidine	69
Isoleucine	87
Leucine	87
Lysine	78
Methionine	88
Met+Cys	-
Phenylalanine	-
Threonine	77
Tryptophan	84
Valine	84
Dispensable amino acid	
Alanine	82
Aspartic acid	77
Cysteine	56
Glutamic acid	83
Glycine	60
Proline	86
Serin	75
Tyrosine	90

(Source: Blok & Dekker 2017)

Sesame meal inclusion rate above 4% of the diet had a negative impact on the laying performance and feed efficiency of layers (Mamputu & Buhr 1995; Cheva-Isarakul & Tangtaweewipat 1993). Sesame meal at high inclusion levels (15–20%) dramatically decreased laying rates, feed efficiency, and weight gain (Jacob et al. 1996). The differences in production performance gained with sesame meals from various sources might be related to the protein's quality or amino acid concentration (Cheva-Isarakul & Tangtaweewipat 1993). Sesame meal consumption in pullet diets above 5% resulted in decreased growth and development, and impaired flock uniformity as well as a delayed start to the lay cycle (Tangtaweewipat & Cheva-Isarakul 1992).

In a study using Japanese quails, feed intake was in decline when sesame meal was added to the diet. This was attributed to the bitter taste of some compounds existing in sesame meal (Rezaeipour et al. 2016; Sina et al. 2014). Sesame meal increased egg size, egg quality, and egg yolk quality. If consumed in the proper amounts and with supplements, sesame meal can reduce cholesterol levels in egg yolk by roughly 8%. Low-cholesterol eggs are in high demand and are slightly more expensive due to the current global trend toward healthy meal options (Karshenas et al. 2018).

Sesame lignans (sesamin and episesamin) reduced blood total cholesterol and LDL-C levels by inhibiting the generation and uptake of cholesterol. Sesamin's hypocholesterolemic effects are brought on via decreased 3-hydroxy-3-methylglutaryl coenzyme-A reductase activity, increased cholesterol bile excretion, and suppressed intestinal cholesterol absorption (Alipoor et al. 2012). In addition, serum TAOC and TSOD enzyme activities were increased by feeding sesame meal, which relates to sesame’s antioxidant properties. The AOC and SOD enzymes are scavenger enzymes that protect cells from oxidative damage and convert reactive oxygen species to oxygen and water (Alipoor et al. 2012). Sesame oil contains about 40 mg of vitamin E per 100 g of oil, which is one of the main antioxidants in the body (Alipoor et al. 2012). Another mode of antioxidant action of sesame might be by limiting tocopherol catabolism resulting in an increase in the amount of tocopherol stored in serum and tissues (Parker et al. 2000).

The performance of laying hens was examined in a 12-week experiment to determine the impact of graded levels of soaked sesame seed meal as a source of methionine and an alternative replacing soybean meal. Sesame seed meal replaced soybean meal weight for weight at 0.00, 12.50, 37.50 and 50.00% in the diet. Synthetic methionine was added in the control diet but was eliminated when sesame meal was added to the experimental diets. The findings revealed a substantial decline in hen-day egg output when sesame meal was added above 25% and egg weight reduced at levels above 12.5% replacement levels. Experimental diets including sesame meal had no effect on shell quality (Diarra & Usman 2008).

Based on the available data from the existing literature, it seems that sesame meal should be used with care in layer diets and only at low levels. If formulation takes into account total digestible amino acids and the ideal protein profile is met, sesame meal can be included in hens' diet up to 10% with no detrimental effects on egg production performance, egg weight or eggshell quality.

2.4.6 Sesame meal in the pig diet

Sesame meal may have comparable digestibility to soybean meal in pigs, which makes it a potential alternative protein source for pigs. In a study conducted by Li Qiao et al. (2000), soybean meal was replaced by 0, 25, 50, and 75% sesame meal to determine amino acid digestibility coefficients in 20-kg barrows using the regression technique. These digestibility values were then used to formulate experimental diets with sesame meal replacing soybean meal at 0, 3, 6, 9, or 12% for growing pigs. The digestibility coefficients for the essential amino acids decreased as the sesame meal inclusion rate rose, except for arginine and phenylalanine. The amino acid digestibility coefficients determined using the regression technique were different to those previously published for sesame meal determined using the direct method. Overall, as the amount of sesame meal in the diet rose, daily weight gain and feed efficiency both decreased.

Pigs reduced their feed intake in response to an increasing sesame meal inclusion rate in the diet in a linear manner, where such an impact of sesame meal has been attributed to its high phytate (approx. 5%) and oxalates (35 mg/100 g), which impart a bitter taste to the meal (Hou, Zhang et al. 2021).

Sesame meal contains reasonable quantities of phytic acid, where phosphorus and calcium availability could be impaired to a great extent. De Souza et al. (2017) cross-factored sesame meal at a 20% inclusion rate (replacing soybean meal) with phytase supplementation in piglets after weaning. The results show that neither the protein source (being soybean meal or sesame meal), nor phytase addition affected gut morphometric parameters, or total trypsin activity. Nutrient digestibility was better in soybean meal compared with sesame meal, which might be due to the higher neutral detergent fibre (NDF) content of sesame meal, however, phytase increased the apparent total tract digestibility of calcium (22.7%) and phosphorous (27.9%).

Table 30 Sesame meal nutritive value for pigs

Pig nutritive values	Unit	Avg
Energy digestibility, growing pig	%	76.0
DE growing pig	MJ/kg DM	15.7
MEn growing pig	MJ/kg DM	14.4
NE growing pig	MJ/kg DM	9.6
Nitrogen digestibility, growing pig	%	88.6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org)

Ileal digestibility of most of its amino acids tended to decline as the inclusion of sesame oil meal increased in pig diets, and daily weight gains and feed efficiency were hampered as the level of sesame oil meal increased from 0 to 12% (diet DM) (Li, Qiao et al. 2000).

It is well known that sesame seeds function as a natural antioxidant. It has been demonstrated that adding 1–3.5 per cent of ground sesame seeds to diets based on non-defatted rice bran, which is prone to rancidity and loss of palatability during storage, reduces peroxidation and increases feed intake and feed conversion ratio in pigs in Vietnam (Yamasaki et al. 2003).

Table 31 Standardised ileal digestibility of amino acids of sesame meal in pigs

Indispensable amino acid	**Sesame meal**
Arginine	95.8
Histidine	93.8
Isoleucine	90.5
Leucine	89.4
Lysine	95.5
Methionine	86.3
Met+Cys	-
Phenylalanine	86.0
Threonine	88.2
Tryptophan	-
Valine	86.7
Dispensable amino acid	
Alanine	83.4
Aspartic acid	88.3
Cysteine	75.9
Glutamic acid	94.2
Glycine	88.8
Proline	86.3
Serin	94.0
Tyrosine	81.6

(Source: Reis de Souza et al. 2021)

Early studies reported that sesame meal could be included at up to 15% of the diet for growing-finishing pigs with no detrimental effects on growth performance (Squibb et al. 1951). Recent research, however, showed that sesame meal should be supplemented with synthetic lysine or a source of lysine (Ravindran 1990). Sesame meal could only replace 10% of the soybean meal in commercial diets (Seerley 1991). In general, it has been suggested to adjust the inclusion of sesame meal in accordance with the type and quantity of the other protein sources in the diet (Ravindran 1990). Considering the apparent ileal digestibility of amino acids, a maximum of 10% sesame meal can be included in the diet without adversely affecting total feed intake, average daily growth, or feed conversion (Tartrakoon et al. 2001). In young piglets, the inclusion rate of sesame meal in starter feed should not exceed 5% (Ravindran 1990).

2.4.7 Carbon footprint and sustainability of sesame production

During our literature review, we did not find much information about the environmental footprint of sesame production. HEALabel (2022b) mentioned that the sesame production process emits 4.2 kg CO_2e to produce 1 kilogram, which equates to a car driving 15.75 km.

2.5 Sunflower meal

Sunflower seeds belong to the genus Helianthus annuus. Cultivated sunflower seeds, one of the 67 global species of genus Helianthus (Jain et al. 2009), have become the second largest reserve of feed and sources of protein, the third most important source of oil consumed by humans and animals, and the fourth major oilseed in production (Garcés et al. 2009).

Sunflowers can be harvested in tropical areas two or three times a year (De Figueiredo et al. 2011). A wide variety of sunflower products is available on the market, from low-quality straw-like livestock meal to high-quality flour. Sunflower meal is the by-product of sunflower seed after oil extraction, comes from whole or decorticated seeds, and can be mechanically and/or solvent extracted. The quality of the meal depends on the plant characteristics (seed composition, hull/kernel ratio, dehulling potential, growth and storage conditions) and on the processing method (dehulling, mechanical and/or solvent extraction) (Sangsoponjit et al. 2017). While solvent-extracted sunflower meal is the main commercially available sunflower meal, oil-rich sunflower meal obtained by mechanical pressure has only popularised since the 2000s, with the development of organic farming and on-farm oil production.

Sunflower meal nutrient content varies in accordance with the processing method used for oil extraction. Solvent extracted sunflower meal has high concentrations of protein, but low concentrations of oil and fibre compared with mechanically extracted sunflower meal. Dehulled sunflower meal has somewhat higher protein concentrations and slightly less fibre (Alagawany et al. 2015). Additionally, sunflower has high α-tocopherol (608 mg/kg seed) content with efficient antioxidants, so is deemed a plentiful source of vitamin E (Kiczorowska et al. 2019). Sunflower meal has a very close chemical composition to soybean meal; however, of major concern are the nature and content of the sunflower seed fibre, which limit the use of its nutrients for monogastric animals (Liu et al. 2018).

2.5.1 Sunflower seed and meal production globally and in Australia

Sunflower seed is one of the major oilseeds cultivated globally, along with cotton seeds, soybeans, and rapeseed. Full, bright sun, constant humidity and well-drained soil best suit sunflower growth. The space needed depends on which varieties are to be cultivated. Branching types with multiple blooms on one stem need more space horizontally than large single-flowered types. Sunflowers are known for their hardiness and survival ability in extreme heat, however, their optimal growth temperatures are between 21 and 26°C, with soil temperatures of at least 13–16°C when the seeds are sown. The average production yield of sunflower ranges from 1.2 to 1.8 tons per hectare (Berglund et al. 2007).

Sunflower meal is available worldwide. World production was estimated to 21.85 million tons in 2019 (IndexMundi 2019). Ukraine and Russian federation are the main producers with respectively 6.3 and 5.1 million tons produced in 2019. The European Union (EU-27) is the third producer with 4.8 million t in 2019 (IndexMundi 2019). EU-27 also imported 3.4 million t sunflower meal in 2019 (IndexMundi, 2019). Other current major sunflower producing countries are Argentina, China and the United States. Turkey also had an estimated area under sunflower cultivation of 760,000 hectares and produced 1.75 million tonnes in 2021/22. The United States Department of Agriculture (USDA) estimated the world sunflower seed production in 2021/22 would reach 56.99 million tonnes.

Australia produces only relatively small amounts of sunflower. Oilseed sunflowers make up the majority of the Australian crop. There are two types of sunflower oilseed: the ‘poly’ and ‘mono’ varieties. Poly is the traditional type that has been grown in Australia and produces the

polyunsaturated sunflower oil used in margarine and bottled oils. Mono, a relatively new development, produces monounsaturated oil with its biggest potential in the food services industry, and a number of margarines and bottled oils. The seed is also used as protein meal in livestock feed, a source of fibre for beef feedlots, and as mushroom compost (ASA 2004). Queensland and New South Wales are the major Australian regions for sunflower cultivation. Most sunflower is grown in Northern New South Wales and Queensland, however, in Western Australia the Ord River catchment and the south-west of the state are considered potential areas for summer rotational crops (ASA 2004).

Table 32 Sunflower production in Australia for 2021–2022

Sunflower	2020/2021 final		2021/2022 estimate	
	Harvested area (hectares)	Production (tonnes)	Sown area (tonnes)	Production (tonnes)
NSW	9,800	19,700	11,000	22,000
QLD	7,700	7,200	7,300	7,800
Total	17,500	26,900	18,300	29,800

(Source: Australian Oilseed Federation)

Prior to October 2000, Australian sunflower meal was produced mostly in Brisbane, which enabled its cost-effective transport back to the pig and poultry producing areas, but since 2000 the major meal production has moved to Newcastle, which is quite distant from the major pig producing areas. The additional freight cost thus incurred in transporting the raw sunflowers to the processing plant and returning the meal to the pig producing areas, has driven up the cost of sunflower meal and contributed to its reduced usage for pigs.

In recent seasons, due to drought in Queensland, sunflower production has been reduced and has become variable; therefore, the feed millers have had to decide in advance of the sunflower season which raw materials they will be able to maintain throughout the whole year. The average Australian all species annual consumption of sunflower meal is approximately 45,000 t/year, however, because the major end user markets are significantly remote from the sunflower meal source, sunflower meal supply to local markets remains a major limitation to increasing sunflower meal usage in Australia (Australian Oilseed Federation (AOF) 2009).

2.5.2 General characteristics

Sunflower meal is one of the major protein meals used for livestock feeding, particularly for ruminants. Sunflower meal quality varies significantly and depends mainly on the type and the extraction process used. Note that the hull represents less than 25% of the seed but hinders both extraction yield and the final meal quality so, frequently, dehulling is undertaken prior to extraction (Borbély et al. 2007).

The whole seeds are crushed and then about 10–12% of the hull's fibrous section is separated physically or pneumatically. The partially dehulled seed fraction is pressurised by expeller pressing, which results in an extraction cake with up to 15% oil content. But in many cases the oil removal process continues with solvent extraction to improve the oil extraction yield, resulting in a final meal with less than 2% fat and high protein concentration. Solvent extraction does not disqualify the sunflower meal from use in pig feed, except in the case of EU organic production, where its use is prohibited (Baümler et al. 2016). Although rich in crude protein, sunflower meal for poultry applications has some limitations because of its fibre, including insoluble fibre, and low levels of specific limiting amino acids such as lysine and methionine. Besides its sufficiency of α-tocopherols with their efficient antioxidants, sunflower has good amounts of Ca, P, vitamin E and vitamin B-complex.

To prevent sunflower meal oxidising and becoming rancid, it should be properly stored prior to processing. Typically, sunflower meal is dry and can be stored for extended periods without significant loss or degradation (Valdés García et al., 2021). The meal should be finely ground to break up the hulls. During the feed mixing and pelleting process, sunflower meal presents little to no problems. In fact, it performs better than soybean meal in terms of capability to form durable pellets, possibly because of its higher fibre content (Garrido-Polonio et al. 2004).

There are fully decorticated meals (high protein, low fibre), partially decorticated meals and non-decorticated meals (low protein, high fibre) with no clear separation between these grades. Like other protein feeds such as fishmeal or soybean meal, sunflower meal is usually graded and sold on the basis of its protein content (NCPA 2008). The colour of sunflower meal ranges from grey to black, depending on the extent of dehulling (meals with fewer hulls are lighter) and on the extraction process (Naidu 2008). Sunflowers can be fed whole, rolled or slightly cracked, but they should not be finely ground, as this exposes more of the fat to the rumen environment in ruminants, which could depress fibre digestion. It is a palatable feed but can be a laxative if fed at high levels (Kalmendal et al. 2011).

2.5.3 Nutritive value for animal feed

Sunflower meal is an excellent source of crude protein (average crude protein 29–32%). Its protein content ranges from 23% DM for some non-dehulled, mechanically extracted meals, to more than 40% for highly decorticated, solvent-extracted meals. Ether extract is about 2.2% and ash content is 7.1% on average. The absence of antinutritional components in sunflower meal makes it particularly intriguing since, unlike other oil meals such as soybean, rapeseed or cotton, it can be fed without heating or other specific preparation. Compared to other protein sources, its amino acid profile is richer in sulphur-containing amino acids, especially methionine, although its lysine level is substantially lower than that of soybean meal (3.5 vs. 6.1 per cent protein). Crude fibre varies from 20 to 26 per cent DM for dehulled and partially dehulled sunflower meals, while it ranges from 27 to 31 per cent DM for meals that have not been dehulled. Even with dehulled meals, the lignin level (between 9 and 12%), is significant. Depending on the amount of pressing, mechanically extracted sunflower meals can include up to 30% oil, while solvent-extracted meals only have about 2–3% DM of residual oil. Expeller meals have more gross energy due to the oil content (22 MJ/kg DM or more compared with 19 MJ/kg DM for meals extracted using solvents), but they also have less protein.

Table 33 Chemical composition of sunflower meal solvent-extracted, dehulled or non-dehulled

Main analysis	Unit	Avg	SD	Min	Max	Nb
Dry matter	% as fed	89.0	1.4	85.1	94.3	14806
Crude protein	% DM	32.4	3.1	23.9	44.7	14755
Crude fibre	% DM	27.9	3.3	16.1	37.4	14519
NDF	% DM	45.0	4.4	31.6	54.3	647
ADF	% DM	32.0	3.6	21.0	39.4	644
Lignin	% DM	10.7	1.6	6.1	13.6	540
Ether extract	% DM	2.2	0.9	0.4	5.6	9688
Ash	% DM	7.1	0.7	5.5	9.4	5882
Total sugars	% DM	6.1	0.8	4.3	7.7	166
Gross energy	MJ/kg DM	19.4	0.3	18.7	20.2	75

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org).

Mechanically extracted sunflower meals contain cysteine, methionine, leucine, valine, isoleucine, tryptophan, alanine, and phenylalanine, which are all necessary amino acids. Phosphorus, thiamine, nicotinic, pantothenic, and riboflavin are the most common minerals and vitamins. The lysine content of sunflower meal (3.5% of the protein) is lower than that provided by soybean meal, or canola meal, which could limit the production (meat, egg, and milk) in animals.

The protein in sunflower meal is more soluble than in soybean meal (34 versus 17% of N, respectively), but processes such as extrusion decrease solubility. Without processing to reduce solubility, greater proportions of the dietary nitrogen provided by sunflower meal are degraded by ruminal microorganisms. As a result of the high proportion of hulls in sunflower, which consists of about 50% cellulose and 25% lignin, the nutritive value of sunflower meal is reduced in pigs and poultry nutrition (Gomaa et al. 2018). Since the main challenge in incorporating sunflower meal in monogastric animals' diet is its high fibre content, which negatively affects growth performance and carcass yield, certain exogenous enzymes such as beta-glucanase or phytase may be added to feed containing sunflower meal to aid fibre digestion, or to solubilise phytic phosphorus (Raza et al. 2018).

Table 34 Minerals and amino acids composition of sunflower meal

Minerals	Unit	Avg	SD	Min	Max	Nb
Calcium	g/kg DM	4.4	0.7	3.0	6.6	1017
Phosphorus	g/kg DM	11.6	1.7	8.6	16.5	1143
Potassium	g/kg DM	16.9	1.4	13.6	19.1	35
Sodium	g/kg DM	0.1	0.1	0.0	0.3	154
Magnesium	g/kg DM	5.6	0.5	4.7	6.4	27
Manganese	mg/kg DM	38	8	25	56	24
Zinc	mg/kg DM	96	9	81	114	24
Copper	mg/kg DM	32	5	25	44	23
Iron	mg/kg DM	271	52	207	361	8
Amino acids	**Unit**	**Avg**	**SD**	**Min**	**Max**	**Nb**
Alanine	% protein	4.3	0.3	3.9	5.1	54
Arginine	% protein	8.1	0.5	7.2	9.1	54
Aspartic acid	% protein	8.8	0.4	8.0	9.7	56
Cystine	% protein	1.7	0.2	1.4	2.1	68
Glutamic acid	% protein	18.9	1.4	17.0	22.4	56
Glycine	% protein	5.6	0.3	5.2	6.5	60
Histidine	% protein	2.4	0.2	2.1	3.0	52
Isoleucine	% protein	4.1	0.2	3.6	4.6	67
Leucine	% protein	6.2	0.3	5.6	7.0	67
Lysine	% protein	3.5	0.2	3.1	4.0	86
Methionine	% protein	2.3	0.2	1.9	2.5	70
Phenylalanine	% protein	4.4	0.2	3.9	4.9	64
Proline	% protein	4.2	0.4	3.5	4.9	26
Serine	% protein	4.2	0.2	3.7	4.6	56
Threonine	% protein	3.6	0.2	3.3	4.0	67
Tryptophan	% protein	1.3	0.0	1.2	1.3	19
Tyrosine	% protein	2.3	0.3	1.7	2.8	40
Valine	% protein	4.9	0.3	4.3	5.6	67

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org).

Sunflower meal has the greatest potential use in ruminant rations. Unhulled or partially dehulled sunflower meal can be substituted for soybean meal on an equivalent protein basis when feeding ruminants (Osuga et al. 2012).

Low-fibre and high protein meals can be utilised in feeding pigs and poultry, while lower levels of lysine and threonine may restrict production, crystalline amino acids can adjust these deficiencies. However, sunflower meal contains an excellent level of methionine, which is a good reason for potentially mixing it with other meals. Its main advantage is as a good source of linoleic acid, but including sunflower meal in the diets of finisher pigs may cause soft fat to develop, depending on the fat level of the meal (high fat in mechanically extracted meals). However, the fat levels in Australian sunflower meal are usually very low, due to the efficient method of extraction, and hence they do not usually present any problems when feeding pigs or poultry (Alagawany et al. 2015).

2.5.4 Antinutritional factors – nutritional limitations

A major benefit of sunflower meal compared to soybean, cottonseed and rapeseed meals, is the absence of antinutritional factors, which makes it a safe ingredient to be included in the feed with no need of heating or processing. Its high fibre and shortage of some amino acids though may introduce some limitations for monogastric animals.

Sunflower meal contains polyphenolic compounds which may restrict its use in pigs and poultry nutrition. Chlorogenic acid is the chief molecule of polyphenolic compounds in sunflower meal with a concentration of 2.70 corresponding to 70% of the total phenolic constituents. In addition to chlorogenic acid, sunflower meal contains other phenolic compounds such as caffeic, rosmarinic and ferulic acids, protocatechuic, o-cinnamic, myricetin, syringic acids, and rutin, which all present in quantities of less than 0.15 ppm (De Leonardis et al. 2005). Chlorogenic acid is the ester of caffeic acid and quinic acid both are found in sunflower polyphenolic compounds at concentrations of 0.38 and 0.20%, respectively. Chlorogenic acid causes brown and green discoloration in feed at alkaline pHs (González-Pérez et al. 2002), and could become a barrier to use in feed products as a colour forming factor, but not as a toxic component. When eggs come into contact with sunflower meal dust, the chlorogenic acid stains the eggshell. This issue is resolved by regularly collecting eggs and feeding sunflower meal pellets to the birds (Daghir 2008). Digestibility and bioavailability of the protein content of sunflower are observably reduced by chlorogenic acid, however, the phenolic compounds, including chlorogenic acid are not toxic. Chlorogenic acid is a vital compound of the hydroxy-cinnamates, components that are ubiquitous in plants and have fascinating biological properties, such as antioxidant activities (Wildermuth et al. 2016).

Luckett et al. (1999) isolated a peptide with 14 amino acids, termed sunflower trypsin inhibitor (SFTI-1), from sunflower seeds, which could also have a negative effect on performance. Methionine and choline addition are recommended to counteract the harmful effect of chlorogenic acid when sunflower meal is used in pigs and poultry diets.

Copper levels in sunflower products can occasionally be excessive due to the usage of copper-containing fertilisers. Sheep are more vulnerable than other livestock to long-term copper toxicity.

2.5.5 Sunflower meal in the laying hen diet

A major factor in using sunflower meal in poultry diets is its cheapness compared to soybean meal, but also it is free from toxic molecules and antinutritional factors, which may affect productive performance (González-Pérez et al. 2007).

Sunflower meal as a protein-rich but lysine-deficient and high-fibre ingredient has limitations for poultry. The majority of the fibre in sunflower meal is made up of insoluble carbohydrates, which

results in low metabolisable energy values (Villamide & San Juan 1998). Sunflower meal is therefore a better ingredient for laying hens than for species with higher protein and energy needs, like broilers and turkeys (CETIOM 2003). In countries where soybean meal is unavailable or too expensive, it might be more affordable to utilise sunflower meal for poultry diets.

Table 35 Sunflower meal metabolisable energy value for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max	Nb
AMEn cockerel	MJ/kg DM	8.6	1.2	6.3	9.9	15

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
AMEn: apparent metabolisable energy.
(Source: Feedipedia.org).

Practical and commercial feed formulation for poultry limits the use of high-fibrous feed ingredients as it dilutes the energy content and impairs feed conversion ratio. High-oil meal and other diets rich in sunflower meal tend to be bulky, which reduces feed consumption. Laying hen diet should contain 35 to 45 g/kg of dietary crude fibre (Shi et al. 2012). Pelletising reduces bulkiness, which improves performance including weight gain and feed conversion ratio (Senkoylu et al. 2006).

Table 36 Standardised ileal digestibility of amino acids of sunflower meal in laying hens

Indispensable amino acid	Sunflower meal
Arginine	89.6
Histidine	82.9
Isoleucine	84.6
Leucine	86.3
Lysine	80.2
Methionine	87.7
Met+Cys	-
Phenylalanine	87.7
Threonine	74.5
Tryptophan	-
Valine	83.1
Dispensable amino acid	
Alanine	82.8
Aspartic acid	82.4
Cysteine	83.0
Glutamic acid	90.4
Glycine	79.5
Proline	85.3
Serin	81.3
Tyrosine	86.0

(Source: Such et al. 2024)

Sunflower meal can be added to layer diets at up to 30% without having any negative effects on performance (Deaton et al. 1979). Pelleting can increase feed efficiency by reducing the bulkiness of diets based on sunflower meal (Vetesi et al. 1998). Numerous studies have reported no negative impact of sunflower meal inclusion in layer diets on live weight, feed consumption, egg production or feed conversion ratio (Casartelli et al. 2006; Shi et al. 2010; Baghban-Kanani et al. 2019). Some studies found sunflower meal inclusion in layer feed to be enhancing the lay performance (Vierira et al. 1992;

Furlan et al. 2001; Tsuzuki et al. 2003; Laudadio et al. 2013). Sunil (2019) reported a significant improvement in lay percentage and feed conversion ratio when sunflower meal was included at 13% in laying hens' diet. In the study by Baghban-Kanani et al. (2019), including sunflower meal, up to 20% of the laying hens' diet together with multi-enzyme supplementation had no adverse effects on the laying rate, egg quality attributes or antioxidant status.

In a recent study by Saleh et al. (2021), sunflower meal was included at 5 and 10% into the basal diet as a complementary protein source. Similar to previous reports, sunflower inclusion not only did not have a negative impact on live weight gain, feed intake, and egg mass, but also the laying rate was increased, feed conversion ratio and the broken egg rate of laying hens were decreased, and egg yolk colour and height were increased. Their results suggested that sunflower inclusion of up to 10% at a late phase of laying could improve production performance, egg yolk quality traits, and nutrient digestibility, while decreasing egg yolk cholesterol.

It has been demonstrated that dietary inclusion of sunflower meal has improved egg yolk quality and colour (Laudadio et al. 2014;). This might be related to the dietary fat content, which is essential for the absorption of pigments and fat-soluble vitamins (Gao et al. 2022). In agreement with these findings, De Morais Oliveira et al. (2016), reported that the amount of fats in the sunflower meal diet increased pigment absorption and enhanced yolk colour.

Sunflower meal inclusion in the poultry diet may aid the effect of fibre on lowering cholesterol. Low-fibre sunflower meal might lower hepatic de novo lipogenesis, which would lower cholesterol levels in serum and egg yolk. Bile acids may be one way for sunflower meal to have a hypocholesterolemic effect. Bile salts are secreted into the gut by the host to assist lipid digestion and absorption. Cholesterol is converted by hepatocytes into cholic and deoxycholic bile acids, which are then conjugated with taurine and glycine, respectively. Insoluble fibre fraction increases the activity of bile-salt hydrolyser bacteria in the hind gut, reducing the recycling of bile-salt, therefore more cholesterol is used for new bile salt synthesis.

It seems that sunflower meal can be safely used in laying hens' diet at up to 20%, replacing soybean meal totally if it is combined with lysine-rich protein sources or supplemented with crystalline lysine.

2.5.6 Sunflower meal in the pig diet

Different opinions exist regarding the use of sunflower meal in pigs' diet. It should be fully avoided, according to some authors, for all classes of growing pigs (CETIOM 2003). Others advise that while young pigs shouldn't consume sunflower meal, older animals can consume sunflower meal at up to 25–33% of their protein source (Blair 2007; Chiba 2001).

Sunflower meal's inclusion in pig diets is constrained by its high fibre content and lack of certain essential amino acids, such as lysine, threonine, and tryptophan. Sunflower meal has a substantially lower energy value and the net energy value of dehulled, high-protein sunflower meal for growing pigs is around 64% that of low-protein soybean meal (6 vs. 9.3 MJ/kg DM, respectively). In a study evaluating different levels of dehulling, net energy estimates ranged from 5.4 to 7.9 MJ/kg DM for standard processes and from 3.5 to 9.0 MJ/k DM for experimental products, which covers a wide range (Perez et al. 1986).

The inclusion of sunflower meal in pig diets will depend on its costs and regional availability. In Turkey, for example, sunflower meal supplemented with lysine has been successfully used to replace food waste in piglets feed, producing comparable results to those of soybean meal, improving animal performance and feed efficiency (Akdag et al. 2008).

Table 37 Sunflower meal nutritive value for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max	Nb
Energy digestibility, growing pig	%	60.1	7.6	53.3	74.8	8
DE growing pig	MJ/kg DM	11.6	1.3	10.5	14.3	8
MEn growing pig	MJ/kg DM	10.6				
NE growing pig	MJ/kg DM	6.0				
Nitrogen digestibility, growing pig	%	81.2	3.2	77.2	88.1	9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
DE: digestible energy.
MEn: metabolisable energy.
NE: net energy.
(Source: Feedipedia.org).

Sunflower meal is not the best choice for young growing pigs with high calorie and protein requirements, unless it is of high quality. When the amount of sunflower meal in the diet was more than 10–11%, it had a negative impact on the growth performance, the quality of the carcass, and the feed intake of piglets and growing pigs (Lipinski et al. 2002; Shelton et al. 2001; Li, Yi et al. 2000). Additionally, sunflower meal resulted in a lower feed efficiency than soybean meal (Shelton et al. 2001). Various investigations revealed that lysine and oil supplementation could reduce this issue but not eliminate it (Shelton et al. 2001; Cortamira et al. 2000). Lysine supplementation into sunflower meal diet when used as the only protein source resulted in inconsistent growth performance (Akdag et al. 2008; Shelton et al. 2001).

Table 38 Standardised ileal digestibility of amino acids of Sunflower meal in pigs

Indispensable amino acid	Sunflower meal
Arginine	92.3
Histidine	80.8
Isoleucine	80.9
Leucine	81.5
Lysine	75.8
Methionine	88.3
Met+Cys	-
Phenylalanine	83.7
Threonine	76.5
Tryptophan	87.3
Valine	79.0
Dispensable amino acid	
Alanine	78.3
Aspartic acid	78.8
Cysteine	73.6
Glutamic acid	87.5
Glycine	69.5
Proline	135.1
Serin	77.1
Tyrosine	83.7

(Source: González-Vega et al. 2012)

Sunflower meal can be safely included in the diets for adult and finishing pigs at a higher rate up to 16 to 21 per cent without impaired growth efficiency or carcass quality (Blair 2007; Chiba 2001; Carellos et al. 2005; Silva et al. 2002; Rodehutscord et al. 2002). Male pigs respond better to sunflower meal and grew faster than females (Silva et al. 2002). It should be noted that higher inclusion levels at finishing pigs, however, may lead to poorer performance and lower meat quality (soft backfat with more linoleic acids) (Blair 2007; Asuming-Bediako et al. 2014).

Sunflower meal can be used as the only protein source for sows and adult boars, as long as the diet is adjusted for the amount of total digestible lysine. Sunflower meal did not impair sows' reproductive performance (Kleisiari et al. 2005) and it can be included for lactating sows as long as they received a protein source high in lysine or simply synthetic lysine (Blair 2007).

In conclusion, sunflower can be added to adult pigs' and sows' diet at an inclusion rate of up to 20% if the lysine is supplemented or sunflower meal is combined with lysine-rich protein sources.

2.5.7 Carbon footprint and sustainability of sunflower production

In sunflower agroecosystems, the highest share of total input energy was reported for electricity, N fertiliser, and diesel fuel with 35%, 19%, and 17%, correspondingly (Yousefi et al. 2017). With this energy use, the carbon footprint and greenhouse gas emissions were recorded 0.875 kg CO_2eqkg−1 for the production of 1kg sunflower and 2042.091 kg CO_2eqha−1 per hectare, in Iran.

Another study reported that the average GHG intensity calculated for irrigated sunflower ranged from 0.39 to 0.65 kg CO_2eq kg−1 if land use change is not considered (Figueiredo et al. 2017). Contrary to this previous study, Forleo et al. (2018) showed that the carbon footprint of sunflower cultivation was on average about 895 CO_2eq per Mg of seed produced.

In a complete oil life cycle study in France, Badey et al. (2013) showed the emission status from oilseed farming to the end-of-life of the packaging. The production of 100 g of refined bulk sunflower emits 89 g equivalent CO_2. Most impacts came from the farming phase – the hotspot. The results of this study may provide a related overview of all sunflower oils, and can be used to make a preliminary assumption for sunflower meal cakes, which come from the oil making process. The crushing and refining stages make up the vast majority of GHG emissions generated, with bottling accounting for just 5−6% (Badey et al. 2013).

2.6 Coconut/copra meal

Coconut (*Cocos nucifera* L.) is a monocotyledon palm from the Palmaceae family (Lima et al. 2015). *Cocos nucifera* L. is generally referred to as a coconut palm and is one of the most useful trees and has great importance: it provides millions of people with food, employment, and business opportunities. Coconut is a multi-use tree, with its fruit full of macro and micro-nutrients, providing nutrition for human consumption (Karandeep et al. 2019). The coconut leaves are turned into thatch, brooms and baskets, while the lumber is used in buildings and furniture. Furthermore, the husks and coconut shells produce charcoal and fuel (Ighalo et al. 2023).

While in the tropics there are many people who regard the coconut as a staple food, in European countries it is often thought of as exotic. Agriculturists refer to the fruit as a drupe, that is, a fruit, nut and seed all rolled into one. On the other hand, many Asians consider the coconut a medical cure for ailments such as rash, fever and nausea, while nutritionists lay big claims on coconuts and how they contain naturally sterile electrolytes, fibre, lauric acid, manganese, potassium, and phosphorus (Xu et al. 2022).

Products from coconut palm include coconut oil, coconut milk, coconut water and coconut meat. Extracted from the coconut meat come coconut oil, coconut milk and copra, and matured coconut kernel. Coconut water has gained in popularity over the last few years as both a refreshment and a sports drink. On top of that, coconuts have been used to create musical instruments in China, Vietnam, the Middle East and Eastern Europe. In the Philippines, alcoholic beverages are created from coconuts (Alouw & Wulandari 2020).

Coconut oil is commonly manufactured from coconut meat (wet kernel) by natural or mechanical means, with or without heat. Copra meal or coconut meal is the matter remaining after extraction of oil from the dried endosperm of the coconut. Even though those two terms (copra meal and coconut meal) are used interchangeably, copra meal is more appropriate as it is a residue of the industrial extraction of coconut oil (Agarwal & Bosco 2017).

Copra meal has been an important protein supplement for livestock and poultry feed for some time. The residual oil content of copra meal varies from 1 to 22% depending on the method of oil extraction, storage conditions and drying process (Moorthy & Viswanathan 2009). Copra meal is a good source of energy and a moderate source of protein for animals, except that its protein is deficient in lysine and methionine (Sundu et al. 2009).

2.6.1 Coconut production globally and in Australia

Coconut trees grow in more than 80 countries, with Asia being the mainstay of the coconut industry. Each tree may produce around 100 coconuts a year, but the work in maintaining the tree plantations to ensure such a good crop is continuous and demanding. Global coconut production in 2020 was 61.52 million tonnes. Of this quantity, 70% is grown in Indonesia, the Philippines, and India. Brazil, Sri Lanka, Vietnam, and Papua New Guinea are the fourth to seventh highest producing countries. Around 70% of the crop is consumed domestically, and over half of it is eaten fresh (Shahbandeh 2022).

As coconut is currently growing in popularity, some Australians have considered growing it locally as a crop, as most of our coconuts and coconut derived products come from overseas, even though we can and do grow it here, in the north. We hold 1% of the world's total coconut oil export market. In Australia, 446 tonnes of coconut oil were sold in 2020. In 2019, we exported 337 tonnes of it, but back in 2018–2019, demand for Australian coconut oil was waning. The 2019 coconut oil sales fell by 35.7%

from 2018. However, between 2017 and 2019, Australia's coconut oil exports overall grew by 81.2%, earning a total of US$1.84 million in 2019 alone. China, the US, France, New Zealand and Canada are Australia's strongest coconut oil export markets.'.

Australia's coconut oil exports are classified as:

- Coconut oil and its fractions, whether refined, but not chemically modified (excluding crude).
- Crude coconut oil.

2.6.2 General characteristics

Coconut fruit largely consists of 51.7% kernel, 9.8% water, and 38.5% shell. Its milk is usually manufactured from grated coconut meat (kernel). Basically, coconut milk is an oil-in-water emulsion, stabilised by some proteins existing in the aqueous phase.

In general, the fruit takes about one year to fully develop. First, the husk and shell grow, and the embryo sac cavity enlarges considerably. This cavity is filled with liquid. After about four months, the husk and shell thicken. The solid endosperm commences forming against the inner cavity wall at six months. This first layer is thin and gelatinous, but after about eight months, the soft white endocarp becomes hard and dark brown, the fruit becoming mature within 12 months (Jarimopas & Ruttanadat, 2007). The mature coconut fruit contains 35% husk (fibrous coat of the fruit), 12% shell (inner hard coat of the fruit), 28% meat (solid endosperm), and 25% water (Angeles et al. 2018).

Coconut proteins generally provide good nutritional value with a relatively balanced amino acid profile. Those proteins contain high levels of essential amino acids (71–77%) and digestibility of 86–94%. In coconut skim milk, the limiting amino acids are methionine, isoleucine, threonine, and tryptophan. Generally, coconut proteins have comparatively high levels of glutamic acid (17.0–27.2%), arginine (14.2–17.9%), and aspartic acid (5.6–8.9%) but are deficient in methionine (1.2–2.9%). Most of the amino acids in copra meal are comparable to those of other vegetable oil meals except methionine.

Copra meal protein is low in lysine and histidine and this, together with the generally high fibre content, limits meal usage for pigs and poultry (Moorthy & Viswanathan, 2009). Neither protein quality nor fibre content is limiting for ruminant animals.

Copra meal contains a high concentration of mannose – based polysaccharides or mannan (Mozin et al. 2021). Of the total carbohydrates present in copra meal, 61% was polysaccharides, containing 42% mannose and 58% glucose (Saittagaroon et al. 1983). Nor et al. (2017) found that most coconut polysaccharides were mannan and galactomannan, constituting 26% and 61%, respectively.

2.6.3 Nutritive value for animal feed

Copra meal contains about 70–75% total digestible nutrients (TDN), 25–30% crude protein and approximately 10–15% crude fibre. The oil content of copra meal varies from 2.5–10%, depending on the oil extraction method. Although meals of higher oil content are very useful in the preparation of high energy diets, they suffer the disadvantage of being susceptible to rancidity on storage. Ash content is about 7% and total sugars 12%. While copra meal provides an acceptable and very useful protein supplement, it is useful in dairy rations, supplying both energy and by-pass protein. Although daily copra meal feed allowance is recommended at 1.5–2 kg maximum safe amount, cows have been fed more than 3 kg/d with no contrary indications (Dery 2009). In diets for dairy cows, increasing the milk fat content is recommended. The milk fats produced from implementing diets with considerable amounts of copra meal, are firm and superb for butter making.

Table 39 Chemical composition of copra meal expeller extraction

Main analysis	Unit	Avg	SD	Min	Max	Nb
Dry matter	% as fed	91.5	1.5	88.5	94.8	240
Crude protein	% DM	22.4	1.2	19.6	24.9	257
Crude fibre	% DM	14.2	2.1	10.1	19.7	251
NDF	% DM	54.7	4.8	43.9	61.7	35
ADF	% DM	28.7	3.4	22.3	36.5	28
Lignin	% DM	6.7	1.9	4.5	12.8	110
Ether extract	% DM	9.8	2.7	5.2	18.4	163
Ash	% DM	6.8	0.5	5.7	8.0	231
Total sugars	% DM	11.4	2.4	7.8	15.8	12
Gross energy	MJ/kg DM	20.1	1.5	18.8	23.8	18

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org).

Although the amino acid profile and digestibility in copra meal are less favourable than those of soybean meal, significant protein and energy in pig diets are provided and the meal may be used to reduce feed costs (Fowler et al. 2018). The protein content of copra meal is about 25%, however, data on the solubility of copra meal indicate that protein quality is low.

Table 40 Minerals composition of copra meal

Minerals	Unit	Avg	SD	Min	Max	Nb
Calcium	g/kg DM	1.2	0.4	0.6	2.2	56
Phosphorus	g/kg DM	5.8	0.5	4.5	6.8	60
Potassium	g/kg DM	20.1	1.8	17.3	23.9	27
Sodium	g/kg DM	0.6	0.4	0.1	1.0	8
Magnesium	g/kg DM	3.0	0.3	2.5	3.6	27
Manganese	mg/kg DM	84	37	43	128	9
Zinc	mg/kg DM	73	49	45	214	11
Copper	mg/kg DM	33	5	26	44	12
Iron	mg/kg DM	964	1019	63	2964	6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org).

In fact, copra meal quality varies widely in accordance with its intrinsic nutrients, extraction process, and storage conditions. The inclusion of copra meal in monogastric animals might be limited mainly due to non-starch polysaccharides content, which makes up 45 to 60% of the dry matter and thus negatively affects the passage rate of diets in the digestive tract and increases the digesta viscosity. Its use in the monogastric industry has gradually increased over the years as technologies are now available to break down the fibre and release nutrients to pigs and poultry (Pipatpaitoon and Paraksa, 2021). Several feed technologies, including enzyme supplementation, dilution of commercial feed and

physical modification (pelleting, crumbling, soaking) improve the digestibility of copra meal for monogastrics and reduce feed cost (Diarra et al. 2015).

Table 41 Amino acids composition of copra meal

Amino acids	Unit	Avg	SD	Min	Max	Nb
Alanine	% protein	4.0	0.1	3.9	4.2	4
Arginine	% protein	10.7	0.9	9.4	11.3	4
Aspartic acid	% protein	7.7	0.3	7.4	8.1	4
Cystine	% protein	1.2	0.2	0.9	1.4	5
Glutamic acid	% protein	17.8	1.6	16.6	20.2	4
Glycine	% protein	4.1	0.1	4.0	4.3	4
Histidine	% protein	1.9	0.1	1.8	2.1	4
Isoleucine	% protein	3.0	0.1	2.9	3.2	4
Leucine	% protein	5.9	0.2	5.7	6.2	5
Lysine	% protein	2.6	0.2	2.3	2.9	8
Methionine	% protein	1.3	0.3	1.0	1.8	5
Phenylalanine	% protein	4.1	0.3	3.8	4.5	4
Proline	% protein	3.4		3.4	3.4	2
Serine	% protein	4.4	0.2	4.1	4.6	4
Threonine	% protein	3.0	0.1	2.8	3.2	5
Tryptophan	% protein	1.3				1
Tyrosine	% protein	2.1	0.2	1.9	2.2	3
Valine	% protein	4.7	0.3	4.3	5.1	4

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org).

Sant'Anna et al. (2003) reported 35% coconut meal solubility when bromelain was used to extract it. Copra meal is poor in essential amino acids, notably lysine and sulphur amino acids (Sundu et al. 2009). Lysine may be partly destroyed by the oil extraction heating. Amino acid supplementation may thus be necessary (Aderolu & Akinremi 2009). Copra meal is very rich in glutamic acid, followed by arginine. Its potassium content is also notable.

2.6.4 Antinutritional factors – nutritional limitations

The antinutritional factors of copra meal include phytic acid, tannins, and non-starch polysaccharides (Akinyeye 2011). A peculiarity of copra meal is its high non-starch polysaccharide content, including arabinoxylogalactan, arabinomannogalactan and galactoglucomannan in addition to mannan, galactomannan and cellulose, which are known to have antinutritional properties in monogastric species (Phoeurk et al. 2018). High fibre concentration in monogastric animal diets reduces weight gain (Walugenbe et al. 2014).

The above constituents are responsible for the physical properties that limit intake. These include the low bulk density (0.56 g/cm^3 vs. 0.75 for soybean meal) and high water-holding capacity (4.14 g water/g feed vs. 2.77 for soybean meal) of copra meal (Sundu et al. 2009). However, copra meal can absorb up to half its own weight of molasses, useful in compound feed manufacturing. It is also

possible that meals high in residual lipid content may be prone to oxidative rancidity under storage in hot and humid tropical conditions, which would reduce its acceptability to pigs and poultry.

Copra encourages the growth of Aspergillus fungi, which produce aflatoxins that adversely affect animal health. Split coconuts are vulnerable to mould growth and consequent aflatoxin contamination while being sun-dried. Most frequently, it happens when the drying time is too short (2–3 days as opposed to 5–7 days) or when the weather is damp. It is recommended to remove damaged coconuts during dehusking and avoid contact between split coconuts and the soil, which is a source of pollution. Additionally, copra meal should have less than 12% moisture, and should be stored in well-ventilated sheds.

Deterioration of the fat from oxidative rancidity or mould formation and mycotoxin contamination may lower the nutritional value and impact the palatability of copra meal (Zohri & Saber 1993).

2.6.5 Coconut/copra meal in the laying hen diet

Copra meal is high in fibre, mostly consists of NSPs, and is deficient in some essential amino acids, primarily lysine and methionine, which makes it a restricted source of nutrients and protein for poultry. In addition, its high water-holding capacity and bulk density can add to the limitations of its use in poultry feed (Sundu et al. 2009).

Table 42 Copra meal metabolisable energy value for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max	Nb
AMEn broiler	MJ/kg DM	8.7		7.5	10.0	2

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org).

Numerous studies have reported the use of copra meal in laying hens' diet. It has been reported that up to 20% inclusion of high-fat copra meal in the diet had no negative effects on performance (Panigrahi 1989; Braga et al. 2005; Lima, Fuentes et al. 2007). However, defatted copra meal inclusion at
15–20% resulted in a lower body weight, and egg production (Moorthy & Viswanathan 2006; Moorthy & Viswanathan 2010), however, egg composition was not altered (Barreto et al. 2006).

Diarra et al. (2014) conducted a trial on laying hens fed copra meal with or without enzyme supplementation for a period of 10 weeks. Copra meal without enzyme supplementation resulted in considerably higher feed intake, hen-day egg production, egg weight, and egg mass. The final body weight and feed conversion ratio were unaffected by diet. They concluded that 20% copra meal can be included in laying hens' diet, improving the production performance. It seemed that enzyme supplementation was not needed. This can have a great cost-saving effects if the copra meal is locally available.

Another study with 20% copra cake with or without enzyme supplementation revealed that pullets fed copra cake-based diets consumed more feed and water than the control. Feeding copra cake at 20% without enzyme resulted in a poorer feed conversion efficiency, although shell thickness, Haugh unit, and yolk colour were unaffected. Enzyme supplementation of copra cake improved hen-day production, egg weight, and egg mass (Diarra et al. 2018).

Table 43 Apparent ileal digestibility coefficients of copra meal for poultry

Indispensable amino acid	Copra meal
Arginine	0.86
Histidine	0.61
Isoleucine	0.74
Leucine	0.76
Lysine	0.51
Methionine	0.71
Met+Cys	-
Phenylalanine	0.79
Threonine	0.63
Tryptophan	-
Valine	0.76
Dispensable amino acid	
Alanine	0.75
Aspartic acid	0.71
Cysteine	-
Glutamic acid	0.78
Glycine	0.70
Proline	-
Serin	0.71
Tyrosine	0.65

Source: Bryden et al. (2009)

In early studies, it has been reported that inclusion of copra meal at 10 or 20% rates did not impair feed intake, egg output or feed efficiency when compared to the control diet (soybean meal). However, higher inclusion at 40% resulted in a 5% decline in feed intake and 6.9% reduced egg output. The whole substitution of dietary corn, primarily with copra at a 40% inclusion rate, increased the proportion of pale yolks, with a predominance of cream-coloured yolks. When corn was added back to the 40% copra-based diet, at a rate of 18%, eggs yolk turned somewhat golden-yellow (Panigrahi 1989).

It is concluded that copra meal can be included effectively in layer diets with the right formulation of energy and total digestible amino acids, at an inclusion rate up to a maximum of 15%. For high-quality expeller copra meal, this cap could be raised to 20%, and for pullets it can be between 10 and 15%.

2.6.6 Coconut/copra meal in the pig diet

Copra meal, if available locally, is an economical and valuable feed for pigs that can replace imported feeds such as soybean meal, partially (Siebra et al. 2008; Kim et al. 2001; Thorne 1992). The high fibre content of copra meal, however, limits its application in pig feeding. High fibre content decreases the passage rate and reduces feed intake as well as organic matter and nutrient availability, resulting in poor growth and production performance (Nguyen Nhut Xuan Dung et al. 2002; Noblet & Perez 1993; Thorne 1992; Lekule et al. 1986). It is essential to supplement copra meal-based diets with crystalline amino acids, due to amino acid deficiencies as well as lower digestibility coefficients of copra meal amino acids, especially for lysine, methionine + cystine and threonine (Han et al. 2003; Mee & Brooks 1973; Thorne et al. 1992).

The recommendation is a 10% inclusion rate of copra meal in pigs' diet, although up to a maximum of 25% can be included in the diet (Pascoal et al. 2010; Siebra et al. 2009; Siebra et al. 2008; Nguyen Nhut Xuan Dung et al. 2002; O'Doherty & McKeon 2000; Lekule et al. 1986; Lekule et al. 1982). Lekule et al.

(1982) reported 500 g per day body weight gain when growing pigs were fed with 10% copra meal. The feed conversion ratio was impaired by inclusion rates greater than 50%, however, if growth performance at these rates is deemed to be acceptable, the low cost of copra meal may reduce the cost per kg of live weight (Mael & Ajuyah 2001; Göhl 1982).

Table 44 Copra meal nutritive value for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max	Nb
Energy digestibility, growing pig	%	55.5	9.6	55.5	85.4	5
DE growing pig	MJ/kg DM	11.2	0.9	11.2	15.2	7
MEn growing pig	MJ/kg DM	10.4	0.4	10.4	14.0	3
NE growing pig	MJ/kg DM	7.1				
Nitrogen digestibility, growing pig	%	70.9	9.9	50.2	77.5	9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
DE: digestible energy.
MEn: metabolisable energy.
NE: net energy.
(Source: Feedipedia.org).

High inclusion of copra meal in pigs' diet may result in firmer carcass fat as the residual oil in copra meal and copra expellers includes 50 to 70% medium-chain, saturated fatty acids (lauric acid and myristic acid). As a result, pigs fed 30% copra meal have three to five times more lauric acid and myristic acid deposited in their backfat than pigs fed 10& copra meal (Stein et al. 2015).

Table 45 Standardised ileal digestibility of amino acids of copra meal in pigs

Indispensable amino acid	Copra meal
Arginine	91.2
Histidine	82.5
Isoleucine	81.6
Leucine	81.6
Lysine	72.8
Methionine	85.5
Met+Cys	-
Phenylalanine	84.5
Threonine	76.7
Tryptophan	88.4
Valine	79.0
Dispensable amino acid	
Alanine	78.2
Aspartic acid	78.9
Cysteine	86.0
Glutamic acid	79.9
Glycine	76.2
Proline	-
Serin	82.0
Tyrosine	82.8

(Source: Sulabo et al. 2013)

Copra meal inclusion in pigs' diet, did not affect meat quality traits such as fatty acid composition or dressing percentage (Mael & Ajuyah 2001; Kim et al. 2001). The fat firmness was not altered either (Göhl, 1982).

Copra meal inclusion in weaned piglets feed (2 weeks after weaning) at a rate of 15%, linearly reduced the body weight gain where piglets grow 1 kg less than the control group within a three-week experimental period (Jaworski et al. 2017). Piglets might be able to maintain their growth performance if copra meal is included at lower rates. Kwon and Kim (2015) fed growing pigs with 30% copra expeller, with or without β-mannanase supplementation. The copra expeller had lower digestible energy content than the control diet (soybean meal), and enzyme addition did not improve the energy digestibility. Data about enhancing copra meal's nutritional value for pigs are scarce. Enzyme supplementation such as β-mannanase failed to improve digestibility of copra meal (Pascoal et al. 2010; Kwon & Kim 2015). Expeller processed copra meal did not improve the growth performance of pigs, even when included as low as 15% (O'Doherty et al. 2001).

Based on the available data in the literature, it seems that 15–20% copra meal can be safely included in grow-finish pigs' diet with no detrimental impact on growth production, meat quality or fat firmness.

2.6.7 Carbon footprint and sustainability of coconut production

It is thought that coconut oil production is moderately sustainable due to its effect on land, soil and forests coming from monoculture farming (HEALabel 2022c). Sampaio et al. (2021) reported that coconut carbon footprint varied from 0.116 to 0.363 kg of CO^2-eq/kg of coconut. The largest contributors to the carbon footprint were land use change (LUC) and coconut cropping. However, farms that adopted organic farming practices accounted for only 23% of total GHG emissions. (Sampaio et al. 2021). Another study on gate-to-gate life cycle analysis of coconut oil production showed that GHG emissions are 2.9271 kg-CO^2 eq (Yani et al. 2022). Again, HEALabel (2022c) mentioned that the carbon emission is 2.1 kg CO^2e to produce 1 kilogram of coconut oil, equivalent to a car driving 5 miles or 8 kilometres. Figure 13 depicts the percentages of carbon emissions from different sub-systems of coconut oil production, where we see that crude coconut oil plant plays the major role (41.15%) in producing emissions (Yani et al. 2022).

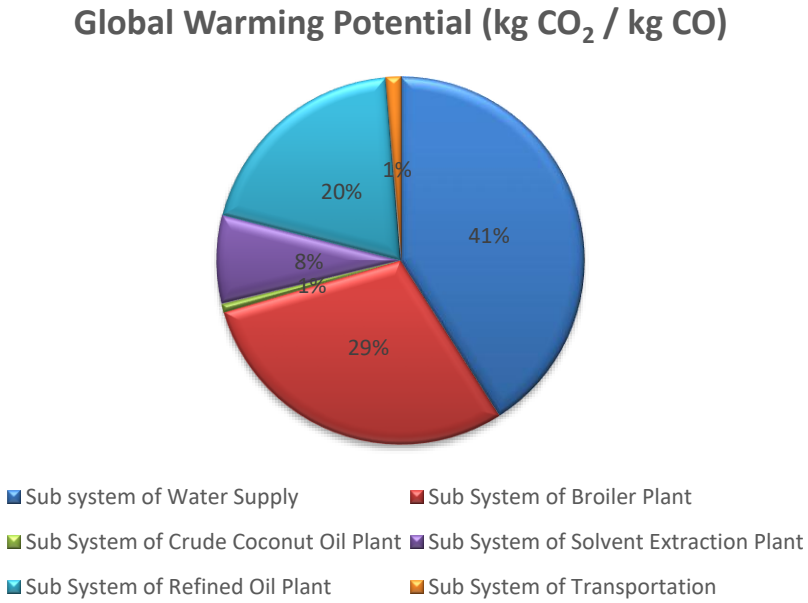


Figure 13 Global warming potential of coconut oil production

2.7 Peanut meal/groundnut meal

The legume peanuts (Arachis hypogaea) originated in South America. Its various names include groundnut, earthnut and goober, along with peanut and groundnut, which are interchangeable.

Originally, peanuts were grown in Peru, from at least 1500 BC, for their seed and oil. After Peru's invasion by Europeans, the peanut spread globally, with Africa developing into a major global supplier in the 19th century (Patee 2005). Peanut meal, flour and protein result from the processing of peanuts, to be used in various baked goods, snacks or in sauces.

Expeller-processed peanut meal contains about 5% unsaturated fat, which develops rancidity easily. Peanut meal is produced only by mechanical (expeller), or mechanical followed by solvent extraction. The extracted flakes are dried to eliminate the solvent, toasted, and then milled to a finely ground material. Solvent-extracted meal is the preferred product and consists of light grey to brownish flakes of varying sizes, containing about 2.1% fat. Peanut meal pellets vary between 1.5 and 40 mm in diameter and are light to dark grey (TIS 2016). It is also sold in pellet form.

Rich in protein, fat and other healthy nutrients, peanut also contains significant potassium, calcium, phosphorus, and B vitamins. Peanut contains healthy fats, protein and fibre, which limits the appetite, lowers the risk of heart disease and regulates blood glucose levels (Su et al. 2011).

Being the sixth most common oil meal after soybean, rapeseed, sunflower, cottonseed and palm kernel meals (USDA 2016), peanut meal is generally considered excellent in food because of its high protein content, low fibre, high oil (for expeller meal) and not many antinutritional factors. It is often the default high protein source in places where soybean meal is too expensive or unavailable. Peanut meal constitutes a palatable protein supplement containing low concentrations of several essential amino acids like lysine and methionine. Its growing season lasts between 75 and 150 days, requiring annual rainfall of 300–1200 mm. In southern and eastern Africa, where it is cultivated at elevations above 1500 meters within the same rainfall range (Freeman et al., 1999).

Even though direct utilisation of peanuts for food has progressively increased since the 1970s, crushing peanuts for oil and meal still represents a significant usage of the peanut crop. Peanuts should form part of a sustainable farming system in rotation with a grass or cereal crop.

2.7.1 Groundnut and meal production globally and in Australia

Currently peanut is a major crop grown in tropical, subtropical, and warm temperate areas in Asia, Africa, Oceania, North and South America, and Europe (Qinzhu et al. 2018). Although it is widely cultivated in Africa, Sudan, Nigeria and Senegal as the main producers, it is also grown in the semi-arid areas of western and central Africa.

About 94% of global peanut production occurs in developing countries, mainly in Asia and Africa, where it is largely grown in high rainfall areas (Fan et al. 2013). Most of the Asian production occurs in India and China though peanut is also grown in Indonesia, Myanmar, Bangladesh and Vietnam. More than 90% of peanut meal is consumed locally, and its trade is rather limited (Tu & Wu 2019). In 2015, about 100,000 t were exported, 70% by Argentina, Senegal, Nicaragua and Sudan (Oil World 2011).

China is the largest peanut producer in the world with 17,392,071 tonnes under production annually. Its crop production is estimated 17.77 million metric tons as quoted by the peanut industry. Approximately 70% of China's nuts are produced in Jiangsu, Shandong, Guangdong and Henan (Fletcher & Shi 2016).

Spanish peanuts are round, and smaller and oilier than other types, and they are the variety favoured for growth in China. They are commonly shelled for use in confectionery, salted as snacks, or used in peanut butter (Fletcher & Shi 2016).

India's 2020–21 peanut crop was the second highest in the world, at around 6.5 million metric tons. The crop is planted in two cycles and harvested in March and October; thus availability is constant. In India, the nuts are grown in Gujarat, Tamil Nadu, Orissa, Karnataka and Maharashtra (Fletcher & Shi 2016).

Major Indian export markets are Indonesia, Pakistan and Malaysia. Peanuts are the primary source of oilseed crops in India and bridge the vegetable deficit in the country.

Sitting at third place in terms of peanut production, and accounting for 30% of Africa's total nut production, is Nigeria, with almost 3.9 million tonnes of peanuts. These are grown mainly in the country's dry areas, including Kano, Kwara, Sokoto, Zamfara and Kaduna. Nuts are used in Nigeria to produce cooking oil and form a source of protein for both humans and animals (Fletcher & Shi 2016). Nigeria accounts for 70% of total global peanut exports and continues to improve seed varieties and good agronomic practices, to obtain high yields that help them improve their nutrition as well as community incomes (Fletcher & Shi 2016).

In 2020, the United States was the fourth largest producer globally, with production at almost 3.7 million metric tons, of which about 25–30% was exported in that year. It is one of the world's leading peanut exporters, with average annual exports of between 200,000 and 250,000 metric tons. Argentina and China are other significant exporters (Fletcher & Shi 2016).

Of the lesser production countries, Argentina and Brazil together account for 66% of the peanut produced in Latin America and the Caribbean, while In Europe, peanut is grown only in Bulgaria and small parts of Greece, Spain and Yugoslavia.

Australian farmers' peanut production is just approximately 40,000 tonnes (t) per year, or about 0.2% of global peanut production (GRDC Report November 2017). Queensland is where more than 90% of the peanuts in Australia are farmed. The industry is based on the large-seeded Virginia varieties and medium to large-seeded Runner varieties. Australia is one of the few nations that produce peanuts, and there are no restrictions on peanut imports. The price of Australian peanuts is greatly affected by global pricing. Recently, Australia has been importing 5,000–8,000 t of peanuts annually, mainly from Argentina and Nicaragua. To meet growing domestic demand and niche export opportunities, Australia's peanut industry, worth over AUD $200 million a year, is currently expanding and moving into new areas with irrigation and appropriate soils for reliable and consistent production.

2.7.2 General characteristics

Because of its few antinutritional factors, high protein and oil content with low fibre, peanut meal is an excellent feed ingredient. The amount of trans fat in peanut butter with 2% stabiliser is 156 times less than that needed to reach the 0 g trans-fat cut-off on food labels (Sanders 2001). Peanut products are more beneficial to heart health than low fat diets. The high monounsaturated fat content of peanuts lowers total body cholesterol by 11% and bad low-density lipoprotein (LDL) cholesterol by 14%, while good high-density lipoprotein (HDL) cholesterol is maintained with reduction in triglycerides (Pelkman et al. 2004). The benefits of peanut diets on cholesterol are comparable to those from the olive oil diet (Matilsky et al. 2009).

Peanuts have more protein than any other nut with levels comparable to or better than a serving of beans. After the oil is extracted, the protein content in the residual cake can reach 50% (Zhao et al. 2011). Peanuts contain all 20 amino acids in variable proportions and is the biggest source of arginine (Yu et al. 2006). Peanut proteins have good emulsifying activity, emulsifying stability, foaming capacity, excellent water retention and high solubility (Kane et al. 2010).

The components in peanuts are highly digestible and comparable with that of animal protein. The limiting amino acid in peanuts varies between lysine, methionine and threonine, according to the study by Venkatachalam and Sathe (2006). Protein quality is defined in line with the amino acid pattern and digestibility (%) of proteins.

The structure of different fatty acids determines fat digestibility variation. Peanuts contain over 50% monounsaturated fats, which are easily digested due to a single unsaturated hydrogen bond, which is easily broken. Being legumes, they contain phytic acid, which is associated with decreases in the bioavailability of phosphorous and other nutrients due to their binding properties, but the amount in peanuts is lower than that in other legumes such as soybean (Schlemmer 2009).

Peanuts are also a good source of fibre, according to the Food and Drug Administration Organisation. Sucrose and starch are the major constituents, while reducing sugars form the minor proportion of the peanut carbohydrates. This may contribute to the peanut's low glycaemic index (GI) and glycaemic load (GL) (Johnston et al. 2007).

Peanuts have been recognised as a great source of niacin, which is important for digestive system functioning, the skin, and the nerves; also, it helps in food to energy conversion. It is thought to protect against Alzheimer's disease and cognitive decline (Morris 2004). Peanut is an excellent source of vitamin E, which can assist in coronary heart disease prevention (Gao et al. 2006). Peanut also contains good amounts of folate, which is especially important in infancy and pregnancy, for the production and maintenance of cells.

2.7.3 Nutritive value for animal feed

Peanut meal is fed to cattle, buffalo, sheep, goats, poultry and pigs. Peanut meal is high in vegetable protein and is produced through a solvent extraction process with carefully controlled processing conditions. It is a highly palatable source of nutrition in animal feed. Peanut meal is an excellent source of protein, minerals and energy.

The available research indicates that peanut meal can replace soybean meal or other oilseed meals in most diets; however, peanut meal is susceptible to contamination with aflatoxin and should be tested before feeding (Vadalà et al., 2023). The protein content is usually about 50–55% of the DM, and ranges from 42% to more than 60%, depending on the amount of oil, skins and hulls. Peanut cake processed on-farm, including shells and more residual oil, can have a protein content of less than 40% of DM.

Peanut meal is deficient in lysine, and low in methionine and tryptophan. Peanut meal is generally more fibrous than soybean meal, with a crude fibre of 10% of DM for a meal containing skin and shell fragments. The residual oil content is highly variable, from less than 3% for solvent-extracted meals to 10% or more for mechanically extracted cakes. Oleic acid (C18:1; 50%), linoleic acid (C18:2; 30%) and palmitic acid (C16:0) account for more than 90% of the fatty acids of peanut oil (Davis et al. 2016). However, their respective proportions vary ranging from 35 to 82% and those for linoleic acid from 3 to 43%, (Davis & Dean 2016).

Table 46 Chemical composition of peanut meal

Main analysis	Unit	Avg	SD	Min	Max	Nb
Dry matter	% as fed	90.4	1.5	86.5	93.4	210
Crude protein	% DM	53.3	5.0	42.5	63.8	221
Crude fibre	% DM	7.1	1.3	4.5	9.9	220
NDF	% DM	16.7	7.2	9.8	37.5	19
ADF	% DM	10.0	1.7	5.9	12.2	18
Lignin	% DM	2.8	1.1	0.5	4.5	25
Ether extract	% DM	2.1	1.2	0.3	4.9	146
Ether extract, HCl hydrolysis	% DM	2.4	0.8	1.0	4.6	14
Ash	% DM	6.9	1.3	4.6	9.6	144
Total sugars	% DM	12.4	2.3	8.1	14.4	8
Gross energy	MJ/kg DM	20.0	0.5	19.2	20.3	6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org).

Peanuts contain various bioactive plant compounds and antioxidants. Most of the antioxidants in peanuts, including p-coumaric acid, resveratrol, and isoflavones, are concentrated in the skin.

Table 47. Minerals and amino acids composition of peanut meal

Minerals	Unit	Avg	SD	Min	Max	Nb
Calcium	g/kg DM	1.8	0.9	0.1	3.9	69
Phosphorus	g/kg DM	6.9	0.6	5.7	8.1	70
Potassium	g/kg DM	13.9	1.6	12.0	17.6	18
Sodium	g/kg DM	0.1				1
Magnesium	g/kg DM	3.9	0.3	3.3	4.3	15
Manganese	mg/kg DM	48	23	29	103	9
Zinc	mg/kg DM	62	5	54	69	8
Copper	mg/kg DM	18	2	14	21	9
Amino acids	**Unit**	**Avg**	**SD**	**Min**	**Max**	**Nb**
Arginine	% protein	11.2				1
Histidine	% protein	2.4				1
Isoleucine	% protein	3.2				1
Leucine	% protein	5.9				1
Lysine	% protein	3.5		3.5	3.5	2
Methionine	% protein	1.0				1
Phenylalanine	% protein	4.8				1
Threonine	% protein	2.5				1
Tryptophan	% protein	0.7				1
Valine	% protein	3.8				1

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
(Source: Feedipedia.org).

The mineral content of 100 g of peanut can provide the recommended daily allowance levels of 127% copper, 84% manganese, 57% iron, 54% phosphorus, 42% magnesium, and its intake is associated with reduced inflammation in the body (King et al. 2005) and a decreased risk of metabolic syndrome and type 2 diabetes (Larsson & Wolk 2007).

The vitamin content of 100 g peanuts can provide up to 75% of the recommended daily allowance of Niacin, 60% of folate, 53% of thiamine, 10% of Riboflavin, 35% of pantothenic acid, 27% Recommended daily amount (RDA) of pyridoxine, and 55.5% RDA of vitamin E.

Peanut meal is highly digestible in ruminants, with digestibility values above 80% (Eugène et al. 2004). Its energy value is about 89–92% that of soybean meal. Peanut meal protein is very degradable (N effective degradability is between 72 and 90%).

2.7.4 Antinutritional factors – nutritional limitations

Peanut meal is susceptible to contamination by aflatoxin, a toxic compound produced by the fungi *Aspergillus flavus* and *Aspergillus parasiticus*. In poultry and livestock, aflatoxins can cause feed refusal, loss of weight, reduced egg production, and contamination of milk (Torres et al. 2014). The source of aflatoxin contaminations is in the field, after peanuts are lifted but before harvest, during transport, and during storage. Aflatoxin production can be increased by either increased temperatures or drought stress, but high temperatures seem to have the bigger influence. The key requirements for postharvest management of aflatoxins are control of seed moisture and insects. Storage at lower levels of moisture, or at 10°C, will prevent aflatoxin production (Payne 2016). There are considerable species differences in susceptibility to the above toxins. Young animals are more susceptible than adult animals of the same species. There are several reports of death in calves below six months of age when fed on contaminated peanut meal. Older cattle are more resistant, but cases of death in cattle, loss of appetite and reduced milk yield in cows have been reported. A metabolite of aflatoxin known as aflatoxin M has been found present in the milk of cows fed on toxic meals. Aflatoxins are relatively heat-stable (Hussain et al. 2015).

New regulatory measures in importer countries, such as EU member states, have led to significant trade restrictions on peanut and peanut products, particularly those produced in sub-Saharan Africa (ICRISAT 2016). As of 2016, the maximum authorised content in the EU for aflatoxin B1 in feed materials is 0.02 mg/kg (20 ppb or µg/kg) (European Commission 2003).

Like other legume seeds, peanuts contain some other antinutritional factors including tannins, which are present in the seed coat, lectins and trypsin inhibitors. Little attention has been paid to these, perhaps because the antinutritional factors in peanut seem less deleterious than those of other legumes. Heat, and moist rather than dry, can render peanut lectins inactive, so it is possible that the regular conditions under which peanut seed and meal are processed are sufficient to ensure peanut product safety for animal feeding. However, tannins may contribute to the low protein digestibility of peanut meal (Chen et al. 2013). Feeding more than 25% peanut meal in the diet leads to laxative action, otherwise it forms an excellent and acceptable protein source.

Peanuts contain antinutrients, substances that impair absorption of nutrients and reduce nutritional value. Of the antinutrients in peanuts, phytic acid is particularly of note. Phytic acid (phytate) is found in all edible seeds, nuts, grains, and legumes. In peanuts, it ranges from 0.2–4.5%. Phytic acid reduces the availability of iron and zinc in peanuts, slightly lowering their nutritional value. This is usually not a concern in well-balanced diets and among those who eat meat regularly. Nonetheless, it may be a problem in developing countries where the main food sources are grains or legumes (Embaby 2010). Peanut oil contains considerable amounts of phytosterols, which impair the absorption of cholesterol

from the digestive tract (De Camargo et al. 2012). The pathogen *Salmonella* can contaminate peanut meal, which can cause problems when fed to animals, especially the young or those under stress.

Peanuts are one of the most common food allergens. Allergy to peanuts is estimated to affect approximately 1% of Americans. They are potentially life-threatening and are sometimes considered the most severe of all allergens.

2.7.5 Peanut meal in the laying hen diet

Peanut meal is a valuable source of nutrients for poultry; however, it is deficient in some essential amino acids such as threonine and lysine, but it is an excellent source of arginine (Yue et al. 2012). The nutrient profile varies depending on the oil extraction method and its fibre and fat content (Batal et al. 2005), however, there are some restrictions for its use in poultry feed including the amino acid profile. This issue can be corrected in feed formulation if peanut meal is mixed with other protein sources or supplemented with crystalline amino acids. The next limitation relates to potential aflatoxin contamination, which in some regions is a greater problem than others (Kana et al. 2013). Processing to detoxify the aflatoxin may reduce amino acid content or availability (Piva et al. 1995; Zhang & Parsons 1996).

Table 48. Peanut meal metabolisable energy value for poultry

Poultry nutritive values	Unit	Avg	SD	Max	Min
AMEn cockerel	MJ/kg DM	11.6	0.2	12.5	11.6
AMEn broiler	MJ/kg DM	11.6	-	-	-

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
AMEn: apparent metabolisable energy.
(Source: Feedipedia.org).

Early studies by Pesti et al. (2003) replaced 100% of the soybean meal with peanut meal in a corn-soybean meal-based diet, at 3 protein levels (6, 18.5, and 21%). The experimental diets were tested in 22-to-34-wk-old commercial Leghorns. The results showed that the feed consumption, egg production and feed efficiency of hens fed peanut meal-based diet (93.8 g/hen per d, 92.2 eggs per 100 hens/d, and 1.22 kg/dozen eggs) were very similar to that of soybean meal-fed hens (93.7 g/hen per d, 92.2 eggs per 100 hens/d, and 1.22 kg/dozen). Dietary protein level did not affect feed intake, egg production rate, or feed efficiency. However, it enhanced body weight gain and increased egg weight (1.2 g vs. 2.5 g per egg). Peanut meal-fed hens laid smaller eggs during the first 6 weeks of the study, although the egg weight was restored in the second half of the study and there were no differences. Feeding peanut meal improved the egg Haugh unit especially after 2 weeks of storage at refrigeration temperature. This study concluded that peanut meal is an excellent ingredient for laying hens that can fully replace soybean meal in the diet.

Few studies have investigated the use of high-oleic peanuts (non-roasted, intact; 22–30% protein and 44–56% total fat) with 80% oleic fatty acid and 2% linoleic fatty acid profile in the laying hen diet (Toomer et al. 2019; Redhead et al. 2021).

In a study on 40-week-old laying hens, high-oleic peanut meal was compared to a conventional soybean meal-corn control diet. Egg production performance and egg quality were similar for hens on

the control diet and the high-oleic peanut meal-fed hens, although the high-oleic peanut meal-based diet reduced the egg weight compared with the control. The egg yolk colour and β-carotene levels improved in hens fed with high-oleic peanut meal. The concentration of oleic fatty acid was greater in hens fed peanut meal, whereas hens fed soybean meal had a greater concentration of palmitic and stearic saturated fatty acids, and trans-fat content. This study also concluded that peanut meal is an abundant commodity, especially in the regions of agricultural markets for peanuts, which can be used in egg farming to provide a potential health benefit to the consumer through improved egg nutrition (Toomer et al. 2019).

Redhead et al. (2021) determined the effects of high-oleic peanuts – as an alternative ingredient – on egg production, ileal digestibility, and gut histology in laying hens' diet. A conventional corn-soybean meal-based diet was compared to a corn-high-oleic peanut-based diet or a corn-soybean meal- oleic acid-based diet in 57-wk-old laying hens. The study duration was 8 weeks. Hens on the corn-soybean meal-oleic acid diet produced a greater number of eggs compared to the two other diets. However, the yolk colour score was higher in hens fed the high-oleic peanut-based diet. There were no differences in laying hen performance, eggshell colour, eggshell strength, eggshell elasticity and egg albumen height, or egg Haugh unit, ileal fat digestibility, or villi surface among treatment groups. The study concluded that intact high-oleic peanuts can be used as an alternative ingredient in laying hens' diet.

Table 49 Standardised ileal digestibility of amino acids of peanut meal in laying hens

Indispensable amino acid	**Peanut meal**
Arginine	91.6
Histidine	89.0
Isoleucine	86.3
Leucine	87.7
Lysine	83.7
Methionine	88.1
Met+Cys	-
Phenylalanine	90.1
Threonine	84.7
Tryptophan	86.4
Valine	87.3
Dispensable amino acid	
Alanine	85.8
Aspartic acid	85.2
Cysteine	79.5
Glutamic acid	88.9
Glycine	69.5
Proline	87.3
Serin	84.2
Tyrosine	90.7

(Source: Li et al. 2023)

Peanut meal is reported to have little or no effects on feed consumption, egg production rate, egg weight, feed efficiency, and body weight (Lu et al. 2013; Pesti et al. 2003), however, some studies have reported a negative impact on the performance of hens when compared to soybean meal (Naulia & Singh 2002 a). The negative effects are observed when peanut meal is used as the main protein source, but not when combining it with other protein ingredients (Naulia & Singh 2002a; Sayda et al. 2011).

Based on the available studies, it seems that peanut meal can be an alternative ingredient to soybean meal in the laying hen diet when combined with threonine- and lysine-rich ingredients. The availability

of purified synthetic threonine at low cost raises the possibility of economically using peanut meal and threonine combinations in poultry diets. Further research is required to investigate the full replacement of soybean meal with peanut meal plus crystalline essential amino acids. including threonine and lysine.

2.7.6 Peanut meal in the pig diet

Peanut meal is a good source of energy and protein in pigs, although it has restrictions, similar to those for laying hens, for use in pigs due to high fibre content and essential amino acid deficiency. The lignified husks are not removed before oil extraction and fibre concentration may reach 20%, which limits its inclusion for pigs. However, if the husks are removed before oil extraction, the fibre concentration won't be a limitation anymore. Amino acid deficiencies can also be corrected by appropriate feed formulation and supplementing crystalline amino acids. The unsaturated peanut oil can cause soft fat deposition in bacon pigs (Yue et al. 2012), and therefore intact peanuts, or high-residue peanut meal-based diets are not recommended for pigs. Dehulled solvent extracted peanut meal may have a similar energy value as soybean meal for pigs.

Table 50 Peanut meal nutritive value for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max
Energy digestibility, growing pig	%	79.0	-	-	-
DE growing pig	MJ/kg DM	15.8	-	-	-
MEn growing pig	MJ/kg DM	14.5	-	-	-
NE growing pig	MJ/kg DM	9.0	-	-	-
Nitrogen digestibility, growing pig	%	81.0	-	-	-

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
Nb: number of values (samples) used.
DE: digestible energy.
MEn: metabolisable energy.
NE: net energy.
(Source: Feedipedia.org).

Old studies from the 1960s and 1970s reported that the inclusion of peanut meal in pigs' diet has detrimental effects on feed intake, growth performance, and feed efficiency (Combs et al. 1963; Orok et al. 1975). Digestion coefficients, measured at 7 to 8 weeks of age, were also lower (Combs et al. 1963). Replacing 50 or 100% of soybean meal with peanut meal impaired the growth rate in 5-week-old piglets. Lysine supplementation to the peanut meal-based diet did not alleviate the growth depression of young pigs (Orok et al. 1975). Later studies (2001) similarly reported that pigs fed with peanut meal had a reduced growth performance compared to soybean meal, even when lysine was supplemented (Chiba 2001). It is fair to mention that it was done several decades ago, and the study may show different results by today's standards.

Some mineral deficiencies have also been reported, which were linked to peanut meal-based diets where the addition of salt and calcium carbonate improved the bone strength, and no signs of weakness were observed.

Two trials were conducted by Li, Xu et al. (2000) to estimate the apparent ileal digestibility of amino acids of peanut meal using a regression technique and then applying the digestibility coefficients obtained in the first trial in a growth trial using grow-finish pigs. Pigs were fed with 0, 5, 10, 15, and 20% peanut meal replacing soybean meal in a corn-based diet. The authors reported that the digestibility of the amino acids decreased by increasing the peanut meal inclusion in the feed. Growth

performance and feed efficiency also decreased linearly by increasing peanut mela inclusion in the feed, however, feed intake was not affected. The authors concluded that the peanut meal can be included at levels up to 15% in grow-finisher pigs' diet.

Table 51 Standardised ileal digestibility of amino acids in pigs fed peanut meal

Indispensable amino acid	Peanut meal
Arginine	93.6
Histidine	81.8
Isoleucine	81.8
Leucine	84.7
Lysine	75.1
Methionine	88.3
Met+Cys	-
Phenylalanine	76.9
Threonine	74.7
Tryptophan	78.6
Valine	83.5
Dispensable amino acid	
Alanine	78.6
Aspartic acid	82.2
Cysteine	87.1
Glutamic acid	86.3
Glycine	68.8
Proline	79.5
Serin	80.4
Tyrosine	82.8

(Source: Li et el. 2014)

Peanut butter is considered a traditional staple food of American diets. The global peanut production has increased by an average of 20% in the last 10 years and so did its consumption. Therefore, the production of peanut meal will follow the growth in peanut production.

Further research is required to investigate the effects of peanut meal inclusion in pigs' diet using proper feed formulation practices, including standardised ileal digestible amino acids, following the ideal protein profile for different stages of growth, and net energy content of peanut meal. It has been discussed that dehulled solvent-extracted peanut meal can be used in pigs at an inclusion rate of up to 15% with no detrimental effects on growth performance, however, the maximum inclusion levels should be updated in new research projects. Studies on amino acid digestibility coefficients show the potential for peanut meal to be an alternative protein-rich ingredient in pigs' diet.

2.7.7 Carbon footprint and sustainability of groundnut production

A study calculated the carbon (C) and nitrogen (N) emissions of the groundnut sector in China by jointly using the carbon footprint (CF) and nitrogen footprint (NF). The results revealed that the mean area-based CF (CFa) and NF (NFa) of peanut farming in China were 1912.58 kg CO_2-eq ha−1 and 41.19 kg N-eq ha−1, correspondingly. The mean yield-based CF (CFy) and NF (NFy) of peanut oil reached 1.38 kg CO_2-eq kg−1 and 28.23 g N-eq kg−1, separately (He et al. 2021).

Figure 14 shows the carbon footprint of the peanut farming subsystem in China during 2008–2017. Another 'cradle-to-gate' study by Bongiovanni et al. (2016) in Argentina reported that crop production and mill processing cause emissions of 87 kg CO_2 eq (37%) and 91 kg CO_2 eq (38%), correspondingly,

while transportation contributes with 59 kg CO_2-eq (25%). The paper also reflects the use of coproducts, such as hull and skin. Although industrial use also produces some emissions, considerable environmental advantages resulted from the incineration of peanut hulls for electricity cogeneration and heat. This lowered CO_2 eq emissions by 196 kg CO_2 eq (-83%), making a closing value of 41 kg CO_2 eq (Bongiovanni et al. 2016).

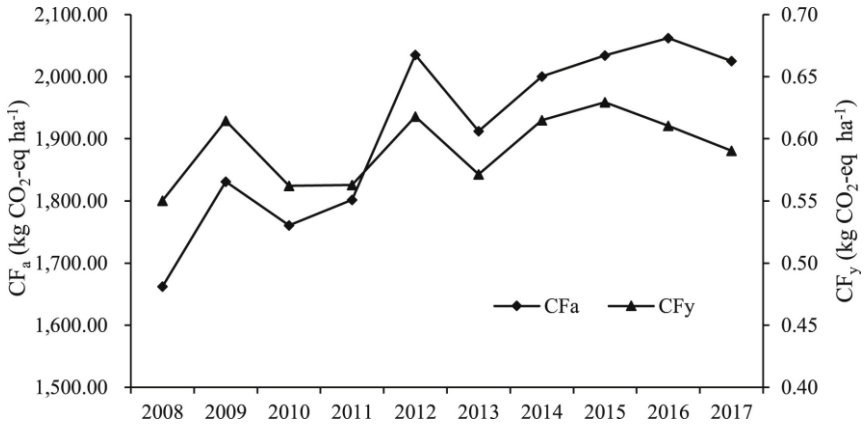


Figure 14 Carbon footprint of peanut cropping in China during 2008–2017

2.8 Palm kernel meal

Palm kernel meal or cake, a by-product of oil extraction from palm (*Elaeis guineensis* Jacq.), is a significant, un-conventional ingredient for animal feed. The palm tree is cultivated firstly for its oil, which has abundancy of high, saturated vegetable fat extracted from the fruit flesh, and secondly for the palm kernel oil, extracted from the fruit kernel (Cui et al. 2020). Oil palm is by far the major oil crop, supplying 40% of global vegetable oil, and over three billion people in the world, especially in Asia, regularly eat palm oils as essential dietary components. Palm oils also have a variety of significant non-food applications, such as in cleaning and sanitising goods.

The fruit of the oil palm consists of an outer mesocarp and inner, hard-shelled nut containing the palm kernel. Palm oil is extracted from the mesocarp, while palm kernel oil comes from the kernel of the nut. Prior to oil extraction, the outer shell should be separated after cracking. The methods usually used for oil extraction are by expeller machine or solvent extraction, generating expeller (cold-pressed) or solvent-extracted palm kernel or palm kernel meal.

Palm kernel meal obtained from the mechanical expeller procedure contains 5–12% oil, while palm kernel meal obtained from the solvent extraction technique contains 0.5–3% oil (Okeudo et al. 2005). Several by-products (fronds, trunks, press fibre, empty fruit bunches, kernel cake, kernel shells, and mill effluent) are generated from oil extraction and are used for livestock feeding (Ebrahimi et al. 2013).

Palm kernel meal is a dark brown protein meal with relatively high oil and high fibre levels, and is a good source of protein and energy. The high fibre levels can be advantageous when fed as part of a balanced diet for cattle, although of restricted use for monogastric animals.

Because of its low cost in the regions where it is produced, such as Asia, the Pacific countries, South America and Africa, palm kernel meal is economically advantageous to be used as an ingredient in livestock production. Palm kernel meal is aflatoxin free, palatable and has considerable potential as a carbohydrate and protein source (Wilkinson & Young 2020).

2.8.1 Palm kernel and meal production globally and in Australia

Palm is cultivated in tropical countries such as Indonesia, Malaysia and Nigeria. Palm oil is extensively produced in Central and South America as well as in East Asia (Sharmila et al. 2014). The world production of oil palm is 81 million metric tonnes of which 72.3 tonnes was mesocarp oil or 'palm oil' while 8.8 tonnes was palm kernel oil. Indonesia and Malaysia together account for almost 85% of the total world's production.

Table 52 Oil palm production 2020

Rank	Country	Palm oil production	
		tonnes	%
1	Indonesia	42.5	58.8
2	Malaysia	18.5	25.6
3	Thailand	2.8	3.9
4	Colombia	1.5	2.1
5	Nigeria	1.0	1.4
	Others	5.9	8.2
	Total	72.3	

(Source: Oil palm in the 2020s and beyond: challenges and solutions)

The world production of palm kernel meal was about 3.63 million tonnes in 1993, of which 3.57 million tonnes was reportedly used as animal feedstuff (Commodities Board for Animal Feedstuffs, 1993). Later, in 2017, palm kernel meal world production exceeded 9.5 million metric tons (Wilkinson & Young 2020). Global production of palm kernel meal has dramatically increased over the recent two decades (15%). In 2019, about 7.6 tonnes palm kernel meal was exported, almost exclusively (98%) from Indonesia and Malaysia (IndexMundi 2021). In order of importance, the major importing countries (75% of total 2019 imports) are the EU, New Zealand and Japan, where the meal is used in a variety of feed formulations, especially for ruminants such as cattle.

Indonesia and Malaysia are the largest producers and exporters of palm oil and palm oil by-products, together producing just over four-fifths of their global total. Nigeria, Colombia and Thailand produce less than 10% of the world crop (Baharuddin 2010). The export volume of palm oil worldwide in 2021/22 showed Indonesia as the leading palm oil exporter, with an export volume of about 28 million metric tons. Malaysia came in second place, with around 16.2 million metric tons (Wilkinson & Young 2020).

The negative environmental effects of oil palm farming, particularly with regard to deforestation and haze creation, have damaged the industry's reputation (Paterson & Lima 2018). Millions of hectares of South-East Asian tropical rainforest, which has the highest biodiversity of any terrestrial environment, have been transformed into oil palm plantations during the past few decades. Several important species, like the orang-utan, have lost habitat as a result of this rapid deforestation (Wakker 2005; Wakker 2000).

2.8.2 General characteristics

The chemical composition of palm kernel meal varies depending on the type of fruits (such as palm sources), efficiency of oil extraction from the kernel, the residual endocarp, and the oil extraction method (solvent or mechanical extraction) (Sundu et al. 2006).

Palm kernel meal is often obtained from mechanical extraction (expeller meal) and its oil content is quite high (6–15% DM). The less common solvent-extracted palm kernel meal contains less oil (about 3% DM) and slightly more protein (19% vs.17% on average) than the expeller meal, but the cell wall constituents and minerals are only slightly affected by the extraction process (Sundu et al. 2006).

Digestible amino acids are essential for determining acceptable sources of protein and dietary supplements. Although low in nutritional value because of its poor amino acid content, especially essential amino acids like lysine and methionine (Lawal et al. 2010), palm kernel meal can be utilised as a source of protein as well as energy in animal feed (Sharmila et al. 2014). The CP values of palm kernel meal range between 14 and 21%, which variation can be attributed to the different processing methods (Pasaribu 2018).

Palm kernel meal is the least nutritionally valuable of the major oil meals in animal nutrition due to its low protein content and its large quantities of cell wall constituents (crude fibre, NDF, ADF and lignin) (Onuh et al. 2010). Although the CP values are sufficient for older birds not requiring high protein diets. The high fibre content of palm kernel meal limits its utilisation in pigs and poultry, especially young animals (Sharmila et al. 2014). Nevertheless, palm kernel meal can be a promising feedstuff for pigs and poultry because of its moderate CP (16.43%) content and energy when proper feed formulation is practised, and the mixed diet is balanced for total digestible amino acids and net energy content (Alshelmani et al. 2016).

Various treatments of agro-industrial and agriculture by-products could improve the nutritive value of palm kernel meal such as solid-state fermentation with cellulolytic and hemicellulolytic bacterial cultures in order to increase the digestibility and the protein value and the availability of nutrients. Protein concentrates with a protein yield of 55–60% can be obtained by extraction of ground palm kernel meal with alkali, followed by precipitation with hydrochloric acid (HCl; pH 3.5). Protein extraction can be performed with alkaline (or saline) solution and drying at 50°C (Arifin et al. 2009).

An alternative method used for palm kernel meal protein isolation is extraction with sodium hexametaphosphate and further isoelectric precipitation of soluble protein at pH 3.7 (Zarei et al. 2016). Palm kernel meal or cake protein hydrolysates that were obtained using various proteases were found to possess antioxidant activity. Among several proteolytic preparations, protein hydrolysed by papain resulted in the production of the hydrolysate with the highest antioxidant activity (Zarei et al. 2012).

Globulin, glutelin-1 and glutelin-2 account for 40, 24, and 33% of palm kernel proteins, respectively. It was found that enzymatic hydrolysates of the globulin showed anticancer, antihypertensive and antibacterial activities; in addition, several peptides obtained from the glutelin-2 could effectively lower the systolic blood pressure of spontaneously hypertensive rats (Zheng et al. 2015).

2.8.3 Nutritive value for animal feed

Because of its low cost and high availability, protein content and bioactive antioxidant peptides, palm kernel meal partially substitutes for feed ingredients such as soybean and maize in livestock feeds such as poultry, swine, and freshwater fish. On average, the chemical composition of palm kernel meal includes 90% (89–95%) dry matter; 18.7% crude protein; 20% crude fibre (6–24.9%); acid detergent fibre (ADF) 43.7%; neutral detergent fibre (NDF) 66.7%; and lignin 21.1%.

Table 53 Chemical composition of palm kernel meal – solvent extracted

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	90.9	1.6	87.8	93.2
Crude protein	% DM	18.7	1.1	16.3	20.5
Crude fibre	% DM	20.2	2.5	15.6	24.9
NDF	% DM	73.2	4.3	67.6	81.7
ADF	% DM	45.0	5.3	40.2	55.8
Lignin	% DM	12.8	2.1	10.5	17.5
Ether extract	% DM	2.8	1.2	1.1	5.1
Ether extract, HCl hydrolysis	% DM	4.2	1.1	2.2	5.6
Ash	% DM	4.6	0.4	3.9	5.5
Total sugars	% DM	3.0			
Gross energy	MJ/kg DM	18.8	1.8	15.4	21.5

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org).

The crude protein content of palm kernel meal is lower than that of copra meal and the cell-wall content is higher, especially lignin (18% in palm kernel meal vs. 13% in copra meal). The solvent extracted palm kernel contains 0.5–3% crude fat, and expeller pressed has 4.5–19.5% crude fat. The ash content is about 3.06 and 5.6% (Akinyeye et al. 2011). More than 75% of palm kernel meal consists

of carbohydrates, made up of 35.2% mannose, 2.6% xylose, 1.1% arabinose, 1.9% galactose, 15.1% lignin, and 5.0% ash (Cerveró et al. 2010). β–mannan is the main component of palm kernel by-product NSPs, which is regarded as a prebiotic and known to enhance bird immune systems and reduce pathogenic bacteria in the small intestine (Sundu et al. 2006). Potassium is the major mineral in palm kernel meal (0.64%) followed by 0.6% phosphorous and 0.3% calcium. The ratios of calcium to phosphorus and sodium to potassium are low in palm kernel meal-based diets and the minerals need supplementation to meet most animals' nutrient requirements (Fadil et al. 2014). Palm kernel meal is a good source of Mn, Zn, Cu, and iron. For these reasons, the nutritive value of palm kernel meal is notably inferior to that soybean meal.

Many studies suggest that animals perform satisfactorily when fed diets containing different levels of palm kernel meal. It is used as a source of protein, energy, vitamins and minerals in dairy cattle (Abd El Tawab et al. 2018), but its relatively low levels of protein and essential amino acids, coupled with high fibre, make palm kernel meal unattractive for use in monogastric livestock diets. In many situations, the limited availability of amino acids for a particular animal may be related to association of protein with complex polysaccharides and antinutrients or inhibitors. The use of enzymes other than protease may enhance protein availability by degrading the structural polysaccharides that associate with and protect protein from degradation by available protease (Du Plessis & van Rensburg 2014).

Table 54 Mineral and amino acid composition of palm kernel meal – solvent extracted

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	2.7	0.4	2.0	3.1
Phosphorus	g/kg DM	6.6	2.2	1.3	8.5
Potassium	g/kg DM	7.4	0.6	6.9	8.1
Magnesium	g/kg DM	3.4	0.4	3.1	3.9
Manganese	mg/kg DM	249			
Zinc	mg/kg DM	52			
Copper	mg/kg DM	31			
Iron	mg/kg DM	177			
Amino acids	**Unit**	**Avg**	**SD**	**Min**	**Max**
Alanine	% protein	4.2		4.0	4.4
Arginine	% protein	12.6		12.3	12.9
Aspartic acid	% protein	8.9		8.5	9.2
Cystine	% protein	1.4		1.2	1.6
Glutamic acid	% protein	18.8		17.9	19.8
Glycine	% protein	4.7		4.5	4.9
Histidine	% protein	2.2		2.0	2.4
Isoleucine	% protein	3.7		3.4	4.1
Leucine	% protein	6.5		6.4	6.6
Lysine	% protein	3.2		3.1	3.2
Methionine	% protein	1.7		1.5	2.0
Phenylalanine	% protein	4.2		4.1	4.3
Proline	% protein	3.0		3.0	3.0
Serine	% protein	4.4			
Threonine	% protein	3.3		3.2	3.5
Valine	% protein	5.4		4.9	5.9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org).

The total amino acid content of palm kernel meal has been reported to be 12g g/kg (vs. 457 g/kg in soybean meal). Among indispensable amino acids, arginine is the major one, whereas histidine, methionine and lysine have the lowest indispensable amino acid contents of palm kernel meal. Glutamic acid is the major dispensable amino acid followed by aspartic acid. The standardised amino acid digestibility of palm kernel meal seems to be moderate, with an average coefficient of 0.75–0.81.

2.8.4 Antinutritional factors – nutritional limitations

Palm kernel meal contains non-starch polysaccharides as the major antinutritional factor, as well as high amounts of copper that can cause toxicity in sheep (Azizi et al. 2021).

Although palm kernel meal can be effectively used by ruminants, there are limits to using it in monogastric animal diets because of its high crude fibre, coarse texture, and gritty appearance. Traditionally, palm kernel meal or cake has not been used widely in pig and poultry diets mainly because of its unpalatability and high fibre content, which reduces its digestibility for these animals (Abdeltawab & Khattab 2018).

The high content of non-starch polysaccharides in palm kernel meal is not only undigestible for monogastric animals but also increases the viscosity of the digesta and reduces the availability of other nutrients by encapsulating them. Exogenous NSP-degrading enzymes can be employed to reduce this factor (Olukomaiya et al. 2019). Furthermore, palm kernel meal has other antinutritional factors such as 0.40% tannic acid, 23.49 mg/g phytic acid, and 5.13 mg/g oxalate, which adversely affect its nutritional quality in monogastric animals (Azizi et al. 2021).

Palm kernel meal is slightly unpalatable. Mixing this feed with palatable feedstuffs (e.g. molasses) will help improve intakes. On the other hand, the protein source of palm kernel meal can be associated with antinutrient components, such as lectins and trypsin inhibitors that interfere with protein degradation and/or amino acid metabolism and absorption from the intestine (Atasie & Akinhanmi 2009). In such instances, it is recommended to employ appropriate proteases to enhance the digestion of proteins and utilisation of dietary amino acids. In juvenile animals with a rapid growth rate, insufficiency in production of protease may interfere with the ability of the animal to metabolise complex proteins leading to nutritional imbalance (Ao et al. 2011). For such animals, the use of appropriate exogenous proteases may enhance digestion of proteins.

2.8.5 Palm kernel meal in the laying hen diet

The use of palm kernel meal in poultry depends on the type, age and sex of the chickens, as well as on the sources and variations of the palm kernel oil and shell content (Alimon 2004; Sharmila et al. 2014). Azizi et al. (2021) suggested that palm kernel meal in poultry diets should be limited to 20%. The same finding obtained by Anaeto et al. (2009) showed that birds could utilise a palm kernel meal-based diet of up to a 20% inclusion rate without adverse effects on their production performance. Laying hen egg production performance can generally be maintained with diets including up to 25% of palm kernel meal (Chong et al. 2008; Perez et al. 2000).

In an old study by Onwudike et al. (1988) even inclusion of high levels of palm kernel meal at 40% did not affect egg quality, but this inclusion rate had negative impact on production performance. Onwudike et al. (1986b), in a different study, reported that pullets can be fed up to 30% palm kernel meal during the starter and growing phases, with no consequences on development and subsequent laying performance.

Table 55 Metabolisable energy value of palm kernel meal for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max
AMEn broiler	MJ/kg DM	11.1		10.9	11.3

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org).

Chong et al. (2008) conducted a trial using 392 laying hens at 22-weeks of age, to investigate the effect of the inclusion of palm kernel meal at two levels of 12.5 and 25% on egg production performance, with or without enzyme supplementation. The metabolisable energy values were comparable for both inclusion rates. Enzyme supplementation, however, significantly improved the metabolisable energy content of palm kernel meal. There were no adverse effects of palm kernel meal inclusion at 12.5% and 25% on egg production or daily egg mass. However, palm kernel meal-based diets increased feed intake and significantly impaired feed conversion ratios compared to the control diet. Enzyme supplementation of diets including 12.5% palm kernel meal restored the feed efficiency of laying hens and there was no difference to the control. The eggshell quality of hens was not affected at either level of palm kernel meal inclusion, while egg yolk colour, however, was deteriorated by palm kernel inclusion at 25% and yolk was much paler than the control group.

Table 56 Standardised ileal digestibility of amino acids in young broilers fed palm kernel meal

Indispensable amino acid	Palm kernel meal
Arginine	65.6
Histidine	49.4
Isoleucine	56.1
Leucine	55.6
Lysine	43.8
Methionine	61.9
Met+Cys	-
Phenylalanine	60.4
Threonine	37.7
Tryptophan	-
Valine	56.3
Dispensable amino acid	
Alanine	55.0
Aspartic acid	27.0
Cysteine	29.0
Glutamic acid	48.7
Glycine	41.0
Proline	44.0
Serin	46.1
Tyrosine	42.8

(Source: Abdollahi et al. 2016)

Another study by Adrizel et al. (2011) evaluated the inclusion of palm kernel meal at 3 inclusion rates (0, 15, 30%) in native hens' diet with or without enzyme supplementation, using 180 hens at 48 weeks of age. Diets were isocaloric (2,758 kcal of ME/kg) and contained 17.51 to 18.39% crude protein, and were provided *ad libitum* together with water for the 6-week trial. The inclusion of palm kernel meal at increasing levels increased feed intake similar to the previous report, however, the egg production was not different. Egg weight and egg quality traits were not affected by the palm kernel meal inclusion either except for the yolk colour, which was pale in hens fed with palm kernel meal-based

diets. The authors reported that no enzyme could be measured due to the fact that palm kernel meal inclusion had no deleterious effects.

As palm kernel meal has higher fibre content than soybean meal, and increases feed consumption but not body weight gain, it can be used as a nutritional strategy to reduce hunger feeling in broiler breeders. Low energy and nutrient density diets formulated including palm kernel meal for broiler breeders, increased feed consumption and resulted in reduced hunger in broiler breeders, which is a welfare issue in broiler breeder farming (Enting et al. 2007).

Based on the available data, it seems that up to 20% palm kernel meal can be included in the layers' diet, however, a proper feed formulation and inclusion of NSP enzymes as well as yolk synthetic and commercial pigments would be recommended.

2.8.6 Palm kernel meal in the pig diet

Boateng et al. (2008) reviewed the potential for including palm kernel meal in diets for growing pigs and concluded that very low levels of dietary inclusion up to 20% of total diet fresh weight for growing pigs could sustain levels of production similar to conventional diets based on maize grain. The high fibre content of palm kernel meal creates limitations for pigs, especially as lysine availability can be reduced during processing due to the Maillard reaction. The energy digestibility of processed (pelleted) palm kernel meal seems to be very low, around 7.8 MJ/kg vs. 16 MJ/kg for corn. Supplementing exogenous enzymes such as NSP enzymes may improve the digestibility and energy values (Ao et al. 2011). Amino acid digestibility is also 20–30% lower than that of corn. Standardised ileal lysine digestibility is only 37% for the palm kernel meal vs. 80% for maize (Février et al. 2001; Sauvant et al. 2004).

Table 57 Nutritive value of palm kernel meal for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max
Energy digestibility, growing pig	%	42.0	3.3	42.0	67.3
DE growing pig	MJ/kg DM	8.4	2.0	8.4	14.1
MEn growing pig	MJ/kg DM	7.8	0.8	7.8	13.5
NE growing pig	MJ/kg DM	5.4			
Nitrogen digestibility, growing pig	%	63.1	6.4	48.0	63.1

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org).

Palatability of palm kernel meal can be an issue especially for young piglets, and it is recommended that palm kernel meal is introduced to the animals gradually, however, pork quality is very good when pigs are fed with palm kernel meal.

In an investigation by Kim et al. (2001), palm kernel meal replaced soybean meal partially (2 or 4% inclusion) (they also tested copra meal), using 150 crossbred pigs with an average body weight of 52 kg. Inclusion of 4% palm kernel meal tended reduce growth performance and resulted in lower amino acids digestibility coefficients. The detrimental effects of palm kernel meal inclusion were attributed to high fibre, especially non-starch polysaccharides content as well as low palatability.

In regions of its production and industrialised temperate countries, palm kernel meal is included in rations for growing-finishing pigs at 5 to 10% inclusion rates, used as a substitute for milling by-

products. It is suggested that supplementing an enzyme complex such as NSPs may counteract the negative effect of palm kernel meal on growth performance (Kim et al. 2001). For young growing piglets, energy intake and digestibility are the main factors for their optimum growth, and therefore inclusion of palm kernel meal might not be suitable. For lactating sows, energy values are also critical to maintain optimum milk production and piglet survival, therefore palm kernel meal is perhaps not recommended. In pregnant sows, however, high inclusion of palm kernel meal, e.g. 30–40% is possible without any detrimental effects on reproductive performance; as a matter of fact, the fibre content might induce beneficial effects. It has been reported that in some countries or regions such as South Africa and Asia, palm kernel meal is an economically valuable alternative ingredient that can be used at high inclusion rates of 30–40% in growing-finishing pigs replacing cereal grains without adverse effects on growth performance or meat quality (Jegede et al. 1994; Rhule 1996; Fatufe et al. 2007).

Table 58 Standardised ileal digestibility of amino acids of palm kernel meal in pigs

Indispensable amino acid	**Palm kernel meal**
Arginine	88.3
Histidine	80.8
Isoleucine	80.4
Leucine	79.7
Lysine	71.1
Methionine	82.2
Met+Cys	-
Phenylalanine	82.2
Threonine	73.9
Tryptophan	87.5
Valine	77.2
Dispensable amino acid	
Alanine	72.5
Aspartic acid	75.8
Cysteine	71.7
Glutamic acid	81.2
Glycine	65.1
Proline	54.9
Serin	80.0
Tyrosine	80.1

(Source: Sulabo et al. 2013)

Based on these findings, palm kernel meal can be included in growing-finishing pigs' diet and that of pregnant sows at up to 30% of the feed, replacing grains and/or partially soybean meal without negative impact on production performance and meat quality.

2.8.7 Carbon footprint and sustainability of palm oil/palm kernel meal production

There is common concern about the growing global production of palm oils, which doubled between 2000-01 and 2018-19, which is linked to mass deforestation, extensive habitat loss for rare species, soil degradation, and the damage of natural pastures in some territories of the world (Wilkinson & Young 2020). Several studies have reported climate change as being one of the most worrisome impacts of the oil palm supply chain (Choo et al. 2011). A significant amount of the GHG emissions connected to the whole life cycle of the oil palm supply chain was from the agriculture stage in the plantation, mainly due to the use of fertilisers and biogas (Table 59).

Table 59 GHG emissions connected to the whole life cycle of the oil palm supply chain

Output	GHG emissions for 1 t CPKO kg CO2-eq
Electricity from grid	74.33
Diesel	
Mill consumption	7.24
Transportation of diesel to mill	7.43
Transportation of palm kernel	6.53
Biogas	583.20
Biogas captured	87.48
Total with biogas	678.73
Total with biogas captured	183.01

The study showed that the production of 1 t of fresh unit bunches (FFB) produces 119 kg CO_2-eq. The production of 1 t of crude palm oil (CPO) emits 971 (without biogas) or 506 kg CO_2-eq (with biogas) (Choo et al. 2011). The study by Subramaniam and May (2012) reiterated that to obtain the best carbon footprint for the palm oil production, the kernel-crushing plant needs to be integrated with a palm oil mill that captures its biogas (Figure 15; Subramaniam & May 2012).

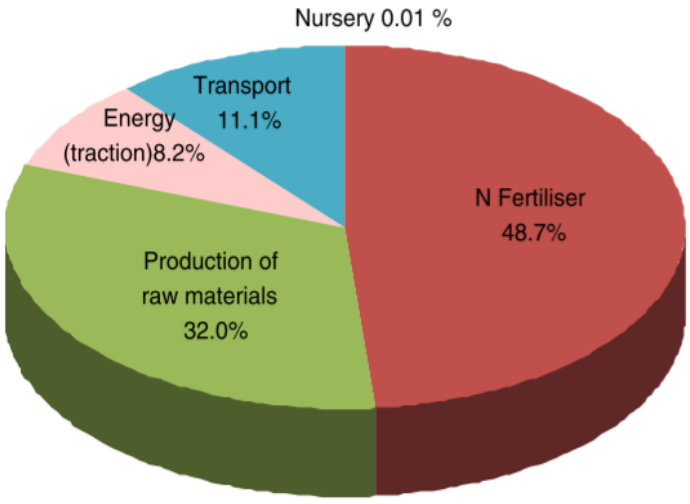


Figure 15 GHG emissions for 1 t crude palm kernel oil from kernel-crushing plants

3 Grain legumes or pulses

A legume refers to any plant from the Fabaceae family that includes leaves, stems, and pods. The Fabaceae or Leguminosae family is the third largest family of flowering plants, consisting of over 20,000 species (Ahmad et al. 2016). While grains refer to cereal grains and legumes refer to pulse crops, the Food and Agriculture Organization of the United Nations (FAO) defines the term 'pulses' as edible seeds of members of the Leguminosae family (FAO 1994). For example, a pea pod is a legume, but the pea inside the pod is the pulse. Pulses are grain legumes produced for human consumption and include 11 main types: beans, broad beans, peas, chickpeas, cowpeas, pigeon peas, lentils, bambara beans, vetches, lupins, and other 'minor' pulses (pulses other than those included in the previous categories, and with minor relevance at the international level). Nevertheless, beans, peas, lentils and chickpeas are amongst the most well-known and frequently consumed pulses worldwide and have been so for a long time (Marinangeli et al. 2017).

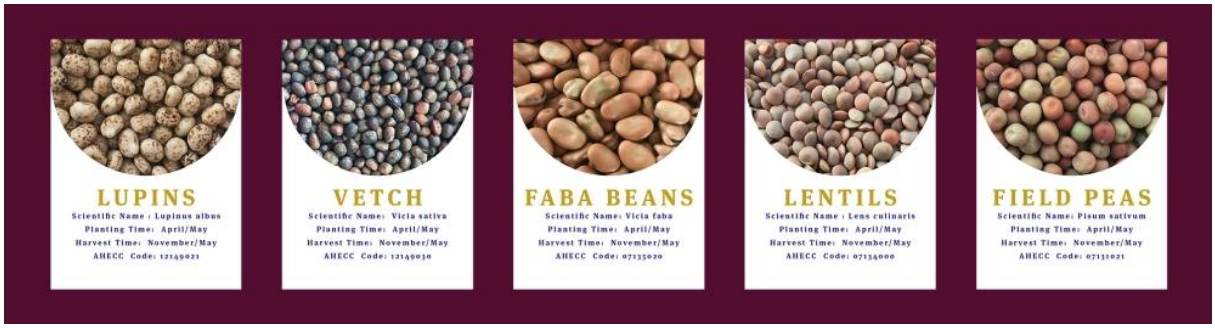


Figure 16 Some examples of pulse grains

As defined further by the FAO, pulses exclude those peas that are largely used for oil extraction, such as soybeans (Ferreira et al. 2021). In addition, crops that are harvested green for forage or vegetables are excluded from the pulse category, as are those grown for grazing or green manure. The leguminous crops with seeds that are used exclusively for sowing, such as alfalfa and clover are also excluded (FAO 2010).

Legume seeds harvested mature and marketed dry, are utilised as food or feed, or are processed into other goods. These plants have the advantage of fixing atmospheric nitrogen for their own needs and for soil enrichment. Legumes and pulses are nutritious diet staples globally and essential in the diet of millions of people around the world (Marinangeli et al. 2017).

Grain legumes or pulses have importance because of the uniqueness of their nutrient-rich profile (Hall et al. 2017), in particular, their high inexpensive protein content. Generally, pulse protein content ranges between 17% and 30% (dry weight) (Boye et al. 2010). They are also excellent for complex carbohydrates, fibre, phytonutrients, B-group vitamins and minerals such as iron, zinc, calcium and magnesium (McDermott & Wyatt 2017).

Grain-legume crops assume significance in their assurance of the sustainability of agri-food systems (European Commission 2018). With their high protein content and symbiotic nitrogen-fixing bacteria in root nodules, they reduce fertiliser use in agriculture, which has become very important for production systems (Foyer et al. 2016).

According to Havemeier et al. (2017), top producers of some grain legumes in the world are:

- Beans, dry – Myanmar
- Broad beans, horse beans, dry – China, mainland
- Chickpeas – India
- Cowpeas, dry – Nigeria
- Groundnuts, with shell – China, mainland
- Lentils – Canada
- Lupins – Australia
- Peas, dry – Canada
- Pigeon peas – India
- Soybeans – US
- Vetches – Ethiopia

Australia's diverse agro-climatic zones produce a wide array of high-quality pulse grains, and average just under 10% of the total area planted to crop. In favourable production areas they can occupy as much as 25% of the total crop area. Pulses are grown in crop rotation with cereals and oilseeds, given their ability to fix nitrogen into the soil and their contribution to sustainable and profitable farming practices.

Australian grain producers are some of the most advanced adopters of technology and crop management globally, and grow highly nutritional pulses, an important addition to the Australian grains industry, for human consumption throughout the southern and northern regions in the crescent known as the Australian grain belt.

A wide range of pulse crops is produced across Australia including dry field pea (*Pisum sativum*), dry faba bean (*Vicia fabae*), chickpea (*Cicer arietinum*), and lentil. Pulses and pulse foods are universally recommended as part of a healthy diet, and feature prominently in some of the world's healthiest diets and longest-lived food cultures, such as Mediterranean diets. The evidence consistently shows higher intakes of pulses are associated with a reduced risk of obesity and chronic diseases, including heart disease, type 2 diabetes and some cancers — which are on the rise globally.

3.1 Beans

From its origins as a wild vine in Central and South America to the thousands of varieties grown around the world today, the common bean (*Phaseolus vulgaris*) has evolved to be one of the world's most important and versatile crops. Beans are commonly referred to as the legume, pea, or bean family. They are an affordable source of protein, fibre, amino acids, iron, and vitamins that offer many health benefits (Hayat et al. 2014). The genera Phaseolus and Vigna each have several species of well-known beans, though a number of economically important species can be found in various genera throughout the family. The term 'bean' in general usage can refer to a host of different species (Sahoo & Jaiwal 2009).

Beans may be called 'the food of the ancients' with literature recording the cultivation of beans, lupins and lentils in the Nile Valley dating as early as 2000 BC. Certain kinds have been credited with medicinal value. Various forms still serve as the principal source of protein for the vast populations in Mediterranean countries and those edging the Indian Ocean (Siddiq & Uebersax 2012).

They are a summer crop needing warm temperatures to grow, and come in three categories:

1. Pulses dry: all mature and dry seeds of leguminous plants except soybeans and groundnuts.
2. Oil crops: soybeans and groundnuts.
3. Fresh vegetable: immature green fresh fruits of leguminous plants.

According to Mastura et al. (2017), there are many types of beans, with some popular varieties being:

- Lima beans
- Chickpeas (garbanzo beans)
- Black beans
- Black-eyed peas
- Soybeans
- Cannellini (kidney) beans
- Navy beans
- Pinto beans
- Red beans
- Faba Beans
- Adzuki Beans

The soybean (*Glycine max*) is the most economically important bean in the world, providing vegetable protein for millions of people and ingredients for hundreds of chemical products. As discussed before, soybeans are the principal ingredient in a number of industrial and medicinal products, as well as a source of animal feed (Huang et al. 2014).

The seeds are 0.5–2 cm long, kidney-shaped and highly variable in colour depending on the variety: white, red, green, tan, purple, grey or black. Immature pods are eaten fresh and can be easily preserved by freezing, canning or dehydrating. Mature pods and seeds are dried. Beans are eaten boiled, baked, fried, or ground into flour. Crop residues, such as dried pods and stems (straw) and processing by-products (discarded pods, pod extremities), can be used as fodder.

3.1.1 Bean production globally and in Australia

Dry beans are grown widely in different global regions. The significance of dry beans and pulses is evident from their wide distribution and consumption in many countries around the world. The world production of dry beans was 23.2 million metric tons (tonnes) in 2012, which represented an almost 70% increase over that of 1980. The area under dry bean cultivation has increased by only 14% during the past three decades and has ranged between 23.83 million hectares (2000) and 28.83 million hectares (2007). Most regions of the world have seen significant increases in production during the past three decades: Africa (145%), Asia (36%), and the Americas (North, Central and South) (49%); only Europe saw a decrease of about 35% (FAO 2011). According to FAO, the common bean global harvested area was 33.1 million ha and production was 28.9 million tons in 2019. According to the report, approximately 22.7 million tonnes of dry edible bean were produced in the US in 2021 (Siddiq et al. 2022). The area under pulse cultivation increased by 23% from 21.5 million hectares to 26.5 million hectares; however, during the 1990–2010 period, the area under pulse cultivation did not change to any great extent, demonstrated by its mere 5.6% increase. The pace of growth appeared the most rapid in 2016 with an increase of 7.7% year-to-year. In that year, the global dry bean market attained its peak level of US$31B. From 2017 to 2018, the growth of the global dry bean market remained at a low figure. The top five dry bean-producing countries in 2010, India, Brazil, Myanmar, China, and the United States, combined, contributed over 50% of the total world production. The countries with the highest volumes of dry bean production in 2018 were India (6.2M tonnes),

Myanmar (4.9M tonnes) and Brazil (2.9M tonnes), with a combined 37% share of global production. Nigeria, Niger, the US, Tanzania, China, Mexico, Uganda, Kenya and Burkina Faso lagged somewhat behind, together comprising a further 36%. Asia shares 50% of the global production of common bean, and Myanmar, India, Brazil, China, and America were the top five dry bean producing countries in the world in 2000–2019 (Nadeem et al. 2021; Figure 17).

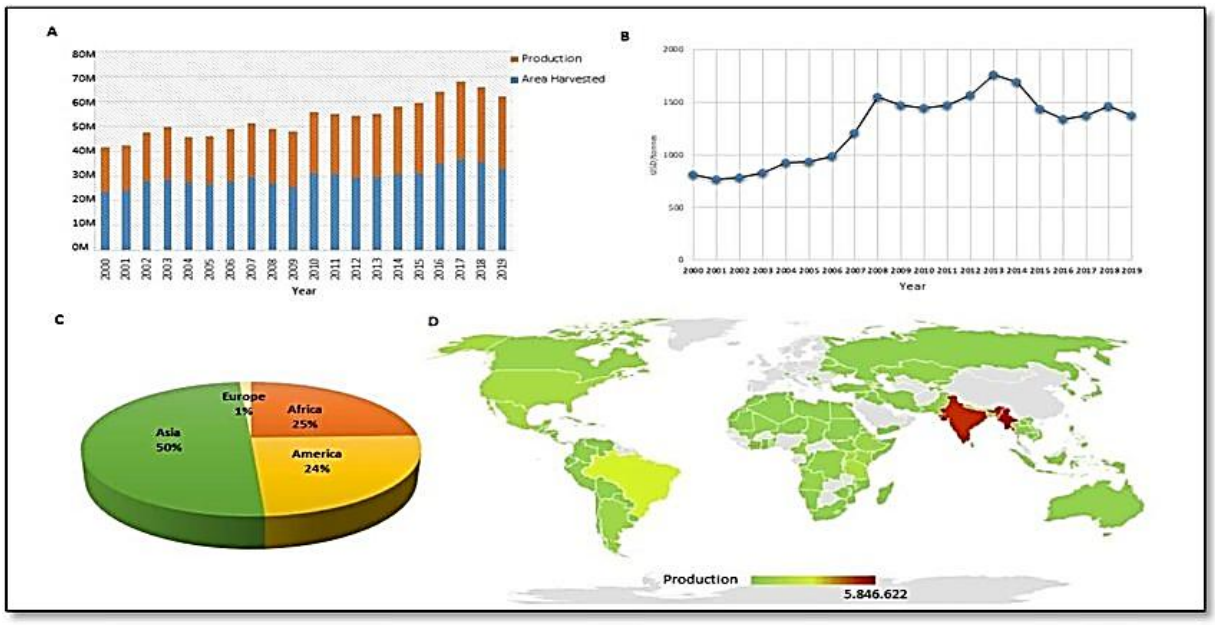


Figure 17 Common bean production in the world

(A) Evolution of common bean seed production and area under cultivation from 2000 to 2019.
(B) Evolution of sale prices of common bean seed from 2000 to 2019.
(C) Production share of common bean seed by continent in 2019.
(D) Map of production quantities of common bean seed by country in 2019.
(Source: Food and Agriculture Organization statistical databases were used to develop this figure – FAOSTAT 2020)

The global dry bean market revenue amounted to US$30.1B in 2018, a -2.4% reduction against that of the previous year. In general, dry bean consumption continues to indicate a relatively flat market trend (Siddiq et al. 2022).

The major dry bean exporting and importing countries are China (the lead exporter), Myanmar and the United States while India is the top-most importer, followed by Mexico and the United States. In 2018, Myanmar was the key global exporter of beans (dry), with 1M tonnes exported, approximately 27% of total exports. The US (439K tonnes) held an 11% share (based on tonnes) of total exports, which put it in second place, and was followed by China (10%), Argentina (8.9%) and Canada (8.8%). Brazil (162K tonnes), Ethiopia (136K tonnes), Egypt (102K tonnes), Nicaragua (83K tonnes), Australia (75K tonnes) and Kyrgyzstan (75K tonnes) followed a long way behind the leaders. Global exports amounted to 3.9M tonnes in 2018 (Siddiq et al. 2022).

The countries with the highest volumes of dry bean consumption in 2018 were India (6.9M tonnes), Myanmar (3.9M tonnes) and Brazil (2.8M tonnes), together accounting for 36% of global consumption. These countries were followed by Nigeria, Niger, the US, Tanzania, Mexico, Kenya, Uganda, China and Burkina Faso, which together accounted for a further 34%. Driven by increasing demand for dry bean worldwide, the market is expected to continue an upward consumption trend over the next decade. Market performance is forecast to decelerate, expanding with an anticipated growth of +2.1% for the period from 2018 to 2030, which is projected to bring the market volume to 48M tonnes by the end of 2030 (Siddiq et al. 2022).

Bean growers in Australia produce pulse, bean and legume crops of soybeans, adzuki beans, navy beans, mungbeans, chickpeas, black eye beans and field peas. While Australia has historically produced some beans for processing, in recent years the proportion of domestic production going to processing has dropped to zero. Australia produced over 29,000 tonnes of beans in 2016-17, consistent with previous years, with most of this supply going to the domestic fresh market. Australia produced around $78 million of fresh beans in 2016-17, up from around $69 million in 2015-16. The majority are grown in Queensland, with most of the remaining production coming from Tasmania and Victoria.

Faba beans have 10–15% of the annual Australian pulse crop. They are cultivated in SA, Victoria and NSW, with a small production area in WA. They are a cool-season crop, planted in autumn and harvested in late spring or early summer (October–December) with more than 300,000 tonnes produced annually. Broad beans are grown across south-west Victoria and south-east SA. They are sown between late April and the end of June. The Australian faba and broad bean industry has grown steadily and is among the top five producers in the world. Australia is currently the world's leading exporter of faba beans, supplying a third of the amount traded internationally (GRDC 2018). Faba beans are exported as either a whole or split product, and are generally consumed whole, canned, split or milled into flour. Australia's trade balance for fresh beans is positive, but the overall trade balance for fresh and frozen beans combined is negative due to heavy importation of frozen beans.

The vast majority of Australian fresh bean exports are sent to New Zealand, while frozen bean exports go primarily to Indonesia, with lesser amounts to New Zealand, Papua New Guinea and Thailand. Exports of fresh and chilled beans earned nearly $5.2 million in 2016-17, which came after consistent annual growth in previous years and was more than double the export value in 2007-08. A total of 32,759 tonnes of common beans were produced in Australia in 2020, which was up from 27,779 million tonnes in 2009. This production is valued at $104 million. The supply per capita was 1.2 kg.

3.1.2 General characteristics

Dry edible beans are particularly important from a nutritional perspective, especially in many countries where protein malnutrition is widely prevalent (van Heerden & Schönfeldt 2004). They are high in protein (16–33%), which is approximately twice that of most cereals, a good source of fibre (5–20%), resistant starches, bioactive components, folate, and possess biofunctional properties (Iqbal et al. 2006).

Table 60 Chemical composition of common bean

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	89.1	1.9	84.5	92.7
Crude protein	% DM	24.8	1.5	22.2	27.4
Crude fibre	% DM	5.2	0.8	4.3	7.9
NDF	% DM	20.0	4.4	16.1	25.8
ADF	% DM	7.6	1.5	4.8	9.9
Lignin	% DM	0.2	0.1	0.1	0.3
Ether extract	% DM	1.7	0.4	1.1	2.4
Ash	% DM	4.6	0.6	4.0	6.5
Starch (polarimetry)	% DM	42.7	2.3	38.5	46.9
Total sugars	% DM	4.9	0.7	3.1	5.7
Gross energy	MJ/kg DM	18.6			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Additionally, beans contain minerals (Ca, Fe, Cu, Zn, P, K, Mg), vitamins (thiamine, riboflavin, niacin, vitamin B6, folic acid) (Kuto et al. 2003), and free unsaturated fatty acids (linoleic and linolenic).

Table 61 Minerals and amino acid content of common bean

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	2.5	1.1	1.2	5.1
Phosphorus	g/kg DM	4.9	1.1	2.1	6.3
Potassium	g/kg DM	16.9	1.5	15.4	19.2
Sodium	g/kg DM	0.0	0.1	0.0	0.1
Magnesium	g/kg DM	2.2	0.4	1.8	2.8
Manganese	mg/kg DM	16			
Zinc	mg/kg DM	36			
Copper	mg/kg DM	9			
Iron	mg/kg DM	89			
Amino acids	**Unit**	**Avg**	**SD**	**Min**	**Max**
Alanine	% protein	4.0	0.7	3.0	5.3
Arginine	% protein	6.4	1.2	4.9	9.2
Aspartic acid	% protein	10.7	1.9	8.0	14.7
Cystine	% protein	1.1	0.1	1.0	1.2
Glutamic acid	% protein	14.8	2.8	9.7	18.8
Glycine	% protein	3.9	0.8	3.1	5.6
Histidine	% protein	2.8	0.3	2.1	3.4
Isoleucine	% protein	4.4	0.9	2.8	5.9
Leucine	% protein	7.8	1.3	5.5	10.0
Lysine	% protein	6.5	1.3	4.0	8.4
Methionine	% protein	1.1	0.4	0.3	1.7
Phenylalanine	% protein	5.4	1.0	3.6	7.1
Proline	% protein	3.5	1.0	2.1	5.1
Serine	% protein	5.5	0.9	4.4	7.2
Threonine	% protein	4.2	0.8	3.2	5.9
Tryptophan	% protein	1.3	0.2	1.1	1.7
Tyrosine	% protein	3.4	0.5	2.7	4.2
Valine	% protein	5.0	0.9	3.4	6.7

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Although protein level is high in dry beans, due to the low amounts of some essential amino acids (i.e. sulphur-containing amino acids), the presence of antinutritional components in the seeds and lower true digestibility compared to some animal proteins, their quality is not rated as high as protein sources of animal origin. The protein in beans is located mainly in the cotyledon and in the embryonic axis of the seeds with small amounts in the testa. Bean proteins are classified according to their water and salt solubilities, heat coagulability, reaction to changes in ionic strength, pH and how their subunits enter into association-dissociation reactions.

Carbohydrates are an important constituent of beans, accounting for up to 550–650 g/kg of the dry matter. The carbohydrate fraction contains starch (75–80%), and non-starch polysaccharides, with smaller but significant amounts of oligosaccharides. Sucrose, stachyose and verbascose are the predominant oligosaccharide fractions in beans, which are present in higher amounts compared to cereals (Belitz et al. 2009).

The health benefits of beans are attributable to their fibre, iron, bioactive proteins and peptides, and to their secondary metabolites such as the phenolic compounds that possess antioxidant properties (Madhujith & Shahidi 2005). Inclusion of beans in the diet may, therefore, help to control and even prevent various metabolic diseases like diabetes mellitus, coronary heart disease and colon cancer (Siddiq & Uebersax 2012). They contain very little sodium and no cholesterol. Beans contain a rich variety of phytochemicals, including phytosterols such as β-sitosterol, campesterol, and stigmasterol (Rochfort & Panozzo 2007).

3.1.3 Nutritive value for animal feed

Grain legumes including beans are primarily grown as human foodstuffs. The seeds that are not used as human foodstuffs are fed to animals. At times, the leaves and stems of legumes are also fed to animals as forage. Research studies indicate that some functional properties of pulse proteins may be comparable to those of other frequently used proteins such as soybean meal. The fibre faction of beans supports the digestive tract to function normally. Legumes are a rich source of vitamin B6 that is required for normal amino acid metabolism and contain vitamin B2, or riboflavin, which ensures energy exchange in cells, as well as fat and protein metabolism. Legumes also contain sugar and starch, which are sources of energy, along with minerals like magnesium, which is vital for normal cardiac function, manganese that is necessary for enzymes, such as transferases, and other elements that improve the metabolic processes of animals. Unlike protein products of animal origin, legumes contain little fat (Osmane et al. 2017).

Tako and Glahn (2010) reported that when diets are formulated on the basis of metabolisable energy and ileal digestible amino acids, faba beans can be used successfully in birds' diets up to levels of 20%. Similar results were reported by Carew and Gernat (2006) who claim that levels of up to 25% could be used in poultry feed. Two limiting factors in using beans in animal feed are market values and availability (in excess of what is needed for human consumption).

Dry beans contain some antinutritional factors that may have adverse nutritional effects, even when present at low concentrations (Abd El-Hady & Habiba 2003). Dietary fibre, along with the presence of certain antinutrients, may account for the low digestibility of legume starch as it can decrease transit time through the small intestine, thereby reducing the time available for starch digestion in the small intestine. Other components of some concern include polyphenols (especially tannins in beans), as they can bind to proteins and make them unavailable for digestion, and oligosaccharides (raffinose and stachyose) as monogastric animals cannot digest these carbohydrates, which results in their fermentation in the gut. Components such as trypsin inhibitors and lectins, which are thermolabile, disappear or are significantly reduced after proper heating processing (see the next section for more details).

The phenolic compounds and oligosaccharides of beans are thermostable and induce functional properties that support digestive tract health status. To deactivate enzyme inhibitors, and increase protein digestibility and mineral bioavailability, the beans must be appropriately heated prior to feed manufacturing (Vidal-Valverde et al. 2002).

3.1.4 Antinutritional factors – nutritional limitations

Common beans contain several antinutritional compounds, notably enzyme inhibitors (trypsin, chymotrypsin, α-amylase), phytic acid, flatulence factors, saponins and lectins. These antinutrients influence the bioavailability and digestibility of nutrients and minerals (Montoya et al. 2010). The nature and activity of these toxic compounds vary greatly among cultivars, for example the trypsin inhibitor of raw navy beans is twice the amount of the corresponding in the red kidney beans, but with

half the lectin activity. These toxic compounds are detrimental to monogastric animals and impair production performance.

Some raw beans contain a harmful, tasteless toxin: the lectin phytohemagglutinin, which must be destroyed by cooking. Red kidney beans are particularly toxic, but other types also pose risks of food poisoning. A recommended method is to boil the beans for at least ten minutes; undercooked beans may be more toxic than raw beans (Linderoth et al. 2006).

Tannins found in the coats of faba bean seed negatively impact the availability of both amino acids and energy in monogastric animals. However, dehulling addresses this problem easily and in any case tannin-free genotypes are now quite easily obtainable. The glycosides, vicine and convicine are known to affect the metabolism of laying hens, but appear to have limited effect on broilers, pigs or ruminants. The discovery of a gene that can reduce the vicine and convicine content by 90–95% means that safe cultivars are now available on the market. Trypsin inhibitor activity in faba beans is not well documented but appears to be low. Recent work has shown that modern faba bean cultivars can be successfully included in both monogastric (pig and poultry) and ruminant (beef, dairy, sheep and goat) feed.

It is then highly recommended to process raw common beans before feeding them to pigs, poultry and other monogastric livestock. Treatments such as heating, autoclaving, cooking or extruding have been shown to remove heat-sensitive antinutritional factors. Biological treatments such as germination, ensiling, treatment with pancreatin or with chemicals can also be effective in removing antinutritional factors in common beans. Lectin content may be reduced by cooking above 100°C but cooking at a lower temperature (80°C) increased lectin content and toxicity (FDA 2012).

3.1.5 Beans in the laying hen diet

Poultry species are sensitive to antinutritional factors contained in raw common beans, though less so than pigs (van der Poel 1990). It has been reported that field beans (faba beans, broad beans, horse beans, ackerbohnen, *Vicia faba* L.) depress egg weight when fed to laying hens. In an old study by Guillaume and Bellec (1977), inclusion of beans in laying hens' diet at a rate of 300 g/kg reduced egg weight, although the relative sizes of yolk, albumen and shell were unchanged. They reported that removing the hulls of the beans did not restore the egg weight similar to the control group. Some years later, Mateos and Puchal (1982) reported that including broad beans in laying hens' diet at a 10% inclusion rate did not affect egg production performance, but higher inclusion rates (e.g. > 200 g/kg) impaired egg weight remarkably and at a 550 g/kg inclusion rate reduced feed intake, egg production and quality as well, but not feed conversion ratio.

A study in Australia reported that faba beans inclusion at 25% to laying hens' diet resulted in reduced production performance (Perez-Maldonado et al. 1999). Later with the development of low-vicine and convicine-faba beans (0.69% vicine and convicine) in Germany, studies showed that new cultivars could be included in the laying hens' diet at 30% with no detrimental effects on feed intake and egg production performance (Dänner 2003). Fru-Nji et al. (2007), however, reported that low-vicine and convicine faba beans (< 0.88% vicine and convicine) can be included in laying hens' diet up to 16% with no significant reduction in egg production or quality. In a study, Laudadio and Tufarelli (2010) showed that including faba bean at 24% in the diets of laying hens, feed consumption was significantly reduced.

Table 62 Standardised ileal digestibility of amino acids of beans in laying hens

Indispensable amino acid	Beans
Arginine	78
Histidine	68
Isoleucine	67
Leucine	69
Lysine	78
Methionine	66
Met+Cys	
Phenylalanine	64
Threonine	67
Tryptophan	67
Valine	66
Dispensable amino acid	
Alanine	70
Aspartic acid	65
Cysteine	59
Glutamic acid	72
Glycine	64
Proline	68
Serin	69
Tyrosine	67

(Source: Rostango et al. 2005)

In a more recent study by Koivunen et al. (2014), the appropriate inclusion level of locally produced unprocessed or expander-processed coloured flowered faba bean (FB) (cv. 'Kontu') seeds for laying hens was evaluated using 560 hens at 40 weeks of age. A diet without faba beans was served as a control diet. Both unprocessed and expander-processed faba bean were tested in proportions of either 50 g/kg or 100 g/kg in the diet. Faba bean inclusion had no effect on the egg production rate, egg mass production, feed consumption, or feed conversion ratio, but it decreased egg weight and tended to increase the mortality rate of hens especially at a 10% inclusion rate. The processing of faba beans did not improve egg weight or hen mortality. These authors concluded that faba beans can be included in hens' feed at a 5% inclusion rate without any negative impact on egg production and quality.

Another recent study conducted by Abd El-Hack et al. (2017), evaluated the effect of increasing inclusion levels of faba bean (0% (control), 25%, 50%, 75% and 100%, substituting soybean meal) with enzyme supplementation on the egg production performance and egg quality parameters of Hisex Brown laying hens. They reported a positive relationship between faba beans levels and hens' body weight. Enzyme supplementation of faba beans significantly affected the final body weight. No significant interaction between FB levels and enzyme supplementation was noticed for BW traits. Increasing faba beans inclusion up to 50% increased feed intake, and had no adverse effects on feed conversion ratio, however, replacing soybean meal at 75% and 100% with faba bean impaired feed intake. Enzyme supplementation at 250 g/ tonnes of feed improved the production performance in faba bean-fed hens. Results from this study concluded that replacing 25% or 50% of SBM with faba beans in laying hen diets had no adverse effects on feed consumption or feed conversion ratio. Egg quality traits maintained at 50% of faba beans inclusion replacing soybean meal.

Nolte et al. (2020) studied different chicken genotypes and reported that a limited adverse effect of the vicine-rich faba bean diet on egg weight was observed.

Considering more recent studies with low-vicine cultivars of faba beans, and the use of processing such as heat treatment or multi-enzyme supplementation, it is possible to replace 50% of the soybean meal (11% of the total diet) with faba beans in laying hens' diet.

3.1.6 Beans in the pig diet

Pigs seem to be more sensitive to the antinutritional factor of raw beans. Young piglets are more vulnerable and therefore the inclusion rate of faba beans should not exceed 5%. Finisher pigs can easily handle higher inclusion rates such as 20% with no detrimental effects on their growth.

Table 63 Standardised ileal digestibility of amino acids of beans in pigs

Indispensable amino acid	**Beans**
Arginine	87
Histidine	74
Isoleucine	77
Leucine	79
Lysine	81
Methionine	67
Met+Cys	-
Phenylalanine	73
Threonine	81
Tryptophan	-
Valine	80
Dispensable amino acid	
Alanine	
Aspartic acid	-
Cysteine	-
Glutamic acid	-
Glycine	-
Proline	-
Serin	-
Tyrosine	-

(Source: Kasprowicz and Frankiewicz 2004)

Partanen et al. (2003) carried out two experiments to study the effects of the inclusion of new faba bean cultivars in grow-finisher pigs' diet. In the first experiment, they replaced canola meal at 0, 25, 50, 75, and 100% with faba beans. Replacing canola meal with faba beans exerted a quadratic effect on daily weight gain and the feed conversion ratio of pigs during the growing period, where the growth performance declined when faba beans replaced canola meal at a 75 and 100% rate. Feed intake was reduced when canola meal was replaced fully with faba beans. The best overall growth performance and feed conversion ratio were observed when 50% of canola meal was replaced with faba beans, where the feed conversion ratio of these pigs was better than with the control diet. The increasing levels of faba bean replacing canola meal resulted in darker pork. The second trial focused on the meat quality of pigs when fed faba beans. In conclusion, authors recommended a maximum of 20% faba bean inclusion in the grow-finisher pigs, replacing conventional protein ingredients (Partanen et al. 2003).

A study in Canada by Zijlstra et al., 2004concluded that zero-tannin faba beans could be included at rates of up to 30% in pig diets without negative effects on feed intake. These authors reported that average daily gain across the entire experimental period was not significantly different between pigs fed soybean meal or faba beans. However, barrows fed soybean meal in the grower phase had a

significantly greater average daily gain and feed conversion ratio than those fed faba beans. The authors hypothesised that this may have been a result of overestimation of the digestible amino acid or net energy content of faba beans. Heat treatment (102°C for 20 min or 136°C for 1.5 min) was shown to have beneficial effects on the nutritive value of common beans as it almost completely destroys antinutritional factors. Heating also enhances the digestibility of dry matter, protein and lysine (van der Poel et al. 1991a). In gestating and lactating sows, high inclusion of faba beans can create bloating and gastrointestinal gases leading to constipation.

In general, it is recommended to introduce faba beans into pig diets gradually, starting from 5% and up to a maximum of 20% in grow-finisher pigs. Based on the previous studies, faba beans together with canola meal (50-50) can replace soybean meal fully when the diet is well-balanced for net energy content and standardised amino acid digestibility values for grow-finisher pigs.

3.1.7 Carbon footprint and sustainability of faba bean production

From an environmental perspective, the faba bean has a comparatively lesser carbon footprint (Maalouf 2018). The carbon footprint of faba bean cultivation is between 0.23 and 0.58 kg CO_2-eq. per kg bean when cultivated in mineral soils (Heusala et al. 2020). In comparison, the carbon footprint of faba bean concentrate protein is 80–90% lower that of oat protein concentrate. In the oat protein concentrate life cycle analysis, the production stage has been identified as the emissions hotspot (Figure 18). Another study by Šarauskis et al. (2020) reported that environmental pollution in faba bean production ranged from 481 to 609 kg CO_2-eq ha−1 where the machinery and fuel constitute from 31 to 52% of total GHG emissions in the production (Šarauskis et al. 2020). Detzel et al. (2022) studied the carbon footprint of producing vegetable meat alternatives (VMA) using faba bean, and they found carbon emissions of 130 g CO_2-eq per 100 g food production.

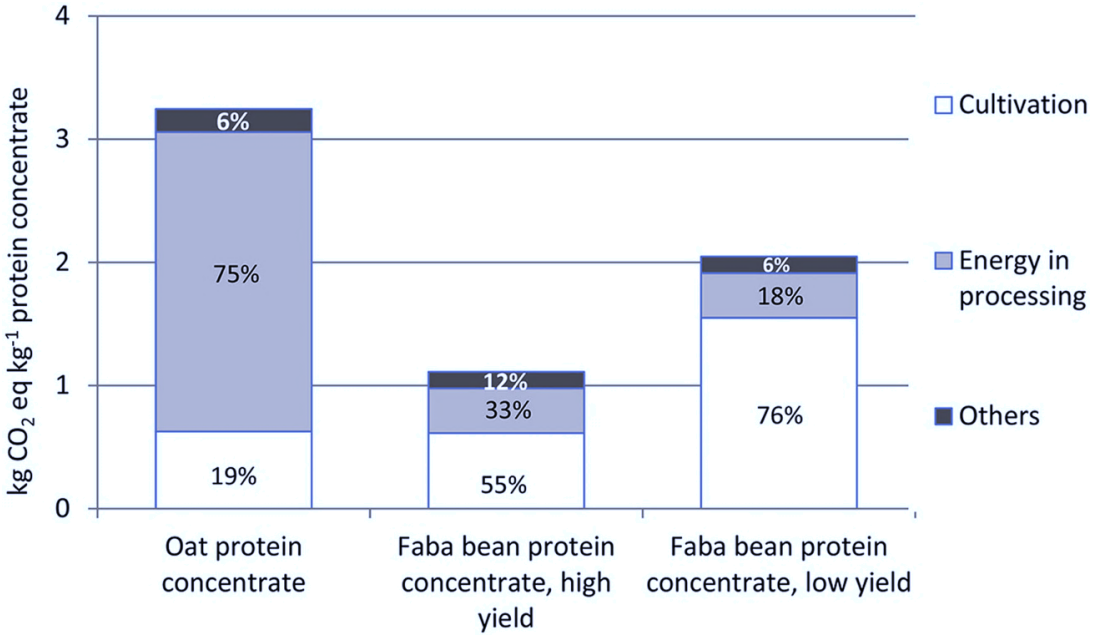


Figure 18 Carbon footprint of oat protein concentrate and faba bean protein concentrate

3.2 Chickpea

Chickpea (*Cicer arietinum* L.), a major grain legume cultivated for its edible seeds in the Mediterranean Basin, Asia and Australia, is an annual plant derived from the Fabaceae family and reproduced from grains. Like all legumes, it enriches the soil with nitrogen and leaves it in good shape. Chickpea occurs in two main varieties: Kabuli and Desi. Desi chickpea grains are small, dark, and have a ridged surface. The Desi variety is grown mainly in semiarid land. The Kabuli variety is slightly larger than Desi, has a thin, bright cover, and is cultivated in temperate climates (Pourdarbani et al. 2019).

Chickpea has been known of for many years in Asia, mainly due to its broad applications. Chickpea leaves have astringent properties, and once cooked may be applied for bone displacement and dislocation, while the extract treats diarrhea or indigestion. In Egypt, chickpea grains have been used to increase body weight, cure head and throat aches, and coughs. Powdered grains are used for the preparation of facial masks and added to antidandruff products. Immature grains can be eaten raw, and the ripe ones can be dried and ground into flour and used as animal feed or as a substitute for coffee. Cooked grains are a great addition to salads, especially popular in Western Europe and the US, while in the Middle East they are consumed coated by sugar or spices. Chickpea flour is also used as an addition to pasta, soups, and bread (Redden & Berger 2007).

Chickpea cropping is attractive in the Mediterranean context because of its low input requirement and resistance to drought (Sellami et al. 2021). Although it is mainly produced for human consumption, feed grade chickpeas can be an energy-protein feedstuff alternative to cereals due to the higher metabolisable energy content and the double protein content over other grains for animals (Bampidis & Christodoulou 2011). Some of the chickpea by-products that are used in animal feed include low-grade and culled chickpeas, bran (a by-product of dehulling, known as chuni in India), crop residues (husks, straw), and chickpea hay, and although they have a similar nutritive value as other legumes such as peas, chickpeas are not very common feed ingredients in livestock farming. Chickpea starch can be used to make plywood and for textile sizing (Bejiga et al. 2006). The leaves are used in traditional medicine and produce a colour similar to indigo (Taylor et al. 2007).

3.2.1 Chickpea production globally and in Australia

Chickpea plays a leading role in food safety in the world by covering the protein deficit of daily food rations among Indian and African Sub Sahara populations. The designed chickpea-based infant formula meets the WHO/FAO requirements for complementary foods and also the EU regulations for follow-on formula with minimal addition of oils, minerals, and vitamins (Muehlbauer & Sarker 2017). Chickpea mostly contains starch, protein and fibre, and is mainly destined for human consumption (Jukanti et al. 2012). Off-grade chickpea is available for animal feeding. Dietary inclusion of chickpea as an energy and protein source to replace soybean meal (SBM) may reduce the feed cost for swine (Woyengo et al. 2014).

Chickpea is mainly grown in temperate and semiarid regions, i.e. Asia, Europe, Australia and North America during cool and dry seasons on residue moisture. Chickpea seed production has been increasing since the 1990s and rose from 7 million t in 1990 to 11 million tonnes in 2011, and further to 15.15 million tonnes of chickpea produced globally in 2017 (FAO 2017 In 2021, India was the leading producer of chickpeas, accounting for approximately 66% of global production (~7 million tonnes). In 2022, Tanzania was the top supplier, exporting $45 million worth of chickpeas and fulfilling 90% of global imports. While Australia is not the largest producer, it remains the top exporter, with total exports reaching $338 million in 2022. Bangladesh and Pakistan made up nearly 80% of Australia's chickpea trade. Other notable producers include Turkey (520,000 tonnes), Iran (200,000 tonnes),

Canada (106,000 tonnes), and the United States (107,000 tonnes), each contributing only a small fraction to global chickpea production (USDA, 2023).

Chickpea is an important crop in Australia's northern farming system but is grown across all grain regions. Australian chickpeas provide a good source of carbohydrates and protein. Being 20–35% of the annual Australian pulse crop, the annual production of approximately 500,000 tonnes (in 2023) focusses mainly on Desi types, with limited production of small to large Kabuli types. About 90% of the chickpea produced in Australia is exported, with Australia commonly being the biggest global exporter.

Australia's chickpea production was at its highest during 2016 and 2017 with 1.3 and 1 million tonnes of the production, respectively. These figures dropped sharply in 2018 to 282,000 tonnes, and then rose to 366,000 tonnes in 2019. Production volumes increased again year to year, reaching just under 500,000 tonnes in 2022–23. Australian production focusses on large uniform grain size, light coloured seed coats, the splitting efficiency and quality of Desi chickpea, and the hydration and cooking characteristics of Kabuli chickpea.

3.2.2 General characteristics

Chickpea is characterised by high protein (19–25% DM), fat (5%), ash (3%), and fibre content (10%) (Wood & Grusak 2007). In addition, chickpea is rich in minerals, both in the case of macrominerals like potassium, calcium, sodium and magnesium, and microminerals such as copper, iron, and zinc (Esmat et al. 2010). The energy value of Desi variety grains is 327 kcal/100 g (20 MJ/kg), while for the Kabuli variety it equals 365 kcal/100g (Maheri-Sis et al. 2008).

The major proteins found in legumes belong to albumins and globulins. Their major globulin proteins include legumin, vicilin, and convicilin (Schwenke 2001). Other proteins present in small amounts are glutens and prolamins (Rachwa-Rosiak et al. 2015).

Table 64 Chemical composition of chickpea seeds, Desi type

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	89.0	1.0	87.6	91.0
Crude protein	% DM	22.1	2.1	18.2	26.5
Crude fibre	% DM	10.5	1.1	8.6	12.9
NDF	% DM	22.8	4.2	14.1	29.5
ADF	% DM	13.8	2.5	7.6	17.6
Lignin	% DM	0.7	0.3	0.2	1.3
Ether extract	% DM	5.0	1.2	3.3	7.8
Ether extract, HCl hydrolysis	% DM	4.7	1.6	2.8	5.7
Ash	% DM	3.3	0.3	2.9	4.0
Starch (polarimetry)	% DM	35.6	7.6	22.3	47.1
Total sugars	% DM	3.6	1.1	1.3	6.3
Gross energy	MJ/kg DM	19.6	0.5	17.6	20.0

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The differences in appearance and chemical composition between chickpea varieties are dependent on the growing region and conditions, which affect the length of the plant growing season or

resistance to various diseases (Rachwa-Rosiak et al. 2015). Chickpeas are also a good source of minerals, such as of Ca, P, Mg, Fe and K, of which chickpea has a higher content than other legumes. The contents of these compounds lessen the thermal processing of chickpea grain (Wang et al. 2010). Chickpea grains and flour are high in monosaccharide, disaccharide and oligosaccharide content.

Major monosaccharides of chickpea are ribose, fructose and glucose.
Its carbohydrate composition also includes sucrose and maltose. The main oligosaccharides included in chickpeas are raffinose, ciceritol, stachyose and a small amount verbascose (Wood et al. 2018). The total lipid content of chickpeas ranges from 4.5 to 6.0 g oil/100 g of seeds. Triglycerides are the major components of neutral lipids, whereas lecithin is the major component of polar lipids. Fat in chickpea grains is characterised by high levels of essential unsaturated fatty acids, primarily, linoleic acid (54.7–56.2% in oil), oleic acid (21.6–22.2% in oil) and linolenic acid (0.5–0.9% in oil), and to a lesser extent palmitic acid (18.9–20.4% in oil) and stearic acid (1.3–1.7% in oil) (Rasool et al. 2013).

Table 65 Mineral and amino acid content of chickpea seeds, Desi type

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	1.7	0.4	1.2	2.6
Phosphorus	g/kg DM	3.9	0.6	1.9	4.7
Potassium	g/kg DM	11.9	1.1	10.2	13.6
Sodium	g/kg DM	0.2	0.1	0.1	0.4
Magnesium	g/kg DM	2.1	0.1	1.8	2.3
Manganese	mg/kg DM	36			
Zinc	mg/kg DM	38			
Amino acids	**Unit**	**Avg**	**SD**	**Min**	**Max**
Alanine	% protein	3.7	0.3	3.2	4.3
Arginine	% protein	8.6	1.1	7.1	12.3
Aspartic acid	% protein	10.6	0.9	9.0	11.9
Cystine	% protein	1.2	0.4	0.6	1.8
Glutamic acid	% protein	17.0	2.7	12.7	20.2
Glycine	% protein	3.5	0.3	3.1	4.3
Histidine	% protein	2.5	0.2	2.1	3.1
Isoleucine	% protein	3.8	0.6	2.6	4.8
Leucine	% protein	7.1	0.5	5.9	7.8
Lysine	% protein	6.6	0.6	5.4	7.7
Methionine	% protein	1.2	0.3	0.7	1.6
Phenylalanine	% protein	5.3	0.4	4.4	6.1
Proline	% protein	4.0	0.3	3.7	4.5
Serine	% protein	4.8	0.3	4.2	5.6
Threonine	% protein	3.4	0.2	3.0	4.0
Tryptophan	% protein	0.9	0.2	0.7	1.2
Tyrosine	% protein	2.2	0.4	1.5	3.2
Valine	% protein	3.9	0.5	2.8	4.9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Chickpeas are a rich source of secondary metabolites such as polyphenols and flavonoids, which have high antioxidant properties. The darker the chickpea peas, the greater the content of polyphenols and

flavonoids, and the higher the antioxidant properties (Turco et al. 2019). The total content of polyphenolic compounds present in the seeds of chickpeas ranges from 0.72 to 1.81 mg/g of seed, and the content of anthocyanin amounts to 14.9 mg/kg of peas, depending on the reagents used in extraction, the extraction time, and the method of analysis used by the researchers (Hithamani & Srinivasan 2014). Tannins vary between 0.7 and 7.9 g/kg DM, with an average content of 3.1 g/kg DM.

3.2.3 Nutritive value for animal feed

Although most chickpeas are produced for human consumption, they provide the livestock industry with an alternative for protein and energy feedstuff. In addition, chickpea straw is used in ruminant feed.

The crude protein content of chickpeas ranges from 137 to 340 g/kg dry matter and is highly dependent on the cultivation system. The sulphur amino acids are the first limiting factors nutritionally, followed by valine, threonine and tryptophan (Jadhav et al. 2015) or aspartic acid and arginine (Hirdyani 2014). Chickpea protein digestibility varies between 48 and 89.01%, reported in various research results (Tavano et al. 2016).

Kabuli chickpea grain exhibits lower neutral detergent fibre (NDF) and acid detergent fibre (ADF), and higher crude fat and starch, than Desi chickpea grain, without differing in other components (Jadhav et al. 2015). Apparent ileal digestibility coefficients of dietary components and amino acids in male piglets fed Kabuli and Desi chickpea diets are particularly high, except for ash, NDF and ADF (Salgado et al. 2001). Furthermore, apparent ileal digestibility coefficients in Iberian pigs fed chickpeas are 0.720 for DM, 0.740 for N, 0.850 for starch, and 0.670–0.920 for fatty acids. True ileal digestibility in Iberian pigs fed chickpeas is 0.890 for N and 0.830–0.970 for amino acids (Rubio 2005).

Chickpea has been tested as a protein-rich alternative to soybean meal and numerous studies have reported its nutritive value in different species. This section provides a general overview of the nutritive value in monogastric animals, where in the next two sections more data are presented for laying hens and pigs specifically.

Brenes et al. (2008) studied the nutritional value of raw and extruded Kabuli chickpeas in broiler chickens from 1 to 21 days of age. Increasing chickpea content in the diet (both raw and extruded) did not affect body weight gain and feed conversion ratio, while relative liver weight increased with both raw and extruded chickpeas, but relative pancreas weight increased only with raw chickpeas.

Christodoulou et al. (2006) also found that raw chickpeas can partially replace soybean meal at inclusion levels of 120 g/kg of diet without affecting the final body weight and feed conversion ratio of broiler chickens, while a higher inclusion level of 240 g/kg of diet adversely affected productive performance, suggesting that birds may have been susceptible to antinutritional factors contained in raw chickpeas. In contrast, Garsen et al. (2008) found that partial replacement of soybean meal with raw chickpeas resulted in similar performance and carcass characteristics of broiler chickens when chickpeas were supplementary to their diet in gradually increasing levels of up to 480 g/kg with respect to the birds' age (i.e. 160 g/kg for 1–14 days of age, 240 g/kg for 15–28 days, 480 g/kg for 29–42 days).

Three recent reports studied the apparent digestibility of dry matter, crude protein, crude fat, starch and the energy of juvenile European seabass and rainbow trout fed extruded chickpeas to inclusion levels of up to 350 g/kg (Tiril et al. 2009). In general, extruded chickpea nutrient digestibility in fish was higher than in mammals or birds.

Overall, results suggest that chickpeas have high nutritional value when fed to animals, equivalent to that of other legumes. A restriction to the use of chickpea in ruminant feeding could be the large portion of rumen degradable protein that, if exceeding the amount required by rumen bacteria, might incur nitrogen loss from rumen and impair feeding efficiency and the feed conversion ratio (Sun et al. 2018).

3.2.4 Antinutritional factors – nutritional limitations

Chickpeas may contain antinutritional compounds that can impair the utilisation of nutrients. The antinutritional compounds found in pulse crops are classified into two categories: protein antinutritional components and nonprotein antinutritional components, and they range in effect from relatively ineffective polyphenols to the relatively harmful protease inhibitors. Antinutritional protein compounds commonly found in legumes include lectins or agglutinins, trypsin inhibitors, chymotrypsin inhibitors, or antifungal peptide (Roy et al. 2010). The antinutritional compounds of chickpea are reduced in varying degrees when chickpea is subjected to heating processes.

Lectins (agglutinins) are carbohydrate-binding proteins. There are several hundred different types of lectins in plants, the four main groups of those that can be distinguished are: legume lectins, chitin-binding lectins, monocot mannose-binding lectins, and the ribosome inactivating proteins type 2. Legume composition includes many lectins. In humans and animals, diarrhea, bloating, vomiting and red blood cell agglutination are reported when sufficient quantities of raw grains or flour are consumed. The agglutination activity of chickpea seeds as compared to lentils and peas is much lower (400 units/g) and may vary depending on variety, growing area and method of collection. Scientific data have demonstrated that the lectins of legumes are poorly understood but can be used as a therapeutic agent for preventing or controlling obesity and reducing the risk of certain cancers (Roy et al. 2010).

In dry chickpeas, trypsin (6.7–14.6 units/mg) and chymotrypsin (5.7–94 units/mg) inhibitors are found, which inhibit the action of protein digesting enzymes and contribute to the deterioration of protein use by the body. The inhibitor of amylase content of chickpea ranges from 0 to 15 units/g. Processing chickpea flour via ultrafiltration reduces the trypsin inhibitor content. Using this procedure, along with degreasing of the flour, leads to increased availability of protein from 22.3 to 88.0% of DM for Desi chickpea varieties, and from 18.9 to 85.7% of DM in the Kabuli variety (Mondor et al. 2009).

Another antinutritional factor present in legume peas is phytic acid, which forms complexes with Ca, Zn, Fe, and some amino acids, and inhibits the absorption of these elements into the body. In comparison to the phytic acid concentration found in seeds of other major grain legumes, it has been discovered that chickpea has lower phytic acid concentrations (4.9–6.1 mg/g) than kidney bean (11–17 mg/g), faba bean (10.1–13.7 mg/g), and soybean (10–14.7 mg/g). Other authors report even lower phytic acid content in chickpea ranging from 1.38 to 1.71 mg/g (Thavarajah et al. 2009).

The oxalic acid content of chickpea straw has been reported to be high, which may potentially make it unpalatable and possibly toxic (Suttie 2000). In addition, chickpea pod husks contain a high amount of tannins, from 6 to 8% DM, which is bound to carbohydrates (Sreerangaraju et al. 2000).

The use of heat treatments such as cooking or extrusion reduces the content of protease inhibitors and amylase inhibitors, condensed tannins and polyphenols, and completely eliminates the activity of agglutination (Srinivasan et al. 2005; Bampidis et al. 2011).

3.2.5 Chickpea in the laying hen diet

Available data on the nutritional value of chickpeas for layers are limited. In a study by Perez-Maldonado et al. (1999), the nutritional value of chickpeas for laying hens of 18 to 58 weeks of age was evaluated. Inclusion of chickpeas at a rate of 250 g/kg supported excellent production, although it increased relative pancreas weight when compared to the control diets. Enlargement of the pancreas occurs in chickens fed diets containing trypsin inhibitors and/or lectins; both of these antinutritional factors exist in raw chickpeas.

Table 66 Metabolisable energy value of chickpea for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max
AME poultry	MJ/kg DM	12.7	0.8	11.5	13.2

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Another old study by Robinson et al. (2001), tested different vegetable protein sources in laying hens' diet in an effort to identify a viable alternative protein-ingredients to soybean meal. Chickpea was one of the alternative ingredients, and they reported that an inclusion rate at above 20% chickpea reduced egg production and egg mass output. Pelleted chickpea could be included at 20–30% without any negative effects on egg production parameters.
Chickpea replacing maize grain in layer feed has resulted in reduced egg yolk colour, and synthetic pigments might be required in the diet to avoid pale yolk colours (Garsen et al. 2007).

Table 67 Standardised ileal digestibility of amino acids of chickpea in laying hens

Indispensable amino acid	Chickpea
Arginine	85
Histidine	78
Isoleucine	70
Leucine	72
Lysine	77
Methionine	80
Met+Cys	-
Phenylalanine	76
Threonine	72
Tryptophan	75
Valine	73
Dispensable amino acid	
Alanine	74
Aspartic acid	75
Cysteine	75
Glutamic acid	79
Glycine	72
Proline	75
Serin	72
Tyrosine	74

(Source: Rostango et al. 2005)

In another study by Sengül and Çalislar (2020), chickpea in three forms (raw, autoclaved, and microwaved) were included in laying quails' diet at two levels (20% and 40%) as a substitute for

soybean meal. The trial included seven groups consisting of control, 20% and 40% raw, 20% and 40% autoclaved, and 20% and 40% microwaved. Heat treatments were applied to the chickpeas to minimise the adverse effects of phenolic compounds and antinutritional factors. No effects of chickpea inclusion were observed for live weight, feed intake, feed efficiency, egg weight, and egg quality. Minor effects including linoleic acid, a-linoleic acid, total saturated fatty acids and palmitic acid among the egg yolk fatty acids were observed when chickpea replaced soybean meal in laying quails' diet.

Higher levels of chickpeas can be used if chickpeas are dehulled and the antinutritional factors are destroyed using heat treatment such as extrusion. Further research is required to study the inclusion of dehulled and heat-treated chickpeas as a substitute of soybean meal in layers' feed where the diet formulation has taken into account the total digestible amino acids. However, based on the available data, a minimum of 20% chickpea can be safe to be included in the laying hen's diet with no adverse effects on egg production performance.

3.2.6 Chickpea in the pig diet

Numerous studies have reported that chickpeas are a valuable source of energy and protein for pigs and can be fed in various forms such as raw, dehulled, cooked or extruded.

Table 68 Nutritive value of chickpea for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max
Energy digestibility, growing pig	%	75.5	2.8	72.1	81.3
DE growing pig	MJ/kg DM	14.6	0.7	13.9	16.3
MEn growing pig	MJ/kg DM	13.9			
NE growing pig	MJ/kg DM	10.0			
Nitrogen digestibility, growing pig	%	79.4	3.1	74.7	83.5

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

In an old study by Visitpanich et al. (1985), feeding chickpeas (Desi and Kabuli types) in proportions of 186:0 g/kg (control) versus 46:263 and 46:272 g/kg, did not affect body weight gain and feed efficiency when compared to soybean meal. Batterham et al. (1993) studied the effects of Opal chickpea, dehulled Tyson chickpea or dehulled pigeon pea meals inclusion at 250, 500, and 750 g/kg compared to soybean meal on pig production performance. The trypsin inhibitor levels were analysed, and it was 0.2 mg/g in the corn-soybean meal diet, where it varied between 1 to 4.7 mg/g in the experimental diets. Diets were offered *ad libitum* for the 20–50 kg growing period. The growth performance of the pigs fed chickpea diets was similar to that of soybean meal. Organ weight was not affected by chickpea inclusion either. These results showed that chickpea can be included at up to 75% of the diet and that levels of trypsin inhibitor up to 4.7 mg/g are probably tolerable to the growing pigs.

In an experiment conducted by Christodoulou et al. (2006), the effect of partial and total replacement of soybean meal with extruded chickpeas, on pig growth and carcass characteristics, as well as on meat quality, was determined in a 17-week trial. Forty-eight growing-finishing pigs were allocated to four dietary treatments with 0, 100, 200 and 300 kg/t of extruded chickpeas . No effects of dietary treatments were reported, and pigs had a similar growth performance and final body weight. The replacement of SBM by extruded chickpeas caused a slight increase in moisture content of the muscle, although no differences were observed for protein, fat and ash contents of the same muscle.

The authors concluded that 300 g/kg of extruded chickpea can be included in the diet with no adverse effects on the production performance (Christodoulou et al. 2006a;). Mustafa et al. (2000), however, reported reduced growth performance in pigs fed 30% raw chickpea.. This might be due to a potentially higher concentration of antinutritional factors such trypsin inhibitor in the tested chickpea cultivar. As 30% extruded chickpea has been successfully used in the grow-finisher pigs' diet fully replacing soybean meal with no negative effects on final body weight and pork quality (Christodoulou et al. 2006). The true ileal digestibility of amino acids in chickpea is very close to that of soybean meal (Rubio 2005; Singh et al. 2005), and the ileal digestibility of starch has been reported to be 85% using cannulated Iberian pigs (Rubio et al. 2005).

Table 69 Standardised ileal digestibility of amino acids of chickpea in pigs

Indispensable amino acid	**Chickpea**
Arginine	79.5
Histidine	73.7
Isoleucine	61.1
Leucine	62.5
Lysine	71.1
Methionine	62.1
Met+Cys	-
Phenylalanine	62.1
Threonine	64.7
Tryptophan	72.6
Valine	62.5
Dispensable amino acid	
Alanine	63.2
Aspartic acid	66.2
Cysteine	47.9
Glutamic acid	71.1
Glycine	65.3
Proline	85.7
Serin	65.8
Tyrosine	70.8

(Source: Wang et al. 2017)

Extrusion offers a practical method for the heat processing of chickpeas to be used in pig diets. Heat treatment such as extrusion improves the utilisation of starch, fat and proteins in pigs. It seems that extruded chickpeas can be used as an alternative protein source to soybean meal at inclusion levels of up to 300 kg/t of diet with no detrimental effects on production performance.

3.2.7 Carbon footprint and sustainability of chickpea production

From a sustainability perspective, chickpea production is relatively sustainable, as there is less damage to air, water, land, soil, forests, etc., as long as fewer inputs have been used. The carbon footprint is reported to be as low as 0.64 kg CO_2eq to produce 1 kilogram of chickpeas (HEALabel 2022c).

As an indirect output, chickpea plays a vital role in reducing the carbon footprint when it is used as a rotational crop for wheat production. Research shows that durum wheat preceded by a pulse crop (chickpea, dry pea, or lentil-produced grain), with a carbon footprint of 0.200 – 0.45 kg CO_2eqkg−1 of product, is 28% lower than when preceded by a cereal crop. The carbon footprint of durum wheat is 19% less when grown after an oilseed crop (canola or mustard) (Gan et al. 2011).

A comparative study shows that the CO_2 emission and ecological carbon footprint were 173 kg CO_2−eq and 0.15 global hectares for lentils and 484 and 0.87 for chickpea production (Aghili Nategh et al. 2021). Other studies (Gan et al. 2011; Jaiswal & Agrawal 2020) also reported high ranking carbon footprint of canola, followed by mustard, flaxseed, spring wheat, chickpea, dry pea, and then lentil (Table 70).

Table 70 Average annual total emissions and estimated carbon footprint of chickpea compared to various field crops grown in Canada

Crop	Total emission, kg CO_2e ha^{-1}			Carbon footprint, kg CO_2e ha^{-1}		
	Brown	Dark brown	Black	Brown	Dark brown	Black
Canola	884	1326	1606	0.691	0.913	0.979
Flaxseed	446	826	829	0.456	0.658	0.727
Chickpea	283	362	N/A	0.254	0.406	N/A
Dry pea	352	602	711	0.189	0.287	0.335
Lentil	189	245	N/A	0.164	0.237	N/A
Spr. wheat	741	1145	1493	0.383	0.533	0.56
Means	484	717	1024	0.391	0.526	0.832

(Source: Gan et al. 2011)

3.3 Lupin

Lupinus, commonly known as lupin, lupine, or regionally, bluebonnet, is a genus of flowering plants (*Lupinus* L.) belonging to the family Fabaceae – fabaceous (leguminous), subfamily Genisteae. The genus comprises 200–300 species of which only five have been used as cultural plants (Boukid & Pasqualone 2022). They are widely cultivated, both as a food source and ornamental plant. The yield of 3,000 to 5,000 kg/ha seeds results in potential production of up to 2,000 kg/ha protein (Trejo et al. 2016).

The first three species of lupin (white lupine, blue lupine and yellow lupine) originated from the Mediterranean countries and are the most cultivated lupines. *Lupinus albus* L., which comes from southern Europe and South America, is widely used in the food industry compared to other species thanks to its whiteness. *Lupinus angustifolius* L. is cultivated in central and eastern Europe, Australia, and New Zealand, while *Lupinus luteus* L. is mainly cultivated in the Mediterranean region and has shallow soil requirements (having less than 50 cm depth of solum). Its cultivated accessions have variable seed yields in Mediterranean environments. On the other hand, Andean lupine (*Lupinus mutabilis* Sweet), also known as chocho or tarwi, is a native species domesticated by indigenous people of the Andean region of South America, where they use it as a food, in animal feed and as natural medicine (Gulisano et al. 2019). White and yellow lupin seeds provide higher protein than blue lupin seeds, which may be of importance when lupins are used to feed animals (Soya UK 2017). Yellow lupin (*Lupinus luteus*) is mostly grown as fodder or green manure.

Traditional lupin species are bitter because of their high alkaloid content (from 1 to 3% of alkaloids in the dry weight of their seeds). Lupanine is the main alkaloid along with other minor alkaloids such as albine, hydroxylupanine, sparteine, anagyrine, lupinine and angustifolin. The high content of quinolizidine alkaloids is associated with severe intoxication, e.g. trembling, shaking, excitation, and convulsion (Boukid & Pasqualone 2021). Yellow lupin is a very effective N-fixing legume, accumulating about 330 kg N/ha (Wolko et al. 2010) and it can be used for land reclamation (Pietrzykowski et al. 2017). Modern breeding programs has focused on selecting lupin varieties with low-alkaloid content to ensure the transition from the 'wild bitter' to 'cultivated sweet' lupin varieties (Gulisano et al. 2019).

At present, so called 'sweet' lupin variants are cultivated, in which the bitter substance content does not exceed 0.05%. A very low content of nutritive-active factors, low allergenicity and a positive impact on prevention of cardiovascular diseases (hypocholesterolaemic effects and anti-hypertensive activity) have been reported in these cultivars, which has led to their increased use in the food industry and animal feed (Boukid & Pasqualone 2022).

Lupin species could be a realistic sustainable alternative source of protein for animal feeding. Their seed protein content is high, and its quality is good; they offer potential health benefits, and they contribute to the sustainability of cropping systems. The high nutritional value of this plant is attributed to its amino acid profile which is close to the composition of animal proteins, and a high nutritional value of lipid fraction.

Lupin has been included among eight potential plant proteins for use in feed and food to replace proteins of animal origin in the diet (Romeo et al. 2018). Lupines also have pharmacological benefits by virtue of their alternative antibacterial and antifungal agency, and agronomic benefits through their contribution to defence against predatory herbivores and microorganisms (Yánez-Mendizábal and Falconí 2018).

3.3.1 Lupine production globally and in Australia

Lupin is an important global crop. Geographically, North America (United States and Canada) holds the largest share in export value followed by Australia, Spain, Canda, Italy, Netherlands, France, Romania, Germany and South Africa.

The world's biggest producer and exporter of lupin seed is Australia, whose production represents 80–85% of global production, of which 90–95% is exported. In 2005–2006 Australian production exceeded 1 million tons of low-alkaloid lupin, of which more than 300,000 tons were for own consumption and the rest was exported to the whole world, including Europe. Approximately 40% of the exported lupin seed is used as feed for dairy and meat-type cattle, 40% as feed for pigs, and the rest is equally distributed for the nutrition of sheep, goats and poultry. The Grain Industry Association of Western Australia (GIWA) estimated that 730,000 tonnes of lupins would be harvested during the 2021/22 season.

Western Australia (WA) accounts for more than 72% of global lupin production. Having such an abundant protein source available in WA for pig producers is beneficial in reducing the cost of feeding (which usually represents more than 65% of the total production cost for pig meat).

The major lupin crop in Australia is *L. Angustifolius*, or the Australian Sweet Lupin. The smaller crop of Australian Albus Lupin (*L. albus*) is also grown and exported. Lupins are grown in large regions of WA and across the south-eastern grain belt, where the soil type is predominantly infertile, sandy and acidic. Australian Sweet Lupin is particularly well adapted to this soil type, where all other pulses, including *L. albus* require more fertile soil types.

Production in Australia focusses on high protein, low alkaloid (bitterness) and improved dehulling efficiency. *Angustifolius* is recognised as a valuable stockfeed and aquaculture feed source, however, it is now finding its way into human foods because of its nutritional value, health benefits and growing consumer acceptance.

Angustifolius exports go to Korea, Japan, the Netherlands and Spain. Australia is the largest supplier of quality, large-seeded Albus lupin to the Middle East. Lupin makes an attractive alternative to dry beans and soybeans for human consumption because the protein and oil are easily digested, and seeds have a high dietary fibre content. Lupins can be flaked, ground for flour, split and fermented, used as a snack base, or in the production of protein concentrates or fermented sauces. Lupin flour is used in breads, biscuits and pasta, and lupins can also be sprouted for consumption. Albus lupins have the potential for processing and use in making near-white vegetable-based products because they have low yellow pigment content.

3.3.2 General characteristics

The seeds of common sweet lupine species (*L. albus, L. angustifolius, L. luteus*) contain 28 to 48% crude protein in dry matter, depending on the species and climatic conditions (Písaříková & Zralý 2009). Genetic and environmental effects determine variability in protein content. Lupin seed is notable for its high fibre and little starch content. Lupin has on average 16% fibre, with 23.9% NDF, 19.1% ADF and about 3.5% ash. Although lupine seed contains low levels of starch (on average 4.8% including 5.8% total sugar), values in the range 1.8% to 10.1% have been mentioned in the literature (Villacrés et al. 2020). Lupin seeds contain more dietetically beneficial crude fibre compared to other leguminous plants. The complex carbohydrates are stored in a thickened cell wall of kernel weight, mostly as pectin-like material (little cellulose/hemicellulose). Lupin fibre can substantially reduce cholesterol levels and improve bowel function while reducing the intestinal transit time, which is

attributed to its fibre fractions. Lupin seeds contain significant levels of oligosaccharides of the raffinose family – α-galactosides, especially raffinose, stachyose, verbascose and ajugose.

Table 71 Chemical composition of blue lupin (*Lupinus angustifolius*) seeds

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	90.2	1.9	82.6	95.7
Crude protein	% DM	33.7	2.9	26.5	44.5
Crude fibre	% DM	16.1	2	10.9	22.2
Ether extract	% DM	6	0.8	4.1	7.7
Ash	% DM	3.5	0.5	2.1	4.5
Insoluble ash	% DM	0.2		0.07	0.5
Neutral detergent fibre	% DM	23.9	3.9	15.8	38.3
Acid detergent fibre	% DM	19.1	2.8	14.8	26.1
Lignin	% DM	1.2	0.7	0.1	2.3
Starch (polarimetry)	% DM	4.8	5.5	0	15.9
Total sugars	% DM	5.8	1.5	4.5	8.8
Gross energy	MJ/kg DM	20.3	0.8	17.9	20.8

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

White lupin seeds contain 7 to 14% α-galactosides, whereas in the seeds of other lupin species levels can reach up to 20%. The most abundant oligosaccharide is stachyose (2.8%), followed by saccharose (1.8%), raffinose (0.4%), and verbascose (0.3%). Verbascose plus stachyose (3.1%) content is lower than the literature reports for soybeans (4.6%) (Ritter et al. 2022). The results indicate that different cultivation and harvest conditions in particular years can affect the oligosaccharide content of seeds of the same variety.

The fact that α-galactosides are to a large extent fermented in the colon can cause flatulence as well as insufficient net energy uptake from lupin seeds, despite their high gross and digestible energy value. The net energy of soybean meal is equal to 52% of its gross energy content, whereas only 43% of the gross energy in the narrow-leaved lupin is net energy. The high digestibility of lupine nutrients in the entire digestive tract, which is the basis for calculating the energy value of feeds for pigs, may lead to overestimation of the energy value of lupin, especially for younger animals. This problem is more important with respect to yellow lupin, which in comparison with white or narrow-leaved lupin seeds, contains more seed hulls and α-galactosides (Zaworska-Zakrzewska et al. 2019).

Písaříková et al. (2008) found the following levels in the seeds of cultivated lupines: crude protein from 336.9 to 435.7, lysine from 16.4 to 22.6, methionine from 2.6 to 5.0, and threonine from 11.6 to 15.8 g/kg DM. Dehulling resulted in an increase of protein and amino acid levels of approximately 13%. In *Lupineus* species, the sum of amino acids is about 90% of the value of N × 6.25. The profile of lupines amino acids is characterised by low levels of methionine (~ 0.2% of the seed, 0.66% protein), cysteine (~ 0.4% of the seed, 1.36% protein) and lysine (1.46% of the seed, 4.75% protein). The threonine level of 1.15% and tryptophane content with 2.76 g/kg is low compared to soybean meal (Boukid & Pasqualone 2021). In contrast, lupines arginine content is markedly higher (31.0 to 48.0 g/kg). The highest level of amino acids within the crude protein is found in white lupine, characterised by a high essential amino acid index (EAAI: 85%; the chemical score (CS): about 60.2%) of essential amino acids; and a high protein efficiency ratio (Kotelnytska et al. 2021).

Table 72 Amino acid profile of blue lupin (*Lupinus angustifolius*) seeds

Amino acids	Unit	Avg	SD	Min	Max
Lysine	% Protein	5	0.4	4	5.6
Threonine	% Protein	3.9	0.3	3.1	4.3
Methionine	% Protein	0.9	0.1	0.4	1
Cystine	% Protein	1.8	0.2	1	1.9
Methionine+cystine	% Protein	2.6	0.4	1.4	3
Tryptophan	% Protein	0.7			
Isoleucine	% Protein	4.7	0.3	3.6	4.8
Valine	% Protein	4.4			
Leucine	% Protein	7.4	0.4	6	7.8
Phenylalanine	% Protein	3.9	0.3	3.1	4.7
Tyrosine	% Protein	4.6			
Phenylalanine+tyrosine	% Protein	8.5			
Histidine	% Protein	2.3			
Arginine	% Protein	10	0.8	9.5	12.3
Alanine	% Protein	3.5	0.2	3.1	4
Aspartic acid	% Protein	10.6	0.6	9.2	11.3
Glutamic acid	% Protein	20.4	2	17.6	25
Glycine	% Protein	4.1	0.1	3.9	4.4
Serine	% Protein	5.4	0.6	3.7	6.2
Proline	% Protein	4.2	0.4	3.2	4.7

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

It is reported that lupin (*Lupinus albus* L.) proteins can decrease blood glucose and improve insulin sensitivity through the inhibition of dipeptidyl peptidase IV enzymatic activity in diabetic and insulin resistance-induced rats (Wiedemann et al. 2015). They have also exhibited cholesterol-lowering effects. Protein hydrolysates of lupin have efficiently reduced plasma total, very-low-density lipoproteins (VLDL) and low-density lipoproteins (LDL) cholesterol concentrations in human cells (Sirtori et al. 2004).

Table 73 Mineral composition of blue lupin (*Lupinus angustifolius*) seeds

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	2.8	0.8	1.9	4.2
Phosphorus	g/kg DM	3.8	1.1	2.7	6.7
Magnesium	g/kg DM	2.1	0.5	1.8	3.2
Potassium	g/kg DM	10.1	2.1	7.5	13
Sodium	g/kg DM	0.5	0.29	0.2	1
Sulfur	g/kg DM	2.5			
Manganese	mg/kg DM	44	14	27	70
Zinc	mg/kg DM	34		30	72
Copper	mg/kg DM	5		3	13
Iron	mg/kg DM	68	31	50	124

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The anti-oxidation properties of lupin proteins are gaining interest due to the increasing focus on finding novel antioxidant compounds for protecting against oxidative stress and reducing the impact of various chronic diseases (Guo et al. 2018).

The higher angiotensin converting enzyme inhibitory activities of lupine protein have been reported in earlier studies (Cruz-Chamorro et al. 2019). The presence of potassium, phosphorus, calcium, magnesium and a low level of sodium is confirmed for the macrominerals of lupin. The manganese content of the seeds is relatively high, ranging from 0.44 to 1.45 g/kg (Zaworska-Zakrzewska et al. 2019). A manganese level of 896 mg/kg has been found in *L. albus*., which approaches the toxicity concentrations for some monogastric species (Andrianova et al. 2019). The following levels of minerals were found in the dry matter of lupines cultivated in Europe: calcium 2.10 to 4.66, phosphorus 4.29 to 7.20, magnesium 1.20 to 2.25 g/kg, potassium 8.6 to 11.1 and sodium 0.1 to 0.2 g/kg (Bebeli et al. 2020).

The reported vitamin levels in mg/kg in Australian lupines are as follows: β-carotene 3.5, thiamine 5.3, riboflavin 2.8, biotin 0.04, folic acid 0.4, choline 3035, niacin 36, pantothenic acid 1.6 and α-tocopherol 2.2. Australian lupins also have a high level of α-tocopherol, at up to 4.2–4.6 mg/kg (Mazumder et al. 2021).

3.3.3 Nutritive value for animal feed

Among the grain legumes, the lupin species seems to be a realistic sustainable alternative source of protein for both monogastric and ruminant feed that can replace soybean without loss in the quantity or quality of livestock products. Nevertheless, the nutritional value of lupin varies greatly among varieties, and breeding efforts have so far been limited, indicating great potential for further improvement (Sedláková et al. 2016).

The use of lupins in livestock farming systems as concentrate (whole seeds, ground seeds or other processed seeds) (Sedláková et al. 2016) or as forage (whole-crop, silage or hay) (Borreani et al. 2009) for both ruminants and monogastrics has many advantages. Beyond their nutritional value, lupins are characterised by high grain productivity (Chiofalo et al. 2012), adaptability to poor and barren soils, fewer requirements than other crops, and finally, are an excellent rotation crop (Fumagalli et al. 2014). Furthermore, White and Staines (2007) suggested that dairy farmers in Australia prefer to use lupins as a supplementary feed source because they are generally cheaper than oilseed proteins, and they are easy to store and handle, thanks to the domestic production.

In ruminants, milk production as well as milk fat and protein increased by the use of lupins instead of cereal grains and soybean. The use of lupins improved the fatty acid profile of milk in relation to human health (White & Staines 2007). Lambs were fed either a proprietary commercial lamb finisher pelleted ration or a feed mix consisting of lupins (27%) with crimped barley (70.5%) and minerals (2.5%). The lupin/barley feed delivered similar levels of protein but with higher energy content than the commercial finisher diet. This was calculated to equate to a cost saving of 19% over the commercial finisher (Almeida et al. 2021).

A feed trial introducing yellow and narrow-leaved lupins into the poultry diet showed no detrimental effects to bird performance or egg quality. No adverse effect was observed for growth or body weight, feed or water intake, egg production (number or weight), or health status. In addition, yolk colour was shown to increase significantly with a diet of either lupin species, which could be argued as a benefit in terms of egg production. Overall, this research has shown that by replacing soybean with lupins in the diet, equivalent performance in terms of egg production and weight gain could be obtained from

slightly lower feed intakes, indicating the potential for enhanced economic gains with this choice of raw ingredients (Kubiś et al. 2018).

Poultry in general appear to be less sensitive to antinutritional factors in lupins than pigs. Studies testing added lupin levels in broiler feeds show reductions in efficiency above 20% inclusion, while adult laying hens are less affected by higher levels of lupin in the feed. No deleterious effects on egg interior quality have been noted in feeding lupins. Using lupins at a 10–15% inclusion rate as an alternative source of protein has been reported to reduce cost in broiler production with no negative impact on efficiency, particularly if appropriate digestibility coefficients are used for amino acids and energy, and exogenous feed enzymes such as NSPs are included to reduce the effects of non-starch polysaccharides on gut function in poultry (Tufarelli et al. 2018).

Lupin usage should be minimised for piglets, while older pigs can be fed 10% lupin without any concerns, provided the alkaloid level is low, and nutrient digestibility is taken into account. Pigs can be sensitive to alkaloid levels, and sweet lupin alkaloid levels should be under 0.04%. Feed enzymes aimed at NSPs, and cellulose will improve energy digestibility, intestinal health and performance (Tuśnio et al. 2020).

3.3.4 Antinutritional factors – nutritional limitations

Main antinutritional factors in sweet lupine are raffinose family oligosaccharides (as the main non-starch polysaccharides), phytic acid and polyphenols. Lupin contains low amount of lectins and trypsin inhibitors compared to other legumes such as cowpea, kidney bean and soybean (Palander et al. 2006). Non-starch polysaccharides are polymers of galactose, arabinose and uronic acid; they are an excellent source of food fibre with high water binding capacity (up to eight-fold volume). These properties affect the utilisation of energy and contribute to the reduction of feed intake and digestibility, mainly in monogastrics. The high level of readily fermentable non-starch polysaccharides in lupines significantly affects the way livestock derive energy from this legume. In single-stomached animals, the energy in monosaccharides absorbed from the small intestine is utilised differently from volatile fatty acids derived from the fermentation taking place in the hindgut.

The typical alkaloid profile in Australian lupines is lupanin 42-59%, 13-hydroxylupanin 24–45%, angustifolin 7–15%, α-isolupanin 1–1.5%, and traces of other alkaloids. Trypsin inhibitor activity is less than 0.3 mg/kg and chymotrypsin inhibitor activity is less than 0.6 mg/kg. The tannins are concentrated in the seed coats (hulls), so dehulling will minimise any adverse effects. However, the concentration of condensed tannins is so low in lupines (~ 0.01%) that it is unlikely to impair protein utilisation by any animal species (Petterson 2000).

Some lupins contain secondary compounds, including isoflavones and toxic alkaloids such as lupinine and sparteine. With early detection, these can be removed through processing, although the presence of these elements means that seeds are not selected for food-grade products.

Lupine allergy has been observed in 15–20% of individuals who already have peanut allergy (Lima-Cabello et al. 2019). Most lupin reactions reported have been in people with peanut allergy. Lupin seeds, particularly in flour form, should be treated as a factor which can trigger off an allergic reaction by inhalation, and which additionally can result in the development of occupational asthma and food allergy. Lupin sensitivity is an emerging food allergy, more prevalent in Mediterranean countries and Australia, where lupin is more consumed, and less in North America and Northern Europe (Sanz et al. 2010).

The proportion of antinutritive substances in newly selected sweet lupin varieties is markedly less than in bitter lupin varieties, and hence these varieties can safely be fed to livestock animals (Aniszewski et al. 2001; Ciesiolka et al. 2005).

3.3.5 Lupin in the laying hen diet

Nutritional value and suitability of lupins depend on the variety (sweet or bitter, yellow, blue or white), nutrient profile and fibre composition, antinutritional factors, processing such as heat treatments (Jeroch et al. 2016). The high protein content, amino acids and fatty acids profile of lupins provide a valuable source of energy and protein for birds. The inclusion of lupins in practical feed formulations depends on regional availability, volume of production and consistent availability throughout the year. In order to maintain the optimum production performance of poultry, metabolisable energy value as well as amino acid standardised ileal digestibility coefficients should be taken into account in feed formulation. A cost-effective method of removing antinutritional factors such as alkaloids, oligosaccharides, etc., needs to be introduced and practised.

The metabolisable energy content of lupins varies between 8.3 and 10 MJ/kg DM, depending on the variety and the cultivar; lower values are observed when seeds contain a high concentration of oligosaccharides, mainly raffinose (Kaczmarek et al. 2016). The protein content is between 28 and 40% DM, with large variations depending on the variety. White lupin (*Lupinus albus*) varieties have lower protein than yellow lupin (*Lupinus luteus*) (Sujak et al. 2006). The amino acid profile also varies according to the family or cultivar.

Table 74 Standardised ileal digestibility of amino acids of lupins in laying hens

Indispensable amino acid	**Lupins**
Arginine	96
Histidine	90
Isoleucine	91
Leucine	93
Lysine	90
Methionine	88
Met+Cys	-
Phenylalanine	93
Threonine	89
Tryptophan	-
Valine	89
Dispensable amino acid	
Alanine	85
Aspartic acid	91
Cysteine	92
Glutamic acid	95
Glycine	-
Proline	93
Serin	90
Tyrosine	92

(Source: Zuber et al. 2019)

As laying hens can't digest fibre or non-starch polysaccharides, dehulling of lupins improves their nutritive value for poultry. It has been reported that after dehulling, the non-starch polysaccharide content is reduced, the metabolisable energy value and, in some cases, the amino acid digestibility is

improved (Brenes et al. 1993; Nalle et al. 2010). Breeding during the last years has resulted in much lower alkaloid content in sweet lupin. The non-starch polysaccharides including oligosaccharides are considered the main antinutritional factor in lupins for laying hens if the diets are well balanced for energy, amino acids (methionine supply) and minerals, and when sweet varieties are used. The high content of oligosaccharides increases digesta viscosity, reduces digestibility by its encapsulating effects, generates sticky droppings, and consequently reduces performance. However, it is important to note that small quantities of oligosaccharides support prebiotic effects and support beneficial bacterial colonisation in the hindgut (Zduńczyk et al. 2014).

Dietary inclusion of lupins at 30%, has negatively impacted metabolisable energy and amino acid digestibility, which is attributed to the non-starch polysaccharides content especially raffinose concentration and its effect on increasing digesta viscosity (Kaczmarek et al. 2016). The addition of exogenous NSP enzymes has been reported to improve the digestibility of nutrients when lupin has been included at +50% (Brenes et al. 1993).

Blue lupins have lower protein and metabolisable energy compared to soybean meal, and higher antinutritional factors, therefore they can only partially replace soybean meal, and inclusion rates of 15% have been reported to be safe with no detrimental effects on egg production (Rubio et al. 2003; Hammershoj & Steenfeldt 2005; Lee et al. 2016), however, lupin inclusion in the study of Hammershoj and Steenfeldt (2005) has resulted in reduced live weight gain.

In a study by Drazbo et al. (2014), soybean meal was replaced at 10 or 20% by blue lupins and the egg laying performance, the fatty acid profile, physicochemical and sensory properties of eggs were studied for a period of 20 weeks. The inclusion of blue lupins in the diet as a substitute for soybean increased dietary fibre content (both ADF and NDF) and raffinose oligosaccharides, reduced feed intake of layers, however, did not impair egg production rate. Blue lupin inclusion improved eggshell weight as a percentage of total egg weight, and eggshell breaking strength, however, reduced albumen quality such as albumen height and Haugh units. Yolk fatty acids were enriched with linolenic and linoleic acid and polyunsaturated fatty acids when hens were fed blue lupins. The authors concluded that inclusion of blue lupin at 20% as a substitute for soybean meal not only doesn't have any negative effects on egg production performance but also improves egg quality and the fatty acid profile of egg yolk.

In another study by Lee et al. (2016), blue lupins replaced soybean meal at a 15% inclusion rate and were tested in 3 experimental diets with whole lupin seeds, dehulled lupin seeds, and dehulled lupin seeds plus enzyme supplementation. Experimental diets were fed to laying hens at the start of lay (16 weeks of age), formulated to be balanced for energy, crude protein and essential amino acids using near-infrared reflectance spectroscopy (NIRS). The inclusion of blue lupin as whole or dehulled, with or without enzyme addition, did not affect the growth rate, final hen weight, feed and water intake, eggs per day, mean egg weight, yellowness of yolk or chroma. The authors concluded that replacing soybean meal with 15% blue lupins in the diet of laying hens has no adverse effects on production or hen health and could be used as part of a balanced ration with inclusion of NSP degrading enzymes to reduce reliance on soya protein.

Data on inclusion of yellow lupin in laying hens' feed are scarce. One study where soybean meal was replaced at graded levels of 10, 20, and 30% with yellow lupin seeds, no adverse effect on laying performance, feed intake, feed conversion ratio, egg production, and egg weight have been observed. It has been reported that yellow lupin could be included in balanced diets at up to 30% without any negative effect on laying performance and egg quality. Yolk colour and fatty acid profile were improved (Krawczyk et al. 2015).

Based on the available data, it seems that dehulled and heat processed lupin seeds may replace soybean meal fully in laying hens' diet (25% of the diet), especially with properly formulated balanced diets using digestible amino acids and updated energy values. More research is required to test and confirm the available data.

3.3.6 Lupin in the pig diet

Dry matter and crude protein digestibility of yellow lupin has been reported at 91 and 90% (Roth-Maier et al. 1993); the digestibility of crude fibre, hemicellulose and NDF were 86, 88, and 87%, respectively (Just et al. 1983). These values are in accordance with the reported 85% crude fibre digestibility observed in earlier studies (Vosloo 1960). Metabolisable energy content were reported at 13.8 and 14.3 MJ/kg DM (Roth-Maier et al. 1993).

In pigs, yellow lupin has been reported to have a better nutritional value than white and blue lupin due to its higher protein and amino acid content, and lower fibre content (Shea et al. 1996). Yellow lupin seeds have been assessed as an alternative protein source to replace soybean meal in various experiments (Kim et al. 2008). The energy digestibility of blue lupin seeds in growing pigs and sows, are 77 and 85%, respectively, for whole seeds, and 81 and 89% for seed kernels.

Table 75 Nutritive value of yellow lupin seeds for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max
DE growing pig	MJ/kg DM	15.6	-	-	-
MEn growing pig	MJ/kg DM	14.4	-	-	-
NE growing pig	MJ/kg DM	9	-	-	-
Energy digestibility, growing pig	%	76	-	-	-
Nitrogen digestibility, growing pig	%	83	-	-	-

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Data concerning the utilisation of lupine in pig nutrition are ambiguous. Some old studies have reported that feeding diets containing 150 to 430 g/kg of lupin seeds to pigs reduced live weight gains (Batterham 1992; Roth-Maier & Kirchgessner, 1993; Zettl et al. 1995). Van Nevel et al. (2000) also documented decreased nutrient conversion and growth depression in pigs receiving diets containing 30% of white lupine. The supplementation of dehulled seeds and amino acids in pig diets failed to increase the feed efficiency of pigs (King et al. 2000). On the contrary, no growth depression was found by Gdala et al. (1996) in pigs fed a diet containing lupine seed (410 g/kg diet) versus a diet based on barley and soybean meal.

The high digestibility of blue lupins results in high digestible energy for growing pigs (with 15.7 and 16.8 MJ/kg DM for whole seeds and seed kernels, respectively). For sows, digestible energy was reported to be higher at 17.3 and 18.6 MJ/kg DM, respectively. These results were confirmed in growing pigs, with reported values of 15.8 and 16.85 MJ/kg DM digestible energy contents for blue lupin seeds and kernels (King et al. 2000).

The inclusion of lupins in newly weaned piglets (BW ~ 6 kg) should be limited to levels of up to 15%. Kim et al. (2012) has reported that inclusion of lupin at above 18% impaired growth performance, increased faecal haemolytic *E. coli* and plasma urea nitrogen. Piglets had lower total tract dry matter digestibility compared to piglets fed the control diet (Kim et al. 2012).

Table 76 Standardised ileal digestibility of amino acids of lupins in pigs

Indispensable amino acid	Lupins
Arginine	94.9
Histidine	91.4
Isoleucine	90.5
Leucine	90.9
Lysine	88.4
Methionine	89.9
Met+Cys	-
Phenylalanine	90.4
Threonine	90.4
Tryptophan	-
Valine	71.4
Dispensable amino acid	
Alanine	86.7
Aspartic acid	91.5
Cysteine	82.2
Glutamic acid	92.3
Glycine	92.2
Proline	102.0
Serin	91.1
Tyrosine	86.8

(Source: Mariscal-Landín et al. 2002)

The inclusion of lupin seeds at a 35% inclusion rate had no effect on animal growth performance and did not affect carcass composition or meat quality. Enzyme supplementation was not necessary as it did not improve overall performance or quality (Kim et al. 2011).

In a study by Kasprowicz-Potocka et al. (2013), replacing 50% or 75% soybean meal by raw or germinated yellow and blue lupin seeds did not significantly affect performance, but the higher level of germinated blue lupin seeds negatively affected feed intake by the pigs (Kasprowicz-Potocka et al. 2013). Grow-finisher pigs at a body weight from 20 to 105 kg could be fed on raw blue lupin seeds that totally replaced soybean meal without altering growth performance (Kasprowicz-Potocka et al. 2016).

Zaworska et al. (2017) studied the effects of fermentation on the apparent ileal digestibility of crude protein and amino acids in growing pigs, compared with raw lupin seeds. The fermentation process has increased the crude protein, fibre, fat, ash and most of the analysed amino acids content (including methionine, cysteine, isoleucine, leucine, phenylalanine and valine) but has reduced the levels of the nitrogen-free extract (NFE contains sugars). Furthermore, the contents of raffinose family oligosaccharides and phytic acids have been reduced by fermentation, but the alkaloid content has increased. They have concluded that fermentation is an effective method to modify the chemical composition of raw ingredients such as lupins and improve digestibility of nutrients.

Hanczakowska et al. (2017) studied the possibility of replacing soybean meal in sow, piglet and grow-finisher pig feed with high and low alkaloid varieties of two species of lupines. Except for the high alkaloid variety of lupin, feeding grow-finisher pigs with lupins had no detrimental effects on weight gain, however, meat quality was affected, and the polyunsaturated fatty acid content of meat was poorer compared to the control.

Pruszyńska-Oszmałek and Frankiewicz (2020) conducted a 28-day experiment investigating the use of raw or fermented lupine seeds to replace 50% of soybean meal in male pigs. Fermentation improved the chemical composition of seeds, but did not affect pigs' performance, metabolic, microbial and

most intestinal morphology, but influenced crypt depth, concentrations of short chain fatty acids and p-cresole in the proximal colon segment and significantly lowered the pH of the middle colon digesta and its ammonia contents.

To sum up, it seems that low alkaloid varieties of blue lupins can replace soybean meal fully in grow-finisher and fattening pigs if diet formulation take into account the amino acid ileal digestibility coefficients and balances the diet with crystalline amino acids. The inclusion of high-alkaloid lupins as well as the use of lupin in weaned piglets must be restricted. Additional research is required to study the effects of other processing methods such as extrusion on the nutritive value of blue lupins for fattening pigs.

3.3.7 Carbon footprint and sustainability of lupin production

Very few studies have looked at the environmental impact of lupin production specifically. However, there are studies where the carbon footprint has been measured under a mixed farming system. Eady et al. (2012) showed that amongst the crops, carbon emissions for cereal grains averaged 0.202 kg CO_2-eq/kg grain, canola 0.222 kg CO_2-eq/kg, and lupins 0.510 kg CO_2-eq/kg. The higher emissions linked to lupins mainly came from the lower yields per hectare for this crop and the direct N_2O discharges from legume crop deposits rather than additional input fertiliser (N). The carbon footprint for lupins modelled in separation was 0.726 kg CO_2-eq/kg, whereas it fell to 0.510 kg CO_2-eq/kg when the mixed farming system was used (Eady et al. 2012). In a recent study, the crop cultivation, transportation, and processing stages have been considered to calculate the environmental impact. It was found that traditional fractionation caused the highest impact on GWP (5.78 kg CO_2eq/kg of protein for lupine). Dry fractionation leads to the lowest impact on GWP: 1.3 kg CO_2eq/kg protein for lupine (Cellura et al. 2022).

3.4 Peas

Peas were among the first cultivated crops, from around 7000-6000 BC, and are thought to have originated from South-Western Asia (possibly North-Western India, Pakistan, Afghanistan and Central Asia) then spread westwards to Russia, Europe and the Mediterranean Basin but also eastwards to China (Powers & Thavarajah 2019). Peas prefer relatively cool climates with average temperatures of between 7 and 24°C, and 800–1000 mm annual rainfall, preferably distributed during the early stages of growth. Peas require only 60 days to reach bloom stage, and 100 days to mature and dry (Messiaen et al. 2006).

Peas (usually *Pisum sativum* L.) are one of the four most important legume crops next to soybean, groundnut and beans, particularly in temperate areas with numerous food (dry seed, vegetable) and feed (seed, fodder) usages. Pulses are defined by the FAO as legumes harvested solely for their seed, which is consumed directly. The FAO list includes eleven primary pulses, including peas, and excludes the oilseed legumes and those consumed in immature form as vegetables (FAO 2011).

There are winter and spring varieties, leafy and leafless, and early- or late-maturing pea crops. Seeds can be green, yellow or pale green, brown or mottled, thin- or thick-hulled, smooth or wrinkled, of varying shape and size. Some varieties are tannin-free, and pea breeding offers a large opportunity to improve the nutritional characteristics of the grain (Kosev et al. 2010).

Peas (*Pisum sativum*), more specifically the yellow or green cotyledon varieties known as dry, smooth or field peas, are grown globally for human and animal consumption with a large genetic diversity and breeding programmes, which have generated many varieties classified as garden peas.

Field pea is a critical economic and nutritive crop due to its high protein, vitamin and mineral, and prebiotic carbohydrate content (oligosaccharides, non-starch polysaccharides, and low price) (Amarakoon et al. 2012). The high nutrient density of field peas makes them a valuable food commodity, capable of meeting the dietary needs of the estimated 800–900 million undernourished individuals worldwide. In recent years, many studies have identified the potential health benefits of pulses, including peas, beyond meeting basic nutrient requirements (Powers & Thavarajah 2019).

In addition, field pea is naturally rich in iron and zinc and thus can address two of the most common micronutrient deficiencies in the world. Despite the potential for higher consumption of field pea to help alleviate hidden hunger, little advancement has been made to increase its production, and therefore its total yields have lagged behind those of cereals (Amarakoon et al. 2012). One of the main issues with field pea, and legumes in general, is that they require much more phosphorous input than other crops due to their nodules needing it for energy transformation (Vance et al. 2003); this presents an issue for sustainable agriculture.

3.4.1 Pea production globally and in Australia

The increasing world population, mainly in the developing regions, is continuously driving consumption demand for dry peas, which also acts as a major driving force behind pea production and the market. Dry peas are ranked fourth in terms of the world production of legumes, below soybeans, peanuts and dry beans. Yellow peas and green peas are commercially grown varieties, with yellow peas dominating global production (Liu et al. 2017).

Dry pea production has been quite variable over the years, primarily due to changes in the former Soviet Union, where output rose significantly through the 1980s and then dropped back in the 1990s.

Total world pea production rose from 7.3 million tonnes in 1961 to 9.8 million tonnes in 2008. In 2019, the production of green peas in China amounted to approximately 13.4 million tonnes. In comparison, the production of green peas in Hong Kong was approximately 416 tons in 2019. Today, the top producer of green peas – by far – is China with 12.2 million tonnes, followed by India (4.8 million tonnes), the US (0.31 million tonnes), France (0.23 million tonnes) and Egypt (0.15 million tonnes). United Kingdom, Pakistan, Algeria, Peru and Turkey complete the top 10. Global pea production is projected to register a 4.3% increase during the forecast period (2021–2026).

Field pea is grown as a winter crop in Australia, which produces mostly dun-type field pea (including 'Kaspa' types), with some minor production of blue and white types. The crop is sown in late autumn to mid (late) winter and harvested in spring.

Peas, like potatoes, are grown almost everywhere in Australia; however, the majority of production occurs in Victoria and South Australia, although it has recently expanded considerably in Western Australia as a result of improved varieties and production technology. More than 90% of the field pea grown in Western Australia is the Kaspa dun-type, with the majority of the grain exported to the Indian sub-continent for food. In 2020, approximately 29,000 tonnes of peas were produced in Australia, valued at AUD $59 million dollars, and 80% of the total production amount was sent for processing.

3.4.2 General characteristics

Peas are a valuable source of protein for both human and animals. Environmental conditions and genetic factors may influence the protein content of peas. Their protein content ranges between 16 and 32% DM with an average value of 24%, which is intermediate between cereals and oil meals (Powers & Thavarajah 2019).

Table 77 Chemical composition of pea seeds

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	86.5	1.2	82.0	90.7
Crude protein	% DM	23.9	1.4	19.0	28.5
Crude fibre	% DM	6.0	0.7	3.7	8.5
NDF	% DM	14.2	3.1	9.1	22.0
ADF	% DM	7.0	0.7	5.6	8.8
Lignin	% DM	0.4	0.2	0.1	1.1
Ether extract	% DM	1.2	0.3	0.7	2.2
Ash	% DM	3.5	0.4	2.7	4.9
Starch (polarimetry)	% DM	51.3	2.0	43.4	57.5
Total sugars	% DM	4.9	0.6	3.6	6.2
Gross energy	MJ/kg DM	18.3	0.1	18.2	18.8

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Energy levels are similar to those of corn for most livestock species with starch (52%) and digestible fibre (hemicellulose fraction) (7%) accounting for most of this. Fat is a modest contributor at 1.2–1.6%. Starch and fibre are major components of peas, 52 and 6% of seed DM, respectively, on average (Pietrasik et al. 2020). Starch is composed of amylose and amylopectin. The ratio of amylose to amylopectin influences the digestibility of starch. Pea starch, like that of most other starchy pulses, contains an intermediate level of amylose, reflected in its unique functionality and its higher levels of enzyme-resistant starch and slowly digestible starch (as compared with cereal, root and tuber starches, most of which are lower in amylose). The relatively low degree of digestibility of starch in

pulses has also been attributed to starch granule nonavailability to amylases enclosed in intact cell wall structures, the presence of anti-nutrients such as amylase inhibitors, phytates and phenolic compounds, and their significant dietary fibre content. The variety, processing method and analytical methodology all affect starch digestibility, specifically, the levels of resistant starch, in peas and other pulses.

Table 78 Amino acid profile of pea seeds

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	4.5	0.2	4.0	5.1
Arginine	% protein	8.4	0.5	7.3	9.7
Aspartic acid	% protein	11.6	0.3	10.8	12.3
Cystine	% protein	1.4	0.1	1.2	1.7
Glutamic acid	% protein	17.0	0.8	15.4	18.7
Glycine	% protein	4.4	0.2	4.0	4.7
Histidine	% protein	2.5	0.1	2.3	2.7
Isoleucine	% protein	4.2	0.2	3.7	4.6
Leucine	% protein	7.1	0.2	6.5	7.5
Lysine	% protein	7.2	0.3	6.7	7.8
Methionine	% protein	1.0	0.1	0.8	1.2
Phenylalanine	% protein	4.7	0.2	4.4	5.0
Proline	% protein	4.2	0.2	3.7	4.5
Serine	% protein	4.7	0.2	4.3	5.1
Threonine	% protein	3.8	0.2	3.5	4.2
Tryptophan	% protein	0.9	0.0	0.8	1.0
Tyrosine	% protein	3.1	0.2	2.6	3.6
Valine	% protein	4.8	0.3	4.2	5.2

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The balance of essential amino acids in peas is great, although sulphur-containing amino acids (methionine and cystine) content is relatively low (Millar et al. 2019). On average, lysine is about 7% of the protein and methionine 1% of the protein. Peas have considerable amount of glutamic acid (17% of protein) and aspartic acid (11.6% of protein). The seed coat contains largely water-insoluble polysaccharides, primarily cellulose, whereas the cotyledon fibre consists of polysaccharides having various degrees of solubility, including hemicelluloses and pectins, along with cellulose. Peas, like other legumes, contain significant concentrations of raffinose-family and other galactose-containing oligosaccharides which may exert prebiotic effects in the large intestine if intake is not too high (Ramirez et al. 2021).

In terms of chemical and physico-chemical characteristics, the majority of pea proteins are storage proteins, or globulins, and the amino acid profile of these determines their nutritional value (Wójcik et al. 2021). The amino acid profiles of all products are similar overall, with the greatest contributions from glutamine, followed by aspartic acid, arginine and lysine, and the lowest contributions from methionine, tryptophan and cysteine. Products from peas tend to be higher in arginine, valine and methionine, and lower in glutamic acid and cysteine, than those from lupin and soybeans. Relative to human requirements, the protein in peas and other pulses is rich in lysine and marginal or deficient in methionine (Millar et al. 2019).

Of the concentrations of macrominerals in four pea samples, potassium (1.13% of dry, dehulled weight) was found to be the most prominent element, followed by phosphorous (0.45%), Mg (0.17%) and Ca (0.12%). The pea samples contain an average of 107 mg/kg DM Fe, 42 mg/kg DM Se, 37 mg/kg DM Zn, 12 mg/kg DM Mo, 11 mg/kg DM Mn, 8 mg/kg DM Cu. The yellow peas from Canada contained higher levels of Fe, Mg and Mn, but lower levels of K, compared with green peas (Princwill-Ogbonna et al. 2019).

Despite the high mineral content of peas, bioavailability may be poor due to high phytate concentrations. Phytate acts as an inhibitor of Zn, Fe and Ca absorption. It is also reported that peas have greater *in vitro* Ca bioavailability compared with other pulses (Zhang et al. 2022).

Table 79 Mineral composition of pea seeds

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	1.2	0.5	0.3	2.9
Phosphorus	g/kg DM	4.5	0.5	3.2	6.0
Potassium	g/kg DM	11.3	0.5	10.6	11.9
Sodium	g/kg DM	0.0	0.0	0.0	0.1
Magnesium	g/kg DM	1.7	0.6	1.0	3.4
Manganese	mg/kg DM	10	3	6	16
Zinc	mg/kg DM	37	8	27	48
Copper	mg/kg DM	8	1	7	10
Iron	mg/kg DM	107	33	63	160

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Peas, like other pulses, contain a variety of phytochemicals, including phenolic compounds, phytates, saponins and oxalates. The major phenolic constituents in pulses are tannins (phenolic acids and flavonoids. Phenolic compounds have been recognised for their actions as antioxidants. Peas contain a variety of phenolics, with the highest concentrations of most occurring in the seed coat, particularly in dark-seeded varieties. The antioxidant activity of pea varieties is significantly correlated with seed coat colour. Examination of the seed coat and cotyledon in two dark-coloured pea varieties reveals that the seed coat contains glycosides of quercetin, luteolin and apigenin, along with a variety of simple phenolics and proanthocyanins. The cotyledon contains mainly hydroxybenzoic and hydroxycinnamic compounds and some of the glycosides found in the seed coat (Pan et al. 2021).

Peas contain other minor bioactive components which may have positive benefits for human health. They include saponins and phytates, exhibiting hypocholesterolaemic and anticarcinogenic activities (Jeyaraj et al. 2021).

Table 80 Secondary metabolites of pea seeds

Secondary metabolites	Unit	Avg	SD	Min	Max
Tannins (eq. tannic acid)	g/kg DM	0.7	0.8	0.0	3.5
Tannins, condensed (eq. catechin)	g/kg DM	0.1	0.0	0.1	0.1

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

3.4.3 Nutritional value for animal feed

Peas can be a vital protein source and a great alternative to soybean meal in animal husbandry, especially when supplemented with crystalline amino acids to correct the deficiencies (Castell et al., 1996). Winter peas have a higher protein level than spring peas, while smooth seeds have a lower protein content than wrinkled seeds (Lu et al. 2020).

Peas have 60% of the crude protein level of soybean meal (Titze et al. 2021). The digestibility of pea crude protein is relatively high, with a range of digestibility coefficients from 83 to 88%, depending on the species. Ruminants readily digest pea protein with about 22% of the protein undegraded in the rumen (Joy et al. 2021). It is one of the highest-quality and least-expensive feeds, with its low price reflecting the minimal transportation costs (Todorenko et al. 2021). However, for livestock species where tryptophan and sulphur-containing amino acids (particularly methionine) are considered essential amino acids, they are deficient (Millar et al. 2019).

Pea seeds make an excellent pellet binder. They improve pellet quality, with a score of 6 (on a scale of 10), which is higher than 5, 5, and 4 for barley, maize, and soybean meal, respectively (Hettiarachchi et al. 2019). Peas have a slower starch breakdown rate (between 4 and 6% per hour) than cereals like barley (between 21 and 34% per hour). By substituting peas for barley in dairy cows (up to 25% inclusion), dry matter intake, milk fat, and protein yield are increased. Peas have a similar energy value to maize for ruminants, which is about 13.5 MJ/kg (Loe et al. 2004). The energy values for monogastric animals including pigs and poultry are slightly lower than maize grain (15.4 vs. 16.1 MJ/kg for growing pigs for pea seeds and maize, respectively).

Peas are an excellent source of protein and energy for birds. They lack sulphur-containing amino acids, and while there are pea varieties with low amounts of antinutritional components, there is still a lot of variation in composition and nutritional variables, resulting in digestibility differences (Nalle et al. 2011). When the nutritional value of field peas (raw or processed) is well characterised and the diet is well-balanced with synthetic amino acids, they can be incorporated into poultry diets at high levels without affecting performance. The suggested maximum levels varied from 20 to 35% for broilers and layers (Nalle et al. 2011).

Heat treatments may reduce the harmful effects of several antinutritional factors by improving starch digestibility. Pelletising, extrusion and cooking are regularly proposed as treatments. Peas can be processed independently or in combination with other raw materials like full-fat oilseeds. Many studies have been carried out to evaluate individual pea varieties or determine the impact of processing procedures on metabolisable energy values, digestibility, laying rate and feed efficiency. (Hall & Moraru 2022).

3.4.4 Antinutritional factors – nutritional limitations

Even though peas have the lowest trypsin inhibitor content (under 2% of total protein), which is 8 times less than raw soybeans, trypsin inhibitors are the predominant antinutritional component in raw peas. The trypsin inhibitory activity of spring pea varieties ranged from 1.69 to 7.56 trypsin inhibiting units (TIU), while it was 7.34–11.24 TIU in winter peas. Smooth peas have more trypsin inhibitors than wrinkled peas (Robinson & Domoney 2021). In the small intestine, trypsin inhibitors attach to trypsin, inhibiting protein digestion. They also caused pancreatic enlargement and increased protein excretion in monogastric species, resulting in reduced nitrogen retention, growth and feed efficiency.

Tannins, which bind to protein before digestion and impair protein digestibility in monogastrics, are another important antinutritional factor of peas. Tannin quantity is proportional to seed coat colour, with darker seed coats containing more tannins. White-flowered peas have a lower tannin concentration than coloured flowered peas (Zuber et al. 2019). The next antinutritional factor is lectins (carbohydrates and glycoprotein-binding proteins). They work in the small intestine by sticking to and disrupting epithelial cells, preventing the absorption of the end products of digestion. They account for around 2% of pea protein (Katoch & Tripathi 2021). Many breeding programmes aim to improve the nutritional value of peas by lowering trypsin inhibitors and tannins. Recent 'protein pea' types are free from tannin and reduced in trypsin inhibitors, making them suitable for animal feed, including monogastric in raw form (Abd El-Hack et al. 2018).

3.4.5 Pea in the laying hen diet

Several different classes of poultry can utilise field pea in their diets with proper feed formulation and a well-balanced diet to meet nutrient requirements. Low levels of trypsin inhibitors in spring-seeded peas allow feeding without needing heat treatment. Grinding is the preferred processing method for peas in all poultry diets, but fines should be avoided. Due to the shorter digestive tract and rapid passage rate, energy derived from field pea by poultry is similar to barley (Amaefule et al. 2007).

Table 81 Metabolisable energy value of peas for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max
AMEn cockerel	MJ/kg DM	12.5	1.1	10.3	13.9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

In an old study, Moran et al. (1968) compared the egg production rate of 28-week-old layers fed two levels (150 and 300 g/kg) of raw or pelleted peas vs. a corn-soybean meal control diet over the 12 weeks of the trial. When supplemented with methionine, pea inclusion at up to 300 g/kg in the diet had no effect on egg production but resulted in less efficient feed utilisation.

On the contrary, Davidson (1980) and Davidson et al. (1981) reported a decline in the egg production rate and feed efficiency in laying hens fed a pea-based methionine-supplemented diet containing 30% peas. A high inclusion rate of peas up to 50% of the diet was studied by Castenon and Perez-Lanzac (1990) in layers. Diets were in mash form, isoenergetic (11.1 MJ ME/kg) and isonitrogenous (169 g CP/kg). There were no negative effects of pea inclusion on the daily feed intakes but, for those fed the highest pea inclusion level, egg production declined from Week 3 to Week 8 compared with the control group. The authors concluded that pea inclusion should not exceed 330 g/kg.

Perez-Maldonado et al. (1999) tested several ingredients including field peas, faba beans, sweet lupins and chickpeas at an inclusion rate of 25% (each) on hens' egg production performance. Where faba beans induced lower hen-day egg production, egg weight and egg mass, hens could maintain egg production performance when they were fed with 25% field peas.

Table 82 Standardised ileal digestibility of amino acids of Pea in laying hens

Indispensable amino acid	Pea
Arginine	90
Histidine	85
Isoleucine	82
Leucine	83
Lysine	88
Methionine	85
Met+Cys	-
Phenylalanine	83
Threonine	81
Tryptophan	79
Valine	82
Dispensable amino acid	
Alanine	86
Aspartic acid	86
Cysteine	73
Glutamic acid	91
Glycine	84
Proline	85
Serin	84
Tyrosine	84

(Source: Rostango et al. 2005)

Another study investigated graded levels of yellow pea (var. Miranda) at levels of 0, 148, 296, 445 and 590 g/kg included in the diets of young hens. It was concluded that 440 g pea/kg of diet, supplemented with adequate methionine and fat, met the requirements of the layer hens from 22 to 58 weeks of age. At the higher level of inclusion, eggshell thickness was negatively affected (Ivusic et al. 1994).

Agwunobi (2000) studied the nutritive value of heat-treated pigeon pea-based diets compared to soybean meal, using 120 pullets at the onset of lay for 56 days. Egg production, egg weight, feed intake and feed conversion ratio were lowest for the pigeon pea ration. Egg albumen quality and eggshell thickness remained unaffected. This report stated that pigeon pea, unlike soybean, cannot satisfy the protein requirement for optimal layer performance.

In the study by Amaefule et al. (2007), pigeon pea seeds (*Cajanus cajan* (L.) Millsp.) were included in Black Bovan Nera pullet diets, in different forms including raw, boiled, or toasted (for 30 min or soaked in water for 24 h), . It was concluded that raw or processed pigeon pea seeds meal could be included as 30% of the whole diet of layers that had received 10 and 20% pigeon pea seed-based diets during their pullet chick and grower stages of life, respectively. Boiled pigeon pea seed diet would improve hen-day egg production, toasted pigeon pea seed diet would increase the feed intake of layers, while pigeon pea seed diets would have no regular effects on the external or internal egg quality characteristics of eggs laid by layers fed pigeon pea seed diets.

Ciurescu & Panâ (2017) studied the effect of replacing soybean meal with field pea (untreated) on the laying performance and egg quality of Lohmann Brown Classic pullets at 18 weeks of age. The experimental diets included standard corn-soybean meal diet; field pea included at 35% of the diet with or without enzyme supplementation (multiple enzymes were tested). They reported that the substitution of soybean meal with untreated field pea did not significantly change the growth performance, feed intake, efficiency of egg production, egg production rate, and none of the egg quality traits were influenced, except for yolk colour which was higher in hens fed the pea diet. The report demonstrated that untreated field peas (*Pisum sativum* L.) could be included in laying hens'

diets at a dietary level up to 350 g/kg, replacing soybean meal for the entire laying cycle, with neither a significant depression in production nor in egg quality, improving yolk colour.

Based on the existing data, it can be concluded that beans can **fully replace soybean meal** in laying hens' diet, with no detrimental effects on production performance or egg quality. The latest study in this topic belongs to 2007 where some of the essential amino acids were not available commercially. Crystalline amino acids have become more available commercially in the past decade at cheaper prices, which helps with the feed formulation practices to well-balance the diets for digestible amino acids levels.

3.4.6 Peas in the pig diet

Similarly to poultry, pigs can also be fed with pea seeds as a substitute for soybean meal, and as such field peas are the most used grain legumes for pig feed in Europe and Canada. One of the big issues in incorporating peas into pig (or poultry) diets, is the high variation in the nutrient composition and the content of the antinutritional compounds. It is therefore wise to analyse peas and characterise their composition prior to feed formulation. The amino acid profile of peas (especially the lysine and threonine content) is fine for pigs; however, methionine is deficient and should be supplemented. In addition, standardised ileal digestible amino acids are lower for peas compared to soybean meal (Noblet et al. 2002), which is due to the presence of antinutritional factors such as trypsin inhibitor and phytic acid. The antitrypsin activity of raw peas creates limitations in its use for pigs, however, appropriate heat processing such as extrusion has improved amino acid digestibility (O'Doherty et al. 2001; Stein et al. 2007).

Table 83 Nutritive value of peas for growing pigs

Pig nutritive values	Unit	Avg	SD	Min	Max
Energy digestibility, growing pig	%	88.3	2.1	84.7	92.5
DE growing pig	MJ/kg DM	16.1	0.4	15.7	17.1
MEn growing pig	MJ/kg DM	15.4		15.4	16.6
NE growing pig	MJ/kg DM	11.2			
Nitrogen digestibility, growing pig	%	84.9	2.5	80.1	88.8

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The digestible energy value has been reported between 14.2 and 17.2 MJ/kg of DM, with an average value of 16 MJ/Kg DM ((Gatel & Grosjean (1990)); Myer et al. (2001) has recommended that peas are palatable and, except for young pigs with a body weight less than 20 kg, all classes of pigs can be fed by peas.

For young pigs (starter feed), a maximum of 10% inclusion of raw peas has been recommended where, by using heat treatments such as extrusion, toasting or steam-pelleting, this can be increased to 20% inclusion (Gatel et al. 1990; Myer et al. 1993). Friesen et al. (2006) conducted a study where soybean meal was replaced by graded levels of peas at 0, 15, 20, 25, or 30% raw peas. The experimental diets were fed to weaned piglets (21 days old) for 35 days. Increasing the levels of peas impaired the daily weight gain and feed intake of nursery piglets. Inclusion of raw peas at 15–30% was detrimental to growth performance, although the feed conversion ratio was not affected.

Stein et al. (2004) reported that feeding raw peas at up to an 18% inclusion rate to pigs just 2 weeks after weaning (weaning age 21 d) had no effect on growth performance compared to the control diet.

This can be explained by a relatively mature digestive system compared to Friesen et al. (2006) where peas were fed to piglets immediately after weaning. Older studies have also reported that growth-depressing effects of raw peas are prevalent in pigs weighing 5–10 kg, where the digestive tract is not fully developed, and the digestive enzymes are still low (Landblom & Poland 1997a; Owusu-Asiedu et al. 2002).

Table 84 Standardised ileal digestibility of amino acids of peas in pigs

Indispensable amino acid	Pea
Arginine	89
Histidine	81
Isoleucine	80
Leucine	78
Lysine	81
Methionine	74
Met+Cys	-
Phenylalanine	77
Threonine	76
Tryptophan	-
Valine	77
Dispensable amino acid	
Alanine	-
Aspartic acid	-
Cysteine	-
Glutamic acid	-
Glycine	-
Proline	-
Serin	-
Tyrosine	-

(Source: Kasprowicz et al. 2004)

Castell et al. (1993) has suggested that if peas are supplemented with protein sources rich in methionine such as canola meal, the growth performance of the growing-finishing pigs will be maintained. Canola meal is rich in sulphur-containing amino acids while peas are a superior source of lysine.

In a study, ground raw peas could totally replace soybean meal in the diet for growing-finishing pigs, provided that the diet is well-balanced for all essential amino acid especially methionine or methionine + tryptophan, which are deficient in peas (Vieira et al. 2003).

Another study was conducted with grow-finish pigs, where soybean meal was fully replaced by either peas or faba beans at an inclusion rate of 30%. Diets were balanced for standard ileal digestible amino acids and net energy content. Production performance was not negatively impacted in pigs fed with soybean-free diets. Pea-based diets resulted in a higher dressing percentage than faba beans-based diets. The lean meat percentage was also higher in pea-fed pigs compared to faba beans-fed pigs (White et al. 2015).

The inclusion of raw peas in gestation and lactation diets is not well-investigated. Inclusion of spring peas at 24% during gestation and lactation has not reduced reproductive performance (Gatel et. 1988), and it has been reported that up to 30% of the soybean meal can be replaced by peas in lactating sow diets, without any adverse effects on reproductive performance (Landblom et al. 2001).

Spring peas have much lower concentrations of antinutritional factors, i.e. anti-trypsin factor compared to other annual legumes, and not considered a problem in feeding field pea to swine. The nutritional value of air-classified field pea for growing pigs was characterised by Gunawardena et al. (2010). The apparent total tract digestibility of energy of field peas was similar to that of corn and the digestible energy of field peas was 1.7% greater than corn starch. The standardised ileal digestible lysine content of field peas was 6% greater than soy protein. The nutritional characterisation showed that field peas are concentrated sources of amino acids and energy for growing pigs with high nutritional demands.

It could be concluded that peas can be included in the diet of pigs above 15–20 kg as a substitute for soybean meal, when mixed with other protein ingredients rich in methionine (sulphur-containing amino acids) such as canola meal, or supplemented with crystalline methionine + cysteine.

3.4.7 Carbon footprint and sustainability of pea production

Not many articles were found on pea bean's GHG emission or carbon footprint, but a couple of report findings related to field peas or dry peas. The GHG emissions for the production and harvesting of field peas were computed at 530 kg CO_2-eq/ha and 0.294 kg CO_2-eq/kg grain. The highest emissions were related to the production and transport of fertilisers (23–28%) and their use in the field (16–23%) (Brock et al. 2016).

3.5 Guar meal

Guar refers to *Cyamopsis tetragonoloba*, which is a bushy legume up to 3 meters high and with trifoliate leaves that can be 10 cm long. Other names include gavar bean, gawar bean or guvar bean. Similar to other legumes, guar is able to fix nitrogen in association with soil bacteria such as Rhizobium species, and it is an essential plant in crop rotation (Gaur & Singh 2014).

Guar is a legume that grows in moderately arid and subtropical areas of East/South-East Pakistan and North/North-West India. It can survive in poor soils without nitrogen fertilisers or irrigation due to its drought resistance. Guar seeds are dicotyledonous, consisting of three parts: Endosperm, germ and hull. The endosperm of guar seeds is composed of large polysaccharides of galactose and mannose, frequently referred to as guaran or guar gum.

Guar gum is water-soluble and produces a gelling ingredient, and it is used as a viscosifier, thickening, binder, gelling, stabiliser, emulsifier, natural coagulant, and moisture retention agent in food and other industries. Guar beans are physically dehulled, soaked, crushed and filtered to remove the endosperms (Mudgil et al. 2014). The processing of guar to manufacture guar gum, leaves a by-product high in protein, which is referred to as Guar meal. Guar meal is made by physically dividing the kernel from the guar seed's germ and hull. It is a blend of germs (25%) and hulls (75%) in a 1:3 ratio (Wielinga 2009). Guar meal is considered as a potential, though unconventional, feed resource for livestock.

The nutritive value of guar can be improved using appropriate processing methods such as addition of enzymes (cellulase, hemicellulose, β-mannanase), heat treatments and fermentation. Autoclaving guar meal and other heat treatments can destroy some of the antinutritional factors such as trypsin-inhibitor but has little impact on the saponin and phytate contents (Rajput et al. 1998).

3.5.1 Guar meal production globally and in Australia

Guar is cultivated mainly in semi-arid and subtropical regions of Pakistan and India. Guar is an African plant brought to India by Arabian dealers as equine feed (Undersander et al. 1991).

India produces about 1.5 million tonnes of guar per year, accounting for 90% of global production; however, the plant is being introduced elsewhere due to rapid growth in population and the need for protein-rich nonconventional feed resources. Minor amounts of guar (gum) are also grown in the US, Australia and China. It did not become popular in the US until the early 1900s. Since locust bean gum was in low supply due to World War 2 in 1945, guar gum has been investigated as a possible substitute for locust bean gum (Gupta & Variyar 2018). Guar gum supply was 200,000 tonnes globally in 2004, out of which 45,000 tonnes was consumed in the US accounting for about 25% of international commerce (Sharma & Gummagolmath 2012). The American oil industry is expected to import 300,000 tonnes of guar gum from India, which is 75% of India’s export total. In the last decades, China has greatly boosted its guar supply. India has been the world's leading producer of guar gum.

India occupies a major share in exporting different products of guar, like gum, splits, and meal, to many countries with 17.5% export share among the agricultural commodities during 2019–2020 The country has exported guar of 169.54 tonnes to various countries of the world, including Germany, Canada, United States of America, Australia, Russia (Benakanahalli et al. 2021).

Guar was brought to Australia from India in 1910, but hardly any study on it as a possible crop was done until the late 1970s and 1980s. Guar might be produced in northern Australia, with yields of 2.0–3.0 tonnes per hectare, according to research conducted in Queensland in the 1970s and 1980s.

Since the 1970s, there have been various attempts to develop guar production in Australia. Based on the genetic diversity of available varieties and changes in the market of guar seed from Australia by international producers, a sustainable industry hasn't evolved in the years after guar had initially been researched in Australia.

Between 1991 and 1997, the estimated yearly shipment was around 2,500 tonnes. Since 2012, there has been increased interest, with a US corporation creating a subsidiary in Australia to attract producers to contract to cultivate guar. In 2012, Australia purchased approximately 6,500 tonnes of guar gum, requiring around 24,000 tonnes of guar seed. The possible utilisation of guar gum by the growing coal seam gas sector for drilling new boreholes sparked increased interest in guar production in Australia in 2013.

Although some road test and seed germination of promising types has taken place, no processing plants have been developed.

Guar gum's rising use and investigations by food/feed and biopharmaceutical businesses, along with its use in oil and gas, are projected to drive the future demand (Mudgil et al. 2014).

3.5.2 General characteristics

Different studies have reported varying values for the chemical and nutrient composition of guar meal. These variations originate from changes in preparation methods and climate-related variations. Previous studies have reported the dry matter content of guar meal to range from 93.2–96.7% (Nadeem et al. 2005; Ahmed 1998; Lee et al. 2009). Guar seeds and meal contain 3.8% and 5.8% ash, respectively (Nidhina & Muthukumar 2015). Guar meal is high in fibre, with an average value of 12.7% crude fibre, with 20.7% NDF and 0.3% lignin.

Table 85 Chemical composition of guar meal (moderate–high protein)

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	92–95	0.9	93.4	96.7
Crude protein	% DM	42–55	1.1	40.0	44.3
Crude fibre	% DM	7.2–12.7	2.8	7.2	16.1
NDF	% DM	20.7–25.6	0.3	20.5	21.0
Lignin	% DM	0.3			
Ether extract	% DM	5.3	1.1	4.2	7.5
Ash	% DM	5.8	0.9	4.7	8.8
Starch (polarimetry)	% DM	4.1–5.4		3.1	5.1
Total sugars	% DM	3.9			
Gross energy	MJ/kg DM	20.5–21.1	1.0	18.4	20.6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

For unprocessed and autoclaved guar meal, the gross energy, apparent and true metabolisable energy (AME and TME) values are reported 20.5 MJ/kg, 11.0 and 11.1 MJ/kg, respectively (San Tan et al. 2016). Minerals such as calcium, iron, sodium, potassium, copper, magnesium, zinc and phosphorus are abundant, however, great variation exists in the reported values. The Ca, P, Mg, Na, and K content in guar meal are 1.25, 0.51, 0.046, 0.54, and 0.68%, respectively. It includes 200 ppm, 828 ppm, and 104 ppm of Cu, Fe, and Zn, sequentially, making it a better supply of micro-minerals than other vegetable

meals. Guar meal is also a rich source of iron, as it provides roughly 400 mg/kg of iron. These reported values by Sabahelkheir Murwan et al. (2012) are different to the table above, which has been adopted from Feedipedia.org.

Table 86 Mineral composition of guar meal

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	7.0	3.3	4.5	12.6
Phosphorus	g/kg DM	6.4	2.1	4.6	9.8
Sodium	g/kg DM	0.8			
Magnesium	g/kg DM	3.4		2.9	3.9
Manganese	mg/kg DM	2			
Zinc	mg/kg DM	61		48	73
Copper	mg/kg DM	18		16	19
Iron	mg/kg DM	433			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Guar meal is an interesting feedstuff due to its relatively high protein content, 40–45% DM for the regular meal and 50–55% DM for the korma meal. Guar meal includes variable crude protein quantities in germ, hull, and mixed guar by-products, ranging from 29.4–45.9% (Sharif et al. 2014). Its lysine (1.72% DM; 4.1% of protein) and sulphur amino acids (methionine + cysteine 0.96% DM) contents are comparable to those of groundnut meal but much lower than those of soybean meal (Feedipedia 2011). Among the amino acids, glutamic acid with 18.3% of protein, and arginine with 12.3% of protein are the most abundant amino acids.

Table 87 Amino acid profile of guar meal

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	4.0	0.1	3.9	4.2
Arginine	% protein	12.3	0.5	11.8	12.9
Aspartic acid	% protein	9.8	0.2	9.6	10.1
Cystine	% protein	1.2	0.1	1.1	1.3
Glutamic acid	% protein	18.3	0.7	17.7	19.3
Glycine	% protein	5.2	0.2	5.1	5.4
Histidine	% protein	2.5	0.1	2.4	2.6
Isoleucine	% protein	3.1	0.2	2.9	3.2
Leucine	% protein	5.6	0.1	5.5	5.8
Lysine	% protein	4.1	0.2	3.9	4.3
Methionine	% protein	1.1	0.0	1.1	1.2
Phenylalanine	% protein	3.7	0.1	3.6	3.9
Proline	% protein	3.5	0.2	3.3	3.8
Serine	% protein	4.7	0.1	4.7	4.8
Threonine	% protein	3.0	0.2	2.8	3.2
Tyrosine	% protein	2.5			
Valine	% protein	3.8	0.1	3.6	3.9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

3.5.3 Nutritive value for animal feed

Guar meal contains about 75–80% total digestible nutrients and 45–55% crude protein. The protein ileal digestibility of guar meal has been reported between 0.64 and 0.69. Overall, the standardised ileal digestibility of essential amino acids is between 0.55 and 0.71. The coefficient of standardised ileal digestibility of lysine, methionine, threonine, isoleucine, and valine are 0.58, 0.57, 0.53, 0.59, and 0.55, respectively.

It also contains a lot of trace minerals. Guar meal is an important component of cattle feed, but its bitterness and the existence of antinutritional factors make its use very limited for poultry and pigs.

Since guar seeds are passed through an ambient temperature of 93.3–105°C during gum extraction operations, the growth-inhibiting effects of antinutritional factors found in guar meal, particularly trypsin inhibitors, are eliminated (Liyanage et al. 2015). Its inclusion as an alternative for soybean meal in cattle feed is associated with improved production, particularly at lower inclusion levels (Salehpour & Qazvinian 2011).

Some of the improved performance in animals fed guar meal-based diets could be due to better ruminal digestion and fermentation, mainly because guar meal protein has a more rumen digestibility than soybean meal protein (Habib et al. 2013).

In broiler chickens, inclusion of guar meal has reduced growth performance even at a very low inclusion rate. Hassan et al. (2013) has reported a 35% reduction in growth performance of broilers when fed a diet supplemented with 2% guar meal compared to the control. Guar meal has a much more significant detrimental effect on young birds. The adverse effects of guar meal have been linked to its antinutritional factors such as higher digesta viscosity, which causes lower nutrient absorption (Gharaei et al. 2012).

Although galactomannans (NSP) in guar meal have always been inadequately metabolised by monogastric animals and have been related to reduced feed efficiency, if included in small amounts as prebiotics they can influence the digestive ecology by providing a substrate for microbial fermentation that promotes beneficial microflora and inhibits pathogens from establishing and colonising epithelial cells inside the gut. Moreover, fermentation of the galactomannans of guar meal by the gut flora results in the production of short-chain fatty acids that are important for the host animal's energy and gut health (Kakani 2013).

Diets including guar meal (up to 15%) fed to broiler chicks resulted in a negative impact on growth performance, which was much more of a detrimental impact on growth performance than the 10% inclusion rate (Dinani et al. 2010). Gum residues in guar meal render gastrointestinal contents extra viscous, leading to reduced nutrient absorption and bioavailability via the digestive tract (Thombare et al. 2016).

Saponins, which also exist in guar meal, are a diverse set of natural phytonutrients with a fat-soluble triterpene or steroidal glycoside nucleus. When birds are introduced to guar meal, specific saponins enhance intestinal epithelial cell membrane permeability. This can contribute to a drop in the trans-membrane electrical potential, which is necessary for efficient absorption of nutrients and hence leads to a reduction in the growth and production performance of birds (Iji et al. 2017).

3.5.4 Antinutritional factors – nutritional limitations

Guar meals contain residual guar gum (about 12% gum residue; Lee et al. 2005), which increases viscosity in the intestine and reduces digestibility and growth (Lee et al. 2009). High viscosity results in a 40% and 35% reduction in glucose or water permeability, respectively. Guar meal contains other types of antinutritional factors: trypsin inhibitors, saponin, haemagglutinins, hydrocyanic acid and polyphenols have been identified (Verma et al. 1982; Gutierrez et al. 2007). Guar meal saponins and polyphenols were linked to kidney, intestine and liver damage in laboratory rats, although they could potentially be helpful to intestinal microbes at very low levels. Because guar meal is largely utilised as a source of protein, these antinutritional factors (galactomannans, saponins, and polyphenols) should be managed by reducing the inclusion rates in diets. The trypsin inhibitors are inactivated by heat treatment.

Guar gum residue in the final diet hardly decomposed or digested. This has been linked to negative outcomes in chickens, pigs and laboratory rats. Guar gum has been shown to reduce glucose absorption in pigs and rats, probably through encapsulating effects, decreasing gastrointestinal blending and decreasing glucose uptake, which will affect performance. However, gum's galactomannans in guar feed act as prebiotics, and have been reported to help intestinal health by minimising colonisation of pathogenic bacteria in the gut (Hassan 2013). An additional problem with guar meal is its palatability. Inclusion of guar meal reduces the palatability of the whole mixed diet and overall feed intake, and productivity will suffer. Thermal treatment associated with gum processing may promote palatability while still inactivating trypsin inhibitors. This is of particular importance for monogastric animals since they do not have a fermentation process before the enzymatic digestion in the gastrointestinal tract (Benţea & Şara 2015).

3.5.5 Guar meal in the laying hen diet

Not many studies have reported the optimum inclusion rate of guar meal in laying hens. Previous studies investigated the effects of feeding guar by-products on the laying performance during late laying phase and reported that generally guar meal inclusion at concentrations of 10% or higher decrease egg production and feed efficiency and diminish egg yolk colour (Tyagi et al. 2015).

Table 88 Metabolisable energy value of guar meal for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max
TME poultry	MJ/kg DM	11.1		10.8	11.3

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Gutierrez et al. (2007) conducted a trial using 21-week-old Lohmann laying hens to evaluate the effect of feeding low concentrations of guar germ or a combination of guar germ and hull (guar meal) on egg production performance during the peak of production. Hens were fed either a control diet (no guar), or 1 of 4 diets containing either 2.5 or 5% guar germ, or 2.5 or 5% guar meal over a 20-week trial period. Inclusion of 2.5% guar meal significantly affected egg weight, total egg mass per hen and feed conversion ratio, whereas inclusion of 2.5 or 5% of guar germ and 5% guar meal did not affect production performance. Egg quality parameters including shell quality (shell thickness, egg breaking force and specific gravity), Haugh units, and egg yolk colour remained unchanged by either level of guar germ or guar meal. The authors concluded that an inclusion rate of 5% guar germ or guar meal in the diet of high-production laying hens has no adverse effects on laying hen performance.

Table 89 Standardised ileal digestibility of amino acids of guar meal in broiler chickens

Indispensable amino acid	Guar meal
Arginine	80
Histidine	62
Isoleucine	40
Leucine	44
Lysine	58
Methionine	64
Met+Cys	92
Phenylalanine	47
Threonine	38
Tryptophan	47
Valine	42
Dispensable amino acid	
Alanine	44
Aspartic acid	60
Cysteine	28
Glutamic acid	72
Glycine	58
Proline	44
Serin	53
Tyrosine	41

(Source: Siegert & Rodehutscord 2020)

A follow up study by the same researchers (Gutierrez et al. 2008), explored the efficacy of diets containing high levels of guar meal in inducing moult, and reducing susceptibility to *Salmonella* Enteritidis colonisation in 68-week-old (late-phase) laying hens. Experimental groups consisted of a feed withdrawal group, full-fed groups combining standard laying hen feed with either 20% guar meal or 20% guar meal supplemented with 250,000 units/kg of β-mannanase, and a full-fed standard laying diet group (non-moulted control) In addition, all birds in all experimental groups were orally challenged with *Salmonella* Enteritidis.

Feeding 20% guar meal supplemented with enzymes significantly reduced *Salmonella* Enteritidis present in crop, liver, ovary, and caecal contents. The results showed that the inclusion of 20% guar meal in the late laying phase is as effective as feed withdrawal to induce moult, however, hens benefited from guar meal inclusion as it improved resistance to *Salmonella* Enteritidis colonisation and translocation. In another study (Soleymani et al. 2011), graded levels of guar meal (0, 3, 6 and 9%), with or without β-mannanase were included in 58-week-old laying hens' diet, and egg production performance was studied for a duration of 12 weeks. The results showed that hen-day egg production significantly decreased when hens were fed diets that contained 6 and 9% guar meal in the first week, and only 9% guar meal in the second week of the experiment, as compared with 0 and 3% GM fed birds. Interestingly, inclusion of 9% guar meal did not affect egg production after the third week of feeding it to the birds, however, egg mass was significantly lower when guar meal was included at 9% compared to 3% and the control diet. Egg quality parameters including specific gravity, wet albumen (%) and wet yolk (%) of whole egg weight, and shell weight and thickness were not affected by guar meal inclusion in the feed. The addition of exogenous β-mannanase did not make any improvements in guar meal included diets. The authors concluded that up to 6% guar meal can be included in laying hens' diet with no detrimental impact on egg production performance or egg quality.

In the study of Ehsani and Torki (2010), Lohmann LSL-Lite hens were fed six iso-caloric and iso-nitrogenous diets including 3 levels of Guar meal (0.0, 35.0 and 70.0 g kg−1) with and without

β-mannanase enzyme supplementation. Their results showed that inclusion of guar meal at more than 3% in laying hens' diets may decrease egg production performance.

Based on the limited studies on guar meal as an alternative ingredient in laying hens' feed, it can be concluded that an inclusion of 3% has no adverse effects on production performance. It is worth stating that several studies have reported guar meal at high inclusion rates as an effective way to induce moulting in laying hens as an alternative to feed withdrawal, and to improve resistance to *Salmonella*.

3.5.6 Guar meal in the pig diet

Similarly to laying hens, the use of guar meal in pigs' feed is also limited due to its relatively high fibre content, high levels of trypsin inhibitors and galactomannan, which inhibit glucose absorption possibly by increasing the digesta viscosity and reducing mixing of intestinal contents. This leads to reduced nutrient absorption and impaired growth performance in pigs. However, thermal processing inactivates more than 80% of trypsin inhibitors in guar meal (Karpiesiuk et al. 2018).

The table below provides the DE, ME, and NE values of guar meal for growing pigs. Old studies have reported that pig diets can be supplemented with up to 6% of guar meal (Heo et al. 1987).

Table 90 Nutritive value of guar meal for growing pigs

Pig nutritive values	Unit	Avg
Energy digestibility, growing pig	%	70.1
DE growing pig	MJ/kg DM	14.4
MEn growing pig	MJ/kg DM	13.2
NE growing pig	MJ/kg DM	8.3

Avg: average or predicted value.
(Source: Feedipedia.org).

In a recent study conducted by Hasan et al. (2020), the inclusion of guar meal (GuarPro F-71) was evaluated on the growth performance and nutrient metabolism in young growing pigs. Sixty crossbred barrows were fed one of five experimental diets, where GuarPro was included at 0, 25, 50, 75, and 100% gradually replacing soybean meal in the standard diet by. All diets were isonitrogenic using crystalline amino acids. The increasing inclusion rate of guar meal quadratically reduced average daily feed intake, although no adverse health effects were observed. The blood plasma concentrations of six metabolites, including urea nitrogen, total protein, albumin, glucose, total cholesterol and total triglycerides, were not affected, indicating that the pigs' metabolic utilisation of nutrients was not compromised. Fitting the data to different models, showed that growth to feed ration was not negatively impacted by the replacement of soybean meal by guar meal up to 75%. It was concluded that the reduction in the final body weight and the average daily gain of pigs fed increasing levels of guar meal originated directly from the reduced feed intake, although feed efficiency was not affected. The underlying mechanisms of reduced feed intake in pigs when fed with guar meal is not well understood.

Karpiesiuk et al. (2018) conducted a study where pigs were fed experimental diets, where soybean meal was partially replaced by guar meal (0, 4.90, 9.90, and 14.60%, which corresponded to 0, 25, 50, and 75% of soybean meal replaced). The results showed that partial replacement of soybean meal at up to 25% (5% of the diet) with guar meal for finishing pigs had no negative effect on their productivity and was found to be economically justified. However, any inclusion level of guar meal above 25% adversely affected the productive performance and cost-effectiveness of pig fattening.

Summarising the limited data on guar meal as a protein source for grow-finisher pugs, it seems that 5–10% guar meal inclusion (replacing 25% of soybean meal) may have no adverse effects on the efficiency of production.

3.5.7 Carbon footprint and sustainability of guar meal production

The environmental footprints of guar gum are primarily attached to irrigation and agricultural machinery use. Studies show that the collective farming, transportation, and downstream processing activities result in 2.67 kg CO_2eq per kg guar gum, or 806 kg CO_2eq per hectare, which should be lower than the farm emissions because of a co-product credit for livestock feed (Summers et al. 2021). Compared to other competitive crops, guar is thought to be a low-emission crop (Gresta et al. 2014). However, there is a shortage of studies aimed explicitly at guar meal carbon footprint.

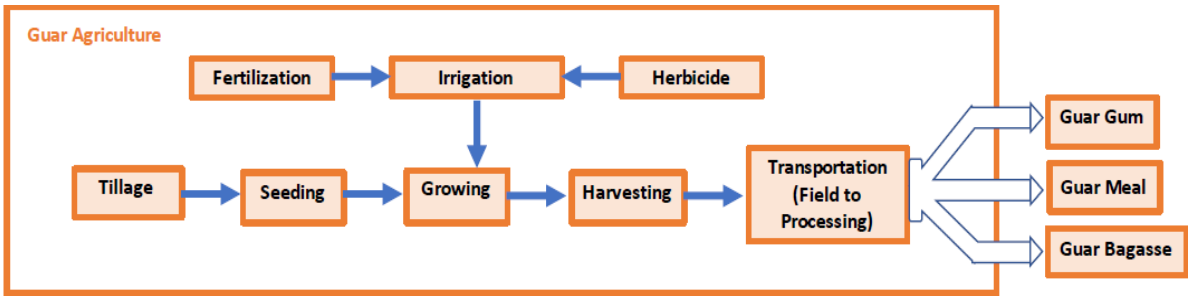


Figure 19 System boundary for the agricultural processes involved in growing guar

(Source: Mealing & Landis 2021)

4 Plant by-product protein sources

Sources of protein for animal feed are many and varied, with considerable opportunities for further diversification and substitutions. More research is required on alternative sources before many of the opportunities can be exploited in practice. Plant by-products are the most popular source of protein for all formulated feeds for poultry and pigs globally (Martens et al. 2012). Several products are made from cereals and other plants for human consumption, including flour, cooking oils, syrup, sugar, and alcoholic drinks. Grain by-products are the components of the crop or vegetation that remain after manufacturing a product. Most by-products have nutritional value that make them more suitable feed components for animals than the original crop or the processing's top finished product (Lennartsson et al. 2014).

4.1 Brewers' grain and DDGS

Alcohol extraction from cereal grains has grown significantly and continues to grow. Aside from ethanol, a substantial portion of by-products is generated and sold as distillers' dry grains with solubles (DDGS) also known as Brewers' grain or spent grain. It is a by-product of the brewing technique involving the malt and grain residual that remains in the mash-kettle just after the crushing and radically altering processes. It is the solid residue left over from the malting of germinated and dehydrated cereal crops (malt) to brew beer and other malt derivatives such as malt vinegar. Although barley has been the most common crop used during brewing, wheat, maize, rice, sorghum and millet also are commonly used for brewing. Grain is steeped in fresh water until it germinates, then processed to generate malt in the brewing process (malting). Barley malt grain is processed and soaked in boiling water, which allows enzymes to convert carbohydrate to sugars (mashing/saccharification). Beer is made by boiling, filtering and fermenting the sugar-rich liquid (wort). Brewers' grains are gathered after all sugars have already been extracted from the grain during the mashing operation (Aghajanzadeh-Golshani et al. 2010). The residual is a protein and fibre concentration, ideal for livestock feed, especially grazing animals.

Approximately 50% of the bulk of discarded grains is a carbohydrate, with the balance essentially proteins and lignin.

Brewers' grains constitute a widely varying by-product whose nutrient benefits and structure differ according to the grain utilised, the manufacturing (fermentation and temperature) and preserving techniques. Brewers' grains can be separated and sold in wet or dried format (Canedo et al. 2016). Distillers' dried grain with solubles (DDGS) is a nutrient-rich co-product of dry-milled ethanol manufacturing that utilises the dried milling process for starch-rich cereals like corn, wheat and barley (Iram et al. 2020). DDGS is a by-product of the brewery industry, specifically ethanol generation from cereals, that accounts for 90 per cent of brewing wastage and is collected as a largely solid product following wort manufacturing in the production process (Shurson & Noll 2005).

DDGS as a feedstuff, and as a protein and energy supplement in animal nutrition is well documented. The DDGS provide an elevated protein-based meal widely available to livestock when mixed into the livestock feed. Cows, pigs and certain chicken species are the most frequent recipients of DDGS. (Böttger & Südekum 2018).

4.1.1 Brewers' grain and DDGS production globally and in Australia

Livestock feed has a rich history with brewers' grain. Prior to the industrial revolution, European farms made their original beer and gave the by-products to their cattle. With the modernisation of brewing and livestock feeding, these techniques altered, and brewers' grains started to be employed in the food business (Moate et al. 2011). Brewers' grains are most often grown in temperate nations during the summer, as beer demand is highest. This implies that during the colder months when food supplements are most required, they are less affordable for animals. If brewers' grains are dried or ensiled, they can be stored to be used during winter (Aliyu & Bala 2011).

Beer waste accounts for 41% of brewers' grain output, whereas malt ingredients account for 31% (Garcia-Garcia et al. 2019). For every 100 litres of beer, 20 kilos of discarded grain are obtained. Indeed, 1.94 billion hectolitres of beer were produced globally in 2018 (Conway 2019). Because they constitute nonhazardous waste, agricultural production by-products are renewable resources. Organic waste valorisation is beneficial to the environment, economy, and human health (Ravindran et al. 2018). Every year, approximately 45 million tonnes of wet spent grain are generated in Australia, most of which are wasted or redistributed to producers as low-value animal fodder. In 2020, Australia's DDGS industry was ranked 24th globally, with a 0.15 per cent trade balance, and 32nd globally, with a 0.51% import share.

4.1.2 General characteristics

Regardless of where the grains are grown or which brewery brewed them, the primary nutrient content includes crude protein (CP) (25% of grain dry matter] and neutral detergent fibre (NDF) (50% of grain DM). Interestingly, certain non-structural carbohydrates and fat content is larger (> 5% of grain DM) than several of the foundation grains used in brewing. Brewers' grains provide valuable feed for all livestock species, serving as a rich source of protein, energy, and fiber.

Table 91 Nutrient profile of dehydrated brewers' grain

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	91.0	2.5	84.1	95.3
Crude protein	% DM	25.8	3.1	19.5	31.9
Crude fibre	% DM	15.8	2.1	11.8	19.9
NDF	% DM	56.3	5.7	42.3	67.4
ADF	% DM	21.9	3.1	15.5	28.6
Lignin	% DM	5.4	1.9	3.0	10.6
Ether extract	% DM	6.7	2.2	1.9	9.9
Ether extract, HCl hydrolysis	% DM	8.6	1.7	6.5	11.9
Ash	% DM	4.6	0.9	3.1	7.8
Starch (polarimetry)	% DM	7.8	4.5	2.3	14.5
Gross energy	MJ/kg DM	19.7	1.8	17.7	22.4

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Due to the elimination of the most soluble carbohydrate components and the relative amounts of carbohydrate originally contained in foundations cereals, the CP level of brewers' cereals is nearly double that of foundation grains. Brewers' grains have a CP level that varies between 21 and 33% of the DM, depending on the grain sources. The CP concentration of brewer's grains has increased over

the years, because of improved barley, corn and rice cultivars used as foundation grains, altered brewing procedures, or improvements in the collection of waste produced during the production process. Brewers' grains' energy value varies depending on the source and variety of the grain. In the grain analysis, the values for ADF and NDF vary from 5.41–12.89%. Despite being a rich source of CP, brewers' grains protein is of lower quality when compared to other protein supplements such as soybean meal, fishmeal, and the critical amino acid compositions of body tissue, dairy, and rumen microorganisms. In pigs given dry brewers' grains, lysine and threonine are the first and second limiting amino acids.

Table 92 Amino acid profile of dehydrated brewers' grain

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	4.8	0.5	4.2	5.7
Arginine	% protein	4.1	1.0	2.2	5.5
Aspartic acid	% protein	5.9	1.2	4.0	7.7
Cystine	% protein	1.8	0.8	1.0	2.5
Glutamic acid	% protein	19.9	2.9	14.8	22.4
Glycine	% protein	3.4	0.6	2.4	3.9
Histidine	% protein	1.8	0.4	1.2	2.3
Isoleucine	% protein	4.2	1.0	2.9	5.9
Leucine	% protein	8.2	1.0	6.4	9.7
Lysine	% protein	3.1	0.6	2.1	3.7
Methionine	% protein	1.5	0.4	1.0	1.9
Phenylalanine	% protein	5.3	0.5	4.5	5.9
Proline	% protein	8.8	0.9	8.1	10.0
Serine	% protein	4.0	0.4	3.4	4.8
Threonine	% protein	3.2	0.3	2.6	3.5
Tryptophan	% protein	1.2		1.1	1.3
Tyrosine	% protein	3.5	0.4	2.9	4.1
Valine	% protein	4.8	0.8	3.8	5.8

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The original grain used for brewing determines the degradability and bioavailability of CP and amino acids, but the manufacturing process has a significant impact. Brewers' grains have an effective nitrogen degradability of 41–49%, however, heat treatment during the drying process affects nitrogen digestibility. Thermal treatment also reduces solubilisation whilst increasing the ADF-bound nitrogen component, which is insoluble.

Total gastrointestinal tract (GIT) nitrogen digestibility ranges between 74% and 84%, which would be significantly smaller than that of soybean meal, corn gluten feed and maize distillers' grains (more than 90%). Lysine is the first limiting amino acid in brewers' grains for high yielding animals (the average content is 3.1%), as it is deficient in cereal grains and associated by-products; hence it must be combined with lysine-rich sources of protein or crystalline lysine (Volden 2011).

Brewers' grains have on average 4.6% ash, 2.7% Ca, 5.7% P, and 2.9% K. It is moderately high in iron (130 mg/kg DM) and zinc (89 mg/kg DM).

Table 93 Mineral profile of dehydrated brewers' grain

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	2.7	0.9	1.5	4.8
Phosphorus	g/kg DM	5.7	0.8	3.6	6.7
Potassium	g/kg DM	2.9	1.4	0.2	3.9
Sodium	g/kg DM	0.3	0.1	0.2	0.7
Magnesium	g/kg DM	2.6	0.5	1.8	4.3
Manganese	mg/kg DM	47	12	16	71
Zinc	mg/kg DM	89	31	2	161
Copper	mg/kg DM	19	5	15	35
Iron	mg/kg DM	130	23	103	174

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

4.1.3 Nutritional value for animal feed

Brewers' grains are better sources of fibre (cell-wall polysaccharides of cellulose, hemicellulose), protein, and several minerals than foundation grains, since sugars and starches are removed during the fermentation and crushing procedure.

Brewers' grains are a great source of protein (27–33% DM). The amount of heat used during the brewing process can impact the protein content, which is helpful to grazing animals but harmful to monogastrics, including pigs and poultry. Brewers' grains are also high in fibre (ADF 17–26% DM), making them ideal for dairy cattle, but not so much for pigs and poultry. Wet brewers' grains are indeed a heavy, low-energy meal that limits their application in monogastric animal feed.

The gross energy of maize DDGS averages 22.7 MJ/kg DM with an average digestibility of 76% in growing pigs; the digestible energy and metabolisable values are then equivalent to 17.2 MJ and 6.1 MJ/ kg of DM respectively (Pedersen et al. 2007).

When starch is depleted throughout the ethanol generation process, the amount of non-fermented micronutrients increases. As a result, CP concentration in DDGS ranges from 300 g/kg DM in maize DDGS to up to 390 g/kg DM in wheat DDGS. As a result, DDGS is used in the feeding of non-ruminants and dairy cattle (Böttger & Südekum 2018).

The CP concentration of raw resources is the most important factor of Brewers' grain CP content. Maize brewers' grain often has a smaller CP than wheat Brewers' grain. Numerous studies have found that the protein value of brewers' grain could be attributed solely to the form or growing environment of the raw resources. Dehydration is not the only essential processing phase impacting CP properties. Milling process, heating, fermenting, distilling, centrifuge, evaporating, mixing, and dryness are all processes in the alcohol production process that will hypothetically influence DDGS (Rosentrater et al. 2012).

The grinding size of the particles, temperature, pharmaceutical additions, and sorting and blending product streams are all other contributing factors (Hruby 2012). It should be emphasised that the chemical structure of brewers' grains is not really a strong predictor of organic material bioavailability. The research contains a wide variety of organic material digestion ratios, ranging between 55 and 80 per cent (Beyer et al. 2003; Volden 2011). The majority of animal food studies have used brewers'

grain samples including 10–14 per cent crude fat; however, recently, most ethanol manufacturers have implemented technology to retrieve more oil from thin stillage during the brewers' grain production process. Distillers corn oil is sold as a biodiesel feedstock as well as a desirable additional lipid source for swine and poultry feeds.

As a consequence, the energy content of the reduced-oil brewers 'grain is thought to be less and much more varied than that of brewers' grain generated prior to the widespread use of oil extraction.

Brewers' grains can be fed to chickens. However, their nutritive value and metabolisable energy are less than the foundation grain due to the high fibre content and low protein digestibility. As a result, brewer's grains are not well adapted to the feeding of monogastrics, especially young broilers. Older birds and laying hens are more tolerant to the high fibre content and low protein digestibility. Brewers' grains are typically fed to chickens in a dry form, as they are easier to handle and more stable than when hydrated. (Abd El-Hack et al. 2019). Brewers' grains could be supplied to pigs; however, their insoluble fibre and poor protein quality (low in lysine, threonine, and tryptophan) make them better suited to gestating sows and boars, rather than to growing piglets and lactating sows, especially in intensive production systems. Brewers' grains are typically offered to pigs in the dry state because they are simpler to store and manage, but they can also be fed wet or ensiled (Boontiam et al. 2022).

4.1.4 Antinutritional factors – nutritional limitations

Brewers' grains are a safe feed provided that they are properly stored. In particular, wet brewers' grains are susceptible to bacterial and fungal contamination (mycotoxins) and care should be taken to feed only unspoilt brewers grains (Asurmendi et al. 2013).

Sulphate toxicity

Due to the use of sulphuric acid in the process, ethanol by-products may be high in sulphate (0.5–1.7% DM) (McAloon et al. 2000), which increases the risk of sulphur toxicity in livestock fed large amounts of distiller's grain. A high concentration of H_2S inhibits the oxidative processes in nervous tissue and results in a central nervous system disorder called polioencephalomalacia, which may affect up to 6% of cattle fed diets containing more than 0.56% sulphur (Gould 1998; Vanness et al. 2009).

Mycotoxins

Maize is susceptible to fungal infections producing mycotoxins, including aflatoxin, fumonisins, deoxynivalenol (vomitoxin), ochratoxin, T2 toxin and zearalenone. Due to the concentration that non-starch components undergo during the distillery process, mycotoxin concentrations are about three-fold in corn distillers grain compared to the original grain. It is thus of utmost importance that maize intended for bio-ethanol production be free of mycotoxins before processing. There are also ways to alleviate mycotoxin problems, such as removing damaged grains before they enter the process (Liu 2011). Chemical treatments (NaOH, NH_4OH, H_2O_2, NaClO, CH_2OH) have been investigated to detoxify mycotoxins in stillage (Bennett et al. 1981; Lillehoj et al. 1979).

Copper

Certain traditional whisky distilleries use copper rather than stainless steel for stills and pipework, and their by-products tend to contain high levels of copper, which is toxic to sheep. Maize distillers dark grain, for instance, may contain between 15 and 120 mg/kg of copper. While copper content and biological copper availability are highly variable in whisky by-products, it is essential to check copper

levels before buying such products if they are to be fed to sheep (Lewis 2002). Copper is not an issue in industrial ethanol production.

Due to the high-temperature process, dry brewers' grains are occasionally stated to have a poorer organic material bioavailability than wet brewers' grains ((Beyer & Jentsch, 2003)). Wet brewers' grains contain a high proportion of water (74%) and hence need special care before being used as a feedstuff for livestock. Wet brewers' grains are a healthy feed, as long as they are handled and stored appropriately.

Wet brewers' grains are particularly susceptible to microbial and fungus infection (mycotoxins); hence only unspoilt brewers' grains must be fed. Proper handling is usually a problem due to high relative humidity. The majority of WBG is kept in a bunker silo just on-farm or even in a Ziploc bag.

Brewers' grains will have a shorter self-life interval throughout the summertime and its deterioration can begin as soon as 5 to 7 days after bags or silos are opened, resulting in greater mould development, lower water content, and lower palatability. If farmers' feeding rates are lower than the rate of spoiling, this can be expensive (Asurmendi et al. 2013).

4.1.5 DDGS in the laying hen diet

A plethora of work exists on the inclusion of DDGS in laying hens' diet, however, it is difficult to compare research regarding the use of dried brewers' grains in poultry diets because of the different sources of the grains.

Table 94 Metabolisable energy value of dehydrated brewers' grain for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max
AMEn poultry	MJ/kg DM	9.2	2.4	7.5	11.9

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

For layers (similarly to broilers), inclusion rates of 10–20% of the diet have been recommended with no detrimental impact on their production and egg quality traits. It has been reported that enzyme supplementation can improve the nutritive value of dried brewers' grains in poultry diets.

Table 95 Metabolisable energy value of corn DDGS for poultry

Poultry nutritive values	Unit	Avg
AMEn cockerel	MJ/kg DM	12.6
AMEn broiler	MJ/kg DM	12.3

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

An old study conducted by Deltoro López et al. (1981), 20 Rhode Island Red laying hens in the seventh month of lay were fed with five experimental diets including 0, 15, 30, 45 and 60% brewers' dried grains. The experiment lasted 75 days, after which pure brewers' dried grains (90%) were offered to the same hens for two weeks. Diets with up to 45% brewers' dried grains were iso-nitrogenous, but

diets with a higher content had a higher level of protein. On a dry matter basis, the brewers' dried grains contained 2.27 kcal ME/g and nitrogen digestibility was 75.4%. Diets containing 45% or more brewers' dried grains showed a significant decrease ($p < 0.05$) in metabolisable-energy content. Diets containing 15% and 30% BDG did not have any adverse effects on feed intake, body weight and egg production traits. Brewers' dried grain at an inclusion rate of 45% caused body weight losses and reduced eggshell quality, suggesting that this level should not be used without further research. At 60% and 90% inclusion rates, brewers' dried grain caused a significant decrease in feed intake, great body weight losses and, in the second week of the experimental period, an inhibition of the lay.

Deniz et al. (2013) conducted a trial with 480 Super Nick white-laying hens, fed five experimental diets including 0 (basal diet), 5, 10, 15 or 20% corn distillers dried grains with solubles (Corn DDGS) with or without supplementing enzyme cocktail for 8 weeks. They reported that feeding up to 15% corn DDGS with or without enzyme cocktail supplementation had no negative effects on egg production parameters (percentage laying rate, egg weight, feed intake and feed conversion), or exterior (eggshell thickness and shell breaking strength), or interior (Haugh units and egg yolk colour) egg quality traits. The use of 20% corn DDGS in the laying hen diets, however, depressed the feed intake and increased feed conversion ratio compared to lower DDGS inclusions. Enzyme supplementation improved the nutritive value of corn DDGS and reduced N and P content in the manure.

Table 96 Standardised ileal digestibility of amino acids of corn distillers dried grains with solubles in laying hens

Indispensable amino acid	**DDGS**
Arginine	74.2
Histidine	70.5
Isoleucine	68.5
Leucine	80.3
Lysine	56.5
Methionine	78.6
Met+Cys	73.8
Phenylalanine	78.0
Threonine	63.8
Tryptophan	-
Valine	66.5
Dispensable amino acid	
Alanine	78.3
Aspartic acid	64.8
Cysteine	69.0
Glutamic acid	80.6
Glycine	65.1
Proline	73.3
Serin	71.7
Tyrosine	-

(Source: Adedokun et al. 2015)

Another recent study by Gebremedhn et al. (2019) was conducted to evaluate the inclusion of dietary brewery spent grain on egg production performance and quality of bovans brown as well as the economic profitability of the rations. Five experimental diets including 0, 10, 20, 30 and 40% levels brewery spent grain were fed to 200 pullets with similar body weight and age. The protein content of the experimental diets varied between 16.54 and 17.04%, and metabolisable energy contents were between 2871 and 2903 kcal/kg DM, respectively. Inclusion of the brewery spent grain at all levels did not affect dry matter intake, feed conversion efficiency or hen-day egg production (58.79, 57, 56.11, 55.11 and 54.13%). Egg quality traits were not impacted by the inclusion of brewery spent grain either.

Feed cost, however, decreased with the increasing level of the brewery spent grain in the rations because of its lower price. These authors concluded that the inclusion of brewery spent grain at up to 40% of the diet of layers does not affect production or egg quality, and it can be economically profitable.

Dried distillers' grain with solubles is a valuable resource for poultry nutrition. The inclusion of 25% DDGS in layer feed has been tested and no adverse effects on production and egg quality have been observed, although yolk colour was improved with DDGS inclusion (Masa'deh et al. 2008). Greater inclusion rates of up to 32% were also tested without effect on performance in a trial where a 16% inclusion rate improved performance compared to the control. The quality of eggs (Haugh index, consumer preference) was improved by DDGS addition (Loar et al. 2010). In contrast, some experiments reported a slight decrease in egg production at an inclusion rate above 10% (Roberson et al. 2005; Shalash et al. 2010).

Considering the literature and existing papers, it seems that DDGS can be safely included in laying hens' feed at 15% with no adverse effects on feed intake, egg production performance, feed efficiency, or egg quality. Higher rates can probably be used with high quality DDGS, provided that the feed is well formulated. This inclusion reduces feed costs, as DDGS is a cheaper source of protein and nutrients compared to conventional protein meals.

4.1.6 DDGS in the pig diet

Comprehensive research has been conducted regarding the inclusion of brewers' grain including DDGS in pig feed. We have summarised some of the recent work with solid outcomes and recommendations on the optimum inclusion rate of DDGS in pig feed.

Table 97 Standardised ileal digestibility of amino acids of DDGS in pigs

Indispensable amino acid	**DDGS**
Arginine	97
Histidine	94
Isoleucine	90
Leucine	90
Lysine	88
Methionine	99
Met+Cys	-
Phenylalanine	92
Threonine	64
Tryptophan	89
Valine	87
Dispensable amino acid	
Alanine	-
Aspartic acid	-
Cysteine	-
Glutamic acid	-
Glycine	-
Proline	-
Serin	-
Tyrosine	-

(Source: Zeng at al. 2017)

A recent study by Amoah et al. (2017), investigated the optimum inclusion rate of sun-dried based brewers' spent grain in feeding trials with 48 weaners and 24 grower-finisher pigs. Experimental diets included 0, 17% and 20%, brewers' grain in weaner diets, and 0, 25 and 30% of brewers' grain in grower-finisher pigs. The feed conversion ratios during the weaner phase were 2.00, 2.08 and 2.50 for 0, 17, and 20% inclusion rates in weaner diets, respectively. Similarly, feed intake and FCR were negatively affected in the grower phase as well when brewers' grain was included in the feed, however, 17% and 25% inclusion rates for weaner and growers were recommended.

Another trial by Mukasafari et al. (2017) formulated five experimental diets where brewers' spent grain replaced sow and weaner meal at 0%, 25%, 50%, 75% and 100% on DM basis. Daily feed intake and weekly live weight, feed conversion ratio and the net profit were recorded for 42 days. Feed intake increased from 0 to 50% inclusion of brewers' grain and then decreased from 50 to 100% inclusion. The average daily gain was affected, although 50% inclusion of brewers' grain was similar to the control diet (0% inclusion). Feed efficiency was also similar in the first 3 diets (0 to 50% inclusion) but impaired for 75 and 100% inclusion. Feed cost decreased with the increase in brewers' grain levels. The net return was highest at 50% brewers' grain inclusion, and it was concluded that brewers' spent grain can replace 50% of sow and weaner meal in grower pigs' diets without adverse effect on daily gain, with good economic returns.

Cerisuelo et al. (2012) conducted a study to evaluate the effects of sorghum distillers dried grains with solubles in diets for growing and finishing pigs. A total of 204 growing pigs with an average body weight of 13.9 ± 2.60 kg were allocated into two dietary treatments, a control diet and a diet containing sorghum-DDGS (DDGS) at inclusion levels of 150 g/kg in pigs from 14–40 kg BW, 300 g/kg from 40–80 kg BW, and 350 g/kg from 80 kg BW to slaughter. During the nursery period, compared to the control diet, feed intake and final body weight was reduced as DDGS was included in the diet. During the growing period, no differences were found in growth performance between pigs fed the DDGS-included vs. the control diets. The backfat thickness was increased with the inclusion pf sorghum-DDGS in the diet. No differences were found in loin depth and carcass weight, and yield between the diets. It was concluded that 150 g/kg of sorghum-DDGS impairs growth performance during the nursery phase, however, 300–350 g/kg sorghum-DDGS can be safely included in grower-finisher pigs' diet, although, it results in a fatter carcass.

Three experiments were conducted by Linneen et al. (2008) to determine the optimal level of dried distillers' grains with solubles (DDGS) from a common ethanol manufacturing facility, and to study the potential interactions between dietary DDGS and added fat on the performance and carcass characteristics of growing and finishing pigs. The experiments were conducted in a commercial facility with a large sample size per experimental diet. The first experiment evaluated diets containing 0 or 15% DDGS and 0, 3, or 6% added choice white grease in a 2 × 3 factorial arrangement, in a 28-day growth study. There was no interaction between the DDGS and added fat, however, fat inclusion linearly improved average daily gain and feed efficiency. The growth performance of pigs fed the control and DDGS diets at 15% inclusion was similar. In the second experiment, diets containing 0, 10, 20, or 30% DDGS were fed to pigs for a duration of 56 days, and growth performance was studied. Increasing DDGS levels reduced feed intake and daily gain, but the greatest reduction happened in pigs fed between 10 to 20% DDGS. The third experiment tested the inclusion of DDGS at 0, 5, 10, 15, and 20% inclusion rates. Feed intake and daily gain reduced with increasing level of DDGS in the feed, however, the greatest reduction happened when pigs fed between 15 and 20% DDGS. The outcomes of the three experiments concluded that DDGS can be fed up to 15% without any adverse effects on the growth performance of grower-finisher pigs.

According to the literature, corn DDGS can be used at moderate to high inclusion rate in piglets, growing-finishing pigs and sows with no detrimental effects on their performance, as long as the

amino acid supply is maintained (Stein et al. 2009). In practice, a 20% inclusion rate is recommended in piglets, growing-finishing pigs and lactating sow diets. A higher inclusion up to 50% in pregnant sow's feed, not only has no detrimental effects on performance, but also can be beneficial and improve the welfare of restrictively fed pregnant sows (Stein et al. 2009). Finishing pigs can tolerate higher inclusion levels, although the high content of unsaturated fatty acids in corn DDGS combined with a high fat content in most corn DDGS induce rather soft body fat, which is unsuitable for processing and carcass conservation. Some authors have suggested that corn DDGS be removed from the diet over the last 2–3 weeks before slaughter in order to reduce the unsaturated fatty acids concentration in body fat.

4.1.7 Carbon footprint and sustainability of DDGS production

The overall environmental footprints of DDGS are low compared to soybean meal and corn in all four categories of global warming potential, land use, water consumption, and fossil resources scarcity, according to Haque et al. (2022). The comparative study mentions that the results of a 28.8% DDGS diet substituted for the standard corn–soybean meal diet (displacement ratio of 0.69) may save global warming potential nearly 0.04 kg CO_2-eq. per lb DDGS feed at the feed manufacturing phase (Haque et al. 2022).

4.2 Corn gluten feed

Corn gluten feed is produced as a by-product of the wet milling process of corn, which separates the starch, germ, and protein components of the kernel, producing high fructose corn syrup and starch. Since most of the carbohydrate fraction is transformed by metabolic enzymes into glucose, fructose and dextrose syrup, it is reasonably rich in proteins, relatively high in fibre (as it has corn bran), and relatively high in energy. The grain will be first steeped in sulfuric acid. Protein, minerals, vitamins and sources of energy are all included in the steep liquor that results. The enlarged kernel is used to separate the starch and oil.

The steep liquor is combined with residual fibre or bran. This product, wet corn gluten feed, has a dry matter content of roughly 40%. The new product, dry corn gluten feed, is made from wet corn gluten feed that has been dehydrated to around 90% dry mass (Park et al. 2018). Corn gluten feed is not the same as corn gluten feed. Corn gluten feed is a by-product of the wet milling process, where most of the starch and germ were eliminated, and part of the fibre has been removed.

Corn gluten feed contains twice the protein content of corn gluten meal. Corn gluten feed has less energy than the initial corn grain, however, it is an effective energy supplement as corn in forage-based diets. Corn grain has been shown to reduce fibre bioavailability, although corn gluten feed does not seem to do so

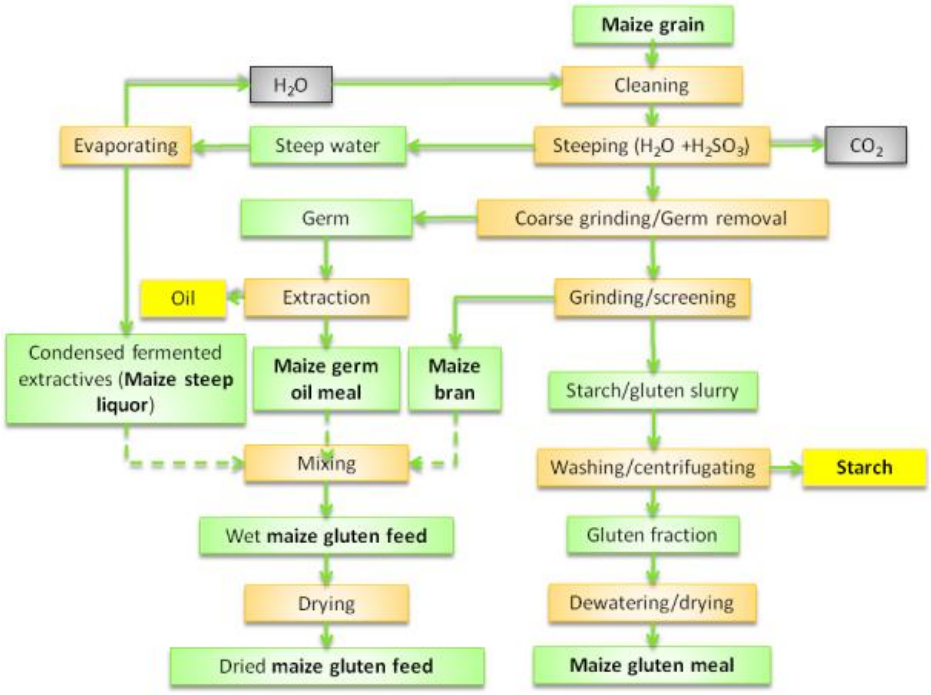


Figure 20 Corn gluten feed production process

Corn gluten feed is a high-protein feed, with up to 65% crude protein (DM-basis), used as a source of protein, energy and pigmentation for animals, including fishes. It is also ideal for the poultry diet because of its methionine content, which is a limiting amino acid for chickens' growth and egg production (Doughty et al. 2019), however, it is low in lysine which has made its application limited unless lysine is supplemented. Corn gluten meal's amino acids are very well metabolised by pigs and poultry, and the bioavailability of amino acids is comparable to those of corn.

4.2.1 Corn gluten feed production globally and in Australia

Dried gluten feed is sold around the world. Because ethanol is primarily manufactured in dry mills, corn gluten meal and corn gluten feed supply have remained relatively stable (RFA 2008). Wet mill corn gluten feed production in the US was 248,856 tons during August 2022, down 8% from July 2022 and down 9% from August 2021. Wet corn gluten feed, with 40% to 60% moisture was 189,203 tons in August 2022, down 15% from July 2022 and down 8% from August 2021. Between October 2010 and September 2011, approximately 14.9 million t of corn gluten meal and corn gluten feed were consumed. The United States supplies 60% of the corn gluten feed traded worldwide (2.1 million tonnes out of 3.5 million tonnes). In 2005, wet mills produced 0.43 million tonnes of corn gluten meal, 2.4 million tonnes of corn gluten feed and corn germ meal, and 0.26 million tonnes of corn oil in Australia (NCGA 2006). The United States (5.6 million t), the European Union (3 million t), South Korea (1 million t), Japan (0.94 million t), and other Asian countries are the largest buyers of both items (1.6 million t).

The EU, South Korea, Turkey, China, Japan, Israel, Egypt and Indonesia were the top buyers in 2010-2011 (Oil World 2011). Over 1.86 million tonnes of corn gluten feed and corn gluten meal were shipped from the United States in the business year that ending 31 August 2019. Ireland (23%) has been the most frequent consumer of US corn gluten feed and corn gluten meal, followed by Israel (12%) and Indonesia (9%) (Borchert et al. 2021). The majority of gluten feed produced across the globe is pelleted to enhance the bulk density by 25%–30%, lowering transportation costs while improving handling qualities (Rausch et al. 2019). Australia doesn't seem to process corn or produce corn gluten feed and corn gluten meal, so it needs to be imported.

4.2.2 General characteristics

Corn gluten feed is mostly composed of corn bran and corn steep liquor (liquid separated after steeping) but may also include distillers solubles, germ meal, cracked maize screens and modest amounts of the end-products of diverse bacterial fermentation processes. Corn gluten feed's chemical makeup varies greatly depending on the milling technique and the relative proportions of bran, steep liquor and other constituents.

Table 98 Nutrient profile of corn gluten feed

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	88.3	1.5	84.3	94.5
Crude protein	% DM	21.7	1.5	17.3	27.2
Crude fibre	% DM	8.3	1.0	5.3	11.4
NDF	% DM	39.6	4.3	31.0	49.1
ADF	% DM	10.6	1.3	8.4	13.3
Lignin	% DM	1.2	0.5	0.6	2.7
Ether extract	% DM	3.4	0.9	1.5	6.9
Ether extract, HCl hydrolysis	% DM	4.1	0.6	3.0	5.4
Ash	% DM	6.9	1.3	4.0	10.3
Starch (polarimetry)	% DM	21.5	3.7	11.0	33.8
Total sugars	% DM	1.8	0.8	0.7	4.4
Gross energy	MJ/kg DM	18.8	0.3	18.3	19.5

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The quantity of steep liquor in the mix has a positive correlation with the energy and protein level of corn gluten feeds (Su et al. 2021). The ratio of steep liquor to bran is usually 1:3 to 2:3, and the nutritional value of products with low or high amounts of steep liquor might range significantly (Erickson et al. 2005). Based on the quantity of steep liquor, processing conditions and dry duration, corn gluten feed can vary in colour from yellow-light brown to dark brown. With increased drying temperature or time, dried corn gluten feed darkens. Heat damage and impaired protein digestibility could occur in incredibly dark corn gluten feed. Crude protein concentration ranges from 17 to 26%, with fat levels ranging from 1 to 7%.

Corn gluten feed has a crude protein percentage roughly double that of corn grain, and a two-fold higher amino acid content than corn, but relative amino acid levels are similar. Corn gluten feed is a protein-rich feed containing from 60 to 75% crude protein (DM). It contains about 15–20% of residual starch in the DM and limited amounts of fibre (crude fibre 1% DM), fat (3% DM) and minerals (2%). Due to its high protein content, corn gluten feed is mostly used as a potential alternative to other plant or animal-based proteins (Leeson & Summers, 2009).

Table 99 Amino acid profile of corn gluten feed

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	6.4	0.5	5.5	7.3
Arginine	% protein	4.4	0.6	3.0	5.6
Aspartic acid	% protein	5.5	0.5	4.7	6.3
Cystine	% protein	1.9	0.2	1.5	2.4
Glutamic acid	% protein	14.2	0.7	12.9	15.3
Glycine	% protein	4.2	0.3	3.6	4.8
Histidine	% protein	2.9	0.2	2.5	3.2
Isoleucine	% protein	3.1	0.2	2.7	3.4
Leucine	% protein	8.2	0.6	6.9	9.4
Lysine	% protein	2.9	0.4	2.1	3.8
Methionine	% protein	1.7	0.1	1.5	1.9
Phenylalanine	% protein	3.5	0.3	2.8	4.1
Proline	% protein	8.3	1.3	6.7	9.8
Serine	% protein	4.1	0.2	3.7	4.5
Threonine	% protein	3.4	0.2	3.1	3.7
Tryptophan	% protein	0.6	0.1	0.5	0.8
Tyrosine	% protein	2.4	0.3	1.8	3.1
Valine	% protein	4.6	0.3	4.0	5.1

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The protein quality, like corn, is poor. Lysine with an average 2.9% of protein is deficient in corn gluten meal (Zhang et al. 2021). Methionine (1.7% of protein) and cystine (1.9% of protein) also have low content. Corn gluten feed is high in phosphorus, potassium and sulphur, while deficient in calcium. The ratio of calcium to phosphorus is roughly 1:10. The quantities of trace minerals and vitamins might vary dramatically from batch to batch (Zhang et al. 2021).

Table 100 Mineral content of corn gluten feed

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	1.6	1.0	0.2	4.5
Phosphorus	g/kg DM	10.2	1.5	7.1	14.1
Potassium	g/kg DM	15.4	2.4	12.0	21.1
Sodium	g/kg DM	3.4	2.4	0.3	8.2
Magnesium	g/kg DM	4.2	0.4	3.4	4.7
Manganese	mg/kg DM	20	6	8	30
Zinc	mg/kg DM	63	10	46	79
Copper	mg/kg DM	6	4	3	18
Iron	mg/kg DM	248	216	80	768

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Similar to corn grain, corn gluten feed's amino acid profile is low in lysine (1.7% of the protein vs. 6.3% for soybean meal and 7.5% for fishmeal) and tryptophan (0.5% vs. 1.4% for soybean meal and 1.1% for fishmeal). It also contains more methionine (2.4%) than lysine, resulting in an unbalanced profile for many livestock species, though the relatively good methionine content is valuable for laying hens.

Table 101 Nutrient profile of corn gluten feed

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	90.0	1.7	87.3	96.2
Crude protein	% DM	67.2	2.9	56.9	76.2
Crude fibre	% DM	1.2	0.5	0.4	2.7
NDF	% DM	4.1	2.5	1.1	8.6
ADF	% DM	1.6	1.1	0.3	3.7
Lignin	% DM	0.3	0.1	0.2	0.6
Ether extract	% DM	2.9	1.2	1.0	6.5
Ash	% DM	2.1	0.8	1.1	4.6
Starch (polarimetry)	% DM	17.6	3.5	9.1	26.0
Total sugars	% DM	0.5	0.2	0.2	1.2
Gross energy	MJ/kg DM	23.1	0.8	21.2	24.1

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Corn gluten feed contains significantly more cell wall elements than corn grain (crude fibre 6–10% DM, NDF 31–49% DM, ADF 8–13% DM, and a low lignin level of around 1.2% DM), which limits its application in pig and poultry diets. The crude fat content is typically less than 4% DM. Corn gluten feed contains a lot of residual starch, ranging from 11% to more than 30% DM. The ash content is also significant (about 7% DM) (Schroeder, 2010).

Table 102 Amino acid profile of corn gluten feed

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	8.5	0.6	7.5	9.6
Arginine	% protein	3.0	0.3	2.5	3.4
Aspartic acid	% protein	5.8	0.4	5.1	6.7
Cystine	% protein	1.8	0.2	1.5	2.1
Glutamic acid	% protein	20.1	1.3	18.0	22.2
Glycine	% protein	2.5	0.3	2.0	2.9
Histidine	% protein	2.0	0.2	1.7	2.4
Isoleucine	% protein	4.0	0.3	3.4	4.4
Leucine	% protein	15.9	0.7	14.7	17.9
Lysine	% protein	1.7	0.1	1.4	2.1
Methionine	% protein	2.4	0.2	2.1	2.7
Phenylalanine	% protein	6.1	0.3	5.5	6.6
Proline	% protein	8.7	0.4	7.9	9.8
Serine	% protein	4.9	0.3	4.4	5.4
Threonine	% protein	3.3	0.2	2.9	3.6
Tryptophan	% protein	0.5	0.1	0.4	0.6
Tyrosine	% protein	4.8	0.4	4.1	5.4
Valine	% protein	4.5	0.3	3.9	5.1

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

4.2.3 Nutritive value for animal feed

Corn gluten feed is a common ingredient in ruminants' diets, especially in beef and dairy production. Eastridge (2006) found that wet corn gluten feed contains 40 to 60% DM, while the dry product has roughly 88% DM. Its fibre is easily digested by grazing animals, and corn gluten feed can be used to replace grains like corn grain in ruminant feed to reduce the starch load (Zebeli et al. 2010). Although wet corn gluten feed has some nutrient value over dry corn gluten feed, the dried product is more convenient to handle. The bunk life of wet corn gluten feed is a few days in the summer and one to two weeks in the winter. Wet corn gluten feed is only available to growers that are within a reasonable distance of the milling plant due to bunk life and transportation expenses (Biricik et al. 2011). Based on existing data in the literature, *in vivo* organic material digestibility ratings for dry corn gluten feed range from 70 to more than 80%.

This variation in nutrient content could be explained by differences in content (steep to bran ratio, starch and fibre content), as well as process circumstances (drying heat and drying duration). Wet corn gluten feed fibre is somewhat more digestible than dry corn gluten feed, allowing for higher wet vs. dry corn gluten feed consumption. Corn gluten feed has roughly twice the available phosphorus compared to cereal grains. Corn gluten feed has a low palatability and may reduce feed intake (Rapisarda et al. 2012). Corn gluten feed has a small particle size (less than 10% of dry matter is retained by a 1 mm screen aperture), increasing the passage rate.

The nutritional content of corn gluten feed varies widely, and it can differ greatly in terms of crude protein, protein degradation rate, and trace minerals. As a result, having CGF evaluated would be beneficial, particularly if large volumes are used. 'Scorching' would be identified by dark pigmentation and a 'burned' odour. Scorching can reduce the nutritional value of corn gluten feed, especially protein bioavailability and digestion (Cai et al. 2021).

Corn gluten feed can be a valuable feed for poultry due to its high protein content, its high pigment (xanthophyll) content, and its high ME content (typically more than 16 MJ/kg DM). However, its amino acid profile is deficient in lysine; the addition of crystalline amino acids can correct this deficiency. The methionine content is relatively high, much higher than that of soybean meal and relatively close to that of fishmeal, which is a desirable trait for layers diets (Crawshaw 2004). The high xanthophyll concentration of corn gluten feed is valuable in markets where a bright yellow colour in egg yolks, skin, and fatty tissues is associated with good health and premium quality by the consumer, but less so in markets that prefer white chicken skins and light-coloured yolks. The inclusion rate of corn gluten feed in poultry diets is, therefore, driven in part by market demand in terms of colouring. In addition, it is also unpalatable to poultry and can't be added at high inclusion rates (Blair 2008).

4.2.4 Antinutritional factors – nutritional limitations

There are certain restrictions regarding corn gluten feed. First, it has a significant sulphur content in comparison to the animal's needs. During the wet milling process, sulphur dioxide is introduced to help extract starch. The additional sulphur is absorbed by the steep liquid, which is one of the components in corn gluten feed. Sulphur content in corn gluten feed ranges from 0.33 to 0.73% on a dry matter basis. Sulphur poisoning can happen by feeding large volumes of corn gluten feed with a high sulphur content, leading to decreased feed consumption and possibly mortality. Polio-encephalomalacia is caused by an excess of sulphur in the brain (PEM or commonly referred to as 'brainers'). The nervous system is influenced, leading to blindness, loss of coordination and convulsions. Copper insufficiency can be exacerbated by too much sulphur in the diet. Copper is a trace mineral that is necessary for growth and immunity, as well as other metabolic processes.
The risk of the total sulphur content of the diet limits the level of corn gluten feed inclusion in practical feed formulas (Wu et al. 2020).

One point to consider is the significant phosphorus content. Phosphorus is a vital nutrient, but the amount in corn gluten feed (0.9 to 1.1%) greatly surpasses the recommended amount (0.25 to 0.35% DM basis). The risk of excessive phosphorous can be reduced by providing enough calcium in feed to make sure that the ratio of 2:1 is maintained. High phosphorus consumption can lead to high phosphorus excretion by the animal, resulting in high phosphorus amounts in the manure, which leads to environmental pollution if manure used as fertiliser (Loy et al. 2019).

Like other corn products, corn gluten feed can be contaminated with mycotoxins. In addition, wet corn gluten feed spoils quickly. It should be fed within 6–10 days or preserved in a sealed building under anaerobic conditions (Change et al. 2023). Mixing it with other feed ingredients like corn grain, corn silage or haylage has yielded positive results. Packing the material into silo bags is a great way to keep it in good shape. Because of the low pH, there is little visible fermentation in the substance. Wet corn gluten feed didn't lose its nutrient content after being stored in a silage bag for a year. Freezing conditions extend the storage period of wet corn gluten feed in cooler environments. It is even possible to keep uncovered wet corn gluten feed on the floor for 4 weeks in winter with very little deterioration. Hot weather conditions, on the other hand, decrease freshness to 3–5 days, presenting palatability issues (Pan et al. 2014).

4.2.5 Corn gluten feed in the laying hen diet

It has been reported that corn gluten feed is not a very good ingredient for poultry, as its protein and energy content cannot meet the high requirements of poultry production (Rochell et al. 2011). However, as the energy requirement of old laying hens is less than broilers, inclusion of 20–25% corn gluten feed does not impair egg production performance, although it may reduce feed intake and decrease egg weight in young hens. In broilers a maximum inclusion level of 10% is recommended

(Castanon et al. 1990; El-Deek et al. 2009). Corn gluten feed may be a good ingredient in induced moult programs for layers (Biggs et al. 2004).

Table 103 Metabolisable energy content of corn gluten feed for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max
AMEn cockerel	MJ/kg DM	8.7	0.5	8.6	10.1
AMEn broiler	MJ/kg DM	8.5			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

El-Deek et al. (2009) studied the gradual inclusion of corn gluten feed at 4, 8, 12, 16 and 20%, on Hy-Line White layers' feed at 32 weeks of age and reported that corn gluten feed can be incorporated in laying hens' diets at up to 20% without affecting egg production and egg weight or egg mass. Feed consumption was decreased with an increasing corn gluten feed inclusion level of 16 and 20%. Additionally, dietary inclusion of corn gluten feed at up to 16% improved the feed conversion ratio throughout the experimental period. They observed no adverse effect on egg quality traits when corn gluten feed was included at up to 20% as compared to the control diet.

Table 104 Standardised ileal digestibility of amino acids of corn gluten meal in laying hens

Indispensable amino acid	Corn gluten meal
Arginine	90.6
Histidine	88.6
Isoleucine	90.7
Leucine	94.7
Lysine	81.9
Methionine	93.3
Met+Cys	-
Phenylalanine	93.3
Threonine	83.9
Tryptophan	-
Valine	86.8
Dispensable amino acid	
Alanine	94.0
Aspartic acid	85.8
Cysteine	85.0
Glutamic acid	93.5
Glycine	-
Proline	92.6
Serin	90.3
Tyrosine	92.0

(Source: Kim et al. 2012)

Corn gluten feed, however, can be a valuable feed for poultry due to its high protein content, its high pigment (xanthophyll) content and its high ME content (typically more than 16 MJ/kg DM). However, an inclusion of 5–10% corn gluten meal in poultry diets had no detrimental effects on production rates, whereas 20% inclusion reduced feed intake and body weight.

Tangendjaja and Wina (2011) conducted a trial where corn gluten meal inclusion at 0, 2, 4, 6, and 8% was tested in brown layers hens in tropics. Experimental diets were isonitrogenous (17%) and isocaloric (2650 kcal/kg). At the end of a 10-week trial, the results showed that the inclusion of corn gluten meal at all levels did not affect egg production performance including egg mass, egg number, and egg weight. Feed intake was similar to the control diet as well. Increasing levels of corn gluten meal increased the yolk colour score, which related to the higher level of xanthophylls content in the egg yolk. They concluded that corn gluten meal can be easily added at up to 8% (the max level they studied) into the layers' diet with no adverse effects on production.

There is lack of data on the use of corn gluten feed and meal in laying hen nutrition. Very few studies have reported egg production performance and egg quality measures when hens were fed with corn gluten feed or meal. Further research is required to test the optimum level of corn gluten meal inclusion in layers, especially formulating diets based on the total digestible amino acids and correcting amino acids deficiencies using crystalline amino acids. Based on the existing data, it seems that up to 20% corn gluten meal can be safely added to layers diet.

4.2.6 Corn gluten feed in the pig diet

The net energy of corn gluten feed for growing pigs is about 60% of that of corn grain, which is because of higher fibre content (Noblet et al. 2002). Adult sows can better digest dietary fibre, and the Net Energy of corn gluten feed is therefore 10% higher in sows than growing pigs (Noblet et al. 2002). The low lysine and tryptophan content of corn gluten meal is not problematic anymore as crystalline amino acids can be supplemented; however, the standardised ileal amino acid digestibility values are 15% lower than that of corn grain, which is a result of a higher dietary fibre (Noblet & Goff 2000).

Table 105 Corn gluten feed nutritive value for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max
Energy digestibility, growing pig	%	65.4	1.6	64.1	68.6
DE growing pig	MJ/kg DM	12.3	0.8	12.1	14.9
MEn growing pig	MJ/kg DM	11.6	0.1	11.6	12.3
NE growing pig	MJ/kg DM	7.7			
Nitrogen digestibility, growing pig	%	60.2	7.1	60.2	83.0

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

High fibre content introduces a limiting factor at physiological stages with high dietary energy requirements, notably starter pigs, grower pigs and lactating sows. Old studies have reported that a maximum of a 20% inclusion rate of corn gluten meal is recommended for pigs after weaning and growing pigs (Castaing et al. 1990). However, finisher pigs and pregnant sows can have a higher inclusion rate of up to 30% as they handle fibre better (Yen et al. 1971).

In sows, corn gluten feed can be used to dilute energy during gestation to reduce hunger and improve welfare (Ramonet et al. 1999), health status (Meunier-Salaün et al. 2001) and reproductive performance (Matte et al. 1994). An inclusion rate of 50–70% of corn gluten feed with tryptophan supplementation has shown no adverse effects on reproductive performance of gestating sows (Honeyman et al., 1990).

Table 106 Nutritive value of corn gluten meal for growing pigs

Pig nutritive values	Unit	Avg	SD	Min	Max
Energy digestibility, growing pig	%	93.0	3.5	82.7	94.4
DE growing pig	MJ/kg DM	21.4	1.0	18.6	21.9
MEn growing pig	MJ/kg DM	19.8	0.5	18.0	20.0
NE growing pig	MJ/kg DM	12.7			
Nitrogen digestibility, growing pig	%	86.2	4.0	85.3	95.0

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

A recent study conducted by Landin et al. (2014) studied the effect of the inclusion of corn gluten feed on the apparent and standardised ileal digestibility of protein and amino acids, and the apparent ileal and total tract digestibility of energy using cannulated pigs. Diets included 0 (corn-soybean meal diet), 6.5, 13.5, and 19.5% of corn gluten feed. They reported that corn gluten feed inclusion of up to 195 g/kg (19.5%) did not diminish the ileal digestibility (apparent or standardised) of protein and amino acids except that of phenylalanine, cystine and proline. However, ileal digestibility of dry matter and energy were adversely affected (reduced by 0.028 and 0.025% units, respectively, per gram of corn gluten feed increment in the diet).

Table 107 Standardised ileal digestibility of amino acids of corn gluten meal in pigs

Indispensable amino acid	Corn gluten meal 21%	Corn gluten meal 60%
Arginine	86.0	94.4
Histidine	72.9	91.8
Isoleucine	78.1	88.6
Leucine	83.9	92.1
Lysine	65.7	85.9
Methionine	83.4	92.5
Met+Cys	73.5	91.4
Phenylalanine	84.9	91.8
Threonine	70.6	90.6
Tryptophan	65.4	80.3
Valine	74.4	89.1
Dispensable amino acid		
Alanine	-	-
Aspartic acid	-	-
Cysteine	-	-
Glutamic acid	-	-
Glycine	-	-
Proline	-	-
Serin	-	-
Tyrosine	-	-

(Source: Rostango et al. 2005)

Corn gluten meal has a higher nutritive value than corn gluten feed. The net energy content of corn gluten meal is slightly lower than that of corn grain but much higher (+ 40%) than that of soybean meal and corn gluten feed. It contains 60% crude protein and a low concentration of NDF (De Godoy et al.

2009). The standardised ileal digestibility of amino acids in corn gluten feed is greater than in corn (Almeida & Stein 2011).

The data investigating the consequences of including corn gluten meal in pig nutrition are scarce, but similar to corn gluten feed, the high fibre concentration limits the inclusion levels. Following recommendations from Hans Stein Monogastric Nutrition Lab, corn gluten meal may be included at less than 20% in diets fed to growing-finishing pigs, and at less than 10% in diets fed to weanling pigs.

4.2.7 Carbon footprint and sustainability of gluten feed production

The environmental footprint for specific gluten feed is rarely studied and no public information is available.

5 Animal/insect protein sources

Insects (Insecta) are the largest group of organisms in the animal kingdom, and around 2 million insect species have been identified to date. In nature, insects account for a significant part of the ecotone and play very important roles (New 2009). Above all, insects are a source of food for other animals, such as fish, amphibians, reptiles, birds and primates, including humans Raubenheimer & Rothman 2013). Most insects provide key ecosystem services that generate benefits for humans and the environment. Insects play a very important role in the carbon and nutrient cycle by decomposing dead organic matter (Yang & Gratton 2014).

5.1 Insect meal

Insects have just been identified as among the most promising substitute protein sources for resolving the global protein challenge for animal feeds. The major advantage of insects over other protein sources is the low environmental cost of cultivation required to meet global protein demands (da Silva Lucas et al. 2020). Insects meet the nutritional needs of animal feed in terms of nutrients and amino acid profiles and are a part of the natural diets in some animal species (Makkar 2020). Large-scale insect production promises decreased greenhouse gas emissions, reduction in land consumption, and the conversion of organic additives into high-value protein products from an ecological standpoint (Meneguz et al. 2018).

Many insects have been utilised as animal diets, with the black soldier fly (BSF), grasshopper, mealworm and housefly larvae being the most successful ones (Khan 2018). Use of insects in biomass conversion, in particular, is an important example of a novel approach and a long-term circular financial system (Schiavone et al. 2018).

The International Platform of Insects for Food and Feed (IPIFF)predicts that the use of insects for food and feed in the European Union will increase from 500 tonnes in 2020 to even more than 1 million tonnes in 2025, with 3 million tonnes by 2030 (larvae and adult). This upward market trend could be due to the profit that stakeholders get from generating insects and raising consumer awareness of the negative effects of animal feed production (IPIFF 2023-). The energy inserted in organic material used to grow insects is totally transformed into high-value edible protein for farm animals' consumption (Derrien & Boccuni 2018).

5.1.1 Insect meal production globally and in Australia

The insect feed market is growing rapidly globally, from USD 687.8 million in 2018 to USD 1,396.4 million in 2024, with an annual growth rate of 12 per cent (Mordor Intelligence 2019). Currently, 1 trillion to 1.2 trillion insects are raised on farms annually for food and animal feed, which equals 10,000 metric tonnes of insects. There are currently between 79 billion and 94 billion insects alive on farms globally on average, on an average day. The countries that farm the most insects in the world are Thailand, France, South Africa, China, Canada and the United States (Rowe 2020).

As of 2018, the insect feed market was dominated by the Asia-Pacific, in response to increased meat consumption. In the coming years, it is predicted to be Europe's fastest developing market. When looking at the insect feed market by animal category, aquaculture is the largest customer (51%).

Many companies worldwide are involved in the production of insect feed and food, some of which are also involved in the production of animal feed. In a low-carbon footprint approach with high feed utilisation efficiency, insect farming is more socioeconomically and ecologically friendly (Van Huis

2013). In this context, the insect feed and food industries face numerous opportunities and challenges, including lucrative scale manufacturing, high-quality standards, excessive volumes, low environmental impact, and the need for dynamic pricing.

Table 108 Summary of Insect farming by species – crickets

Crickets farmed annually	Total farmed	Slaughtered	Sold live	Other deaths	Average population
Totals	370B–430B	210B–250B	67B–90B	81B–100B	34B–41B
US & Canada	35B–45B	4.6B–11B	19B–28B	7.3B–11B	3.3B–4.4B
Europe	34B–41B	4.3B–10B	18B–25B	7B–9.9B	3B–3.8B
Asia	220B–270B	140B–180B	18B–38B	46B–64B	20B–26B
Middle East & Africa	36B–44B	28B–31B	1.6B–4.7B	7.5B–11B	3.3B–4.1B
Latin America	35B–49B	24B–35B	1.5B–5B	7.5B–12B	3.3B–4.7B

(Adapted from Abraham Rowe 2020)

In 2018, the market for insect feed in China was worth USD 112.2 million, and it is expected to grow to USD 228.3 million by 2024, with a CAGR of 11.9 per cent over the forecast period.

Table 109 Summary of Insect farming by species – black soldier fly

Black soldier fly farmed annually	Total farmed	Slaughtered	Sold live	Other deaths	Average population
Totals	200B–300B	120B–220B	20B–34B	40B–74B	8.2B–16B
US & Canada	1.3B–2.7B	120M–340M	850M–1.7B	280M–610M	56M–140M
Europe	20B–42B	9.6B–21B	5.6B–13B	4.5B–9.9B	900M–2.2B
Asia	6.9B–14B	2.4B–5.1B	3B–6.2B	1.5B–3.3B	300M–750M
Middle East & Africa	130B–260B	93B–190B	6.2B–17B	28B–61B	5.8B–13B
Latin America	6.6B–14B	4.5B–10B	340M–1.3B	1.4B–3.3B	310M–750M

(Adapted from Abraham Rowe 2020)

Animals are fed protein-rich insects to suit the state's growing demand for nutritious meat. As a result, the insect feed industry for livestock, such as poultry and pigs, has developed in China, pushing the overall insect feed market in the country. Government measures in Europe, together with farmers' upkeep of large poultry flocks, are expected to drive insect feed market revenue. Insects are all on course to become an AUD 10 million business in Australia. First Nations peoples have devoured over 60 native bug species in the past. Eating edible insects is more common among young Australians. Australia already has 14 insect-based enterprises.

Table 110 Summary of Insect farming by species – mealworms

Mealworms farmed annually	Total farmed	Slaughtered	Sold live	Other deaths	Average population
Totals	290B–310B	150B–170B	52B– 4B	76B–90B	25B–30B
US & Canada	26B–33B	2.1B–4.4B	16B–21B	6.8B–9.6B	3.9B–5.5B
Europe	27B–31B	4.1B–6.3B	14B–17B	6.8B–9.1B	3.6B–4.9B
Asia	130B–140B	76B–90B	10B–20B	32B–43B	9B–13B
Middle East & Africa	73B–85B	47B–54B	5.7B–8.7B	19B–25B	4.9B–7.4B
Latin America	23B–32B	15B–21B	1B–3.1B	6.1B–9.1B	1.6B–2.6B

(Adapted from Abraham Rowe 2020)

5.1.2 General characteristics

As part of a varied diet, edible insects can provide nutrients and nutritional energy to suit the needs of animals and humans (Barroso et al. 2014). Insect nutritional composition, on the other hand, varies greatly between and within species, depending on the metamorphosis stage, habitat and diet. They are high in proteins, carbs, lipids and a variety of minerals (such as calcium, iron, zinc and phosphorus), as well as vital vitamins (e.g. vitamin A, B complex and vitamin C). According to studies, edible insects are suitable for food because they contain 77 to 98 per cent protein. The essential amino acids content of insect protein such as cysteine, lysine, methionine and threonine is high (Da-Silva Lucas et al. 2020). Insects such as BSF, crickets, silkworms, houseflies, yellow mealworms, grasshoppers and housefly maggots have been mentioned as potential protein meal sources in livestock feed.

Insects contain high levels of fatty acids, particularly unsaturated fatty acids, and their nutritional value originates from high concentrations of protein and amino acids (Van Huis 2013). Yellow mealworms (*Tenebrio molitor*; TM), common houseflies (HF) and black soldier flies (BSF) have amino acid profiles similar to that of soybean meal and fishmeal (Veldkamp & Bosch 2015). The insect species' protein level is comparable to soybean meal but lower than fishmeal, and its fat content is higher than both soybean meal and fishmeal. Their huge potential as a feed ingredient is due to their limited lifespan and, as a result, their ability to be reared on a large scale at competitive trade prices when compared to other species recommended as animal feeds.

The inclusion of insect meal in the diet of fish, poultry and dairy cattle has been examined earlier as an alternative to the traditional protein and fat sources of fish, oil and soybean meal (Makkar 2018). Mammalian performance, gut morphological traits and product quality have all benefited. Insects have also acquired popularity as dietary additives to improve intestinal health. Antimicrobial peptides, lauric acids and chitin immune-boosting capabilities are bio-bacterial components that have health benefits in monogastric animals (Gasco et al. 2018; Veldkamp et al. 2021).

5.1.3 Nutritive value for animal feed

House cricket

The house cricket (*Acheta domestica*) is easy to farm and can produce from 6 to 7 generations per year. It is omnivorous and can eat a large range of organic materials. Production is feasible at temperatures higher than 20°C, the ideal temperature being 28–30°C. 2000 insects can be bred on

1 m². The cricket population self-regulates by cannibalism (Hardouin et al. 2003). The nutrient composition of the house cricket consists of 28.5% DM (fresh, not dried), 63.3% crude protein, 18.5% NDF, 10.0% ADF, 17.5% crude fat and 5.6% ash.

Table 111 Nutrient composition of the house cricket, fresh

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	28.4	4.5	22.9	33.2
Crude protein	% DM	63.3	5.7	55.0	67.2
NDF	% DM	18.3	2.9	15.7	22.1
ADF	% DM	10.0		9.6	10.4
Ether extract	% DM	17.3	6.3	9.8	22.8
Ash	% DM	5.6	2.4	3.6	9.1

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The house cricket has 10.1 g/kg calcium, 7.9 g/kg phosphorous, 1.2 g/kg magnesium and 40 mg/kg manganese. Its lysine content is about 5.4% of the protein and methionine 1.4.

Table 112 Mineral composition of the house cricket

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	10.1	5.3	2.1	13.2
Phosphorus	g/kg DM	7.9		7.8	7.9
Magnesium	g/kg DM	1.2		0.8	1.6
Manganese	mg/kg DM	40	10	30	53
Zinc	mg/kg DM	215	60	159	297
Copper	mg/kg DM	15	7	9	22
Iron	mg/kg DM	116	58	63	197

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Amino acid content of the house cricket, especially essential amino acids, is very close to soybean meal amino acid content; however, some essential amino acids are higher and some lower compared to that of SBM.

Table 113 Amino acid profile of the house cricket

Amino acids	Unit	SBM-Avg*	Avg	Min	Max
Alanine	% protein	4.3	8.8	8.8	8.9
Arginine	% protein	7.3	6.1	6.1	6.1
Aspartic acid	% protein	11.3	7.7	7.1	8.4
Cystine	% protein	1.6	0.8	0.8	0.8
Glutamic acid	% protein	17.9	10.4	10.4	10.5
Glycine	% protein	4.2	5.2	5.1	5.3
Histidine	% protein	2.7	2.3	2.2	2.3
Isoleucine	% protein	4.6	4.4	4.3	4.6
Leucine	% protein	7.7	9.8	9.5	10.0
Lysine	% protein	6.2	5.4	5.4	5.4
Methionine	% protein	1.4	1.4	1.3	1.5
Phenylalanine	% protein	5.1	3.0	2.8	3.2
Proline	% protein	5.0	5.6	5.5	5.6
Serine	% protein	4.6	4.6	4.2	5.0
Threonine	% protein	3.8	3.6	3.6	3.6
Tryptophan	% protein	1.4	0.6	0.5	0.6
Tyrosine	% protein	3.5	5.2	4.9	5.5
Valine	% protein	4.8	5.1	4.9	5.2

* The amino acid content of soybean meal (SBM) has been included as a reference for comparison.
Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Grasshopper meal

Orthoptera, like other insects, are highly nutritious and contain large amounts of protein. Various grasshopper, katydid and cricket species are already used for pets and zoo animals and have been investigated for livestock feeding.

Table 114 Nutrient profile of grasshopper meal

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	91.7	2.3	89.5	94.0
Crude protein	% DM	57.3	11.8	29.2	65.9
Crude fibre	% DM	8.5	4.1	2.4	14.0
Ether extract	% DM	8.5	3.1	4.2	14.1
Ash	% DM	6.6	2.5	4.3	10.0
Gross energy	MJ/kg DM	21.8	2.0	19.5	23.7

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Because of the availability of large quantities of dead locusts, resulting from locust outbreaks, they are a good potential feed for livestock, especially poultry, and locust meal has been proposed as a poultry feed since the 1930s. Poultry are also a means to control locust and grasshopper populations. Since the early 2000s, the development of aquaculture in Africa and Asia and the search for alternative sources of protein have led to trials on the feeding value of locusts and grasshoppers for catfish and tilapia.

Table 115 Mineral profile of grasshopper meal

Minerals	Unit	Avg
Calcium	g/kg DM	1.3
Phosphorus	g/kg DM	1.1
Potassium	g/kg DM	1.1
Sodium	g/kg DM	3.2
Magnesium	g/kg DM	1.5
Zinc	mg/kg DM	10
Iron	mg/kg DM	13

Avg: average or predicted value.
(Source: Feedipedia.org)

The nutrients profile of grasshopper meal has been reported by many investigators. Locusts and other Orthoptera species are generally rich in protein, in the 50–65% DM range, though some lower values (less than 30%) have been reported. The dry matter content is 23–35%. The fat content is variable and ranges from relatively low values (less than 5%) to over 20%. The calcium content is low, as in other insect species. The fibre content may be significant and increases with age; adult crickets contain up to 22% DM of NDF vs. 12% for nymphs (Finke 2002). On average, grasshoppers include 146.0 ppm calcium, 153.0 ppm phosphorous, 56.40 ppm magnesium, 344.0 ppm potassium, 22.50 ppm zinc, 05.30 ppm copper, 01.40 ppm manganese and 32.20 ppm iron. Lysine content is 4.7% of protein and methionine is 2.3%.

Table 116 Amino acid profile of grasshopper meal

Amino acids	Unit	SBM-Avg*	Avg	Min	Max
Alanine	% protein	4.3	4.6	4.1	5.1
Arginine	% protein	7.3	5.6	3.7	7.4
Aspartic acid	% protein	11.3	9.4		
Cystine	% protein	1.6	1.1	0.5	1.7
Glutamic acid	% protein	17.9	15.4		
Glycine	% protein	4.2	4.8	4.7	4.8
Histidine	% protein	2.7	3.0	1.9	4.2
Isoleucine	% protein	4.6	4.0	3.9	4.1
Leucine	% protein	7.7	5.8	5.6	5.9
Lysine	% protein	6.2	4.7	3.4	5.9
Methionine	% protein	1.4	2.3	2.3	2.3
Phenylalanine	% protein	5.1	3.4	2.3	4.5
Proline	% protein	5.0	2.9	2.1	3.8
Serine	% protein	4.6	5.0		
Threonine	% protein	3.8	3.5	2.9	4.0
Tryptophan	% protein	1.4	0.8		
Tyrosine	% protein	3.5	3.3	3.1	3.6
Valine	% protein	4.8	4.0	3.8	4.3

* The amino acid content of soybean meal (SBM) has been included as a reference for comparison.
Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The addition of grasshopper meal to chickens' diets has been reported to improve feed conversion and protein digestibility. The physical quality parameters of chicken meat did not alter when grasshopper meal was added to the diet, but the sensory aspects appear to increase (Brah et al. 2017).
Black soldier fly larvae

Black soldier fly larvae are a high-value feed source, rich in protein and fat. They contain about 40–44% DM protein. The amount of fat is extremely variable and depends on the type of diet, and on its fat content, for which the reported fat values are: 15–25% DM (larvae fed on poultry manure, Arango Gutierrez et al. 2004); 28% DM (swine manure, Newton et al. 2005); 35% DM (cattle manure, Newton et al. 1977); and 42–49% DM (oil-rich food waste, Barry 2004). They tend to contain less protein and more lipids than housefly maggots (*Musca domestica*). Ash content is relatively high but variable, from 11 to 28% DM. The larvae are rich in calcium (5–8% DM) and phosphorus (0.6–1.5% DM) (Newton et al. 1977; St-Hilaire et al. 2007b; Arango Gutierrez et al. 2004; Yu et al. 2009).

Table 117 Nutrient composition of black soldier fly larvae (*Hermetia illucens*), dehydrated

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	91.3	1.1	90.0	92.5
Crude protein	% DM	42.1	1.0	41.1	43.6
Crude fibre	% DM	7.0			
Ether extract	% DM	26.0	8.3	15.0	34.8
Ash	% DM	20.6	6.0	14.6	28.4
Gross energy	MJ/kg DM	22.1			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Black soldier fly contains 2.14% calcium, 1.15% phosphorous, 0.39% magnesium and 1.35% potassium. The micromineral content of black soldier fly includes Zn (13.10 mg/kg), Cu (11.20 mg/kg), Mn (23.20 mg/kg) and Fe (20.40 mg/kg) (Shah et al. 2022). Jamaican field crickets, black soldier fly larvae (BSFL) and mealworms are all potential insect protein sources for livestock.

Table 118 Mineral composition of black soldier fly larvae, dehydrated

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	75.6	17.1	50.0	86.3
Phosphorus	g/kg DM	9.0	4.0	6.4	15.0
Potassium	g/kg DM	6.9			
Sodium	g/kg DM	1.3			
Magnesium	g/kg DM	3.9			
Manganese	mg/kg DM	246			
Zinc	mg/kg DM	108			
Copper	mg/kg DM	6			
Iron	mg/kg DM	1370			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia)

The nutritional composition of BSFL is insufficient for use as protein-rich biomass in feed for pig, fish, and poultry produced for human consumption. Insect digestibility is also influenced by processing

processes and restrictions, as well as the insect species and breeding substrate (e.g., time and temperature). Average dry matter digestibility of intact BSF larvae was 71 ± 2.8% when fed to leopard geckos and 26 ± 9.9% for mountain chicken frogs. Protein, magnesium, potassium, sodium, iron, zinc, copper, and molybdenum also saw significant gains in digestibility (Boykin et al., 2020). Some discrepancies in indigestion could be due to different proportions of larvae in different trials (Jayanegara et al. 2017).

The amino acid profile is particularly rich in lysine (6–8% of the protein). The dry matter content of fresh larvae is quite high, in the 35-45% range, which makes them easier and less costly to dehydrate than other fresh by-products (Newton et al. 2008).

Table 119 Amino acid profile of black soldier fly larvae, dehydrated

Amino acids	Unit	SBM-Avg*	Avg	SD	Min	Max
Alanine	% protein	4.3	7.7	0.8	6.9	8.8
Arginine	% protein	7.3	5.6	0.3	5.3	6.1
Aspartic acid	% protein	11.3	11.0	1.8	8.5	12.5
Cystine	% protein	1.6	0.1			
Glutamic acid	% protein	17.9	10.9	2.4	8.7	13.5
Glycine	% protein	4.2	5.7	0.8	5.2	6.8
Histidine	% protein	2.7	3.0	1.0	2.3	4.5
Isoleucine	% protein	4.6	5.1	0.5	4.7	5.6
Leucine	% protein	7.7	7.9	0.6	7.1	8.4
Lysine	% protein	6.2	6.6	0.9	6.0	8.0
Methionine	% protein	1.4	2.1	0.3	1.7	2.4
Phenylalanine	% protein	5.1	5.2	0.4	4.6	5.6
Proline	% protein	5.0	6.6		5.5	7.7
Serine	% protein	4.6	3.1	1.9	0.3	4.2
Threonine	% protein	3.8	3.7	1.7	1.3	4.8
Tryptophan	% protein	1.4	0.5			
Tyrosine	% protein	3.5	6.9	0.7	6.0	7.7
Valine	% protein	4.8	8.2	1.3	6.4	9.1

* The amino acid content of soybean meal (SBM) has been included as a reference for comparison.
Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

As can be seen from the table above, black soldier fly larvae have a comparable amino acid content to that of soybean meal, which is particularly important for essential amino acids. The valine and tyrosine content of black soldier fly larvae is double that of soybean meal.

Animal feeding trials have demonstrated the high biological value of edible insects' protein. The protein quality and biological value of giant grasshopper were evaluated in rats and compared with soybean and cray fish containing diets in a 28-day feeding trial (Solomon et al. 2008). The rats' weight gain, food efficacy ratio (gain in weight/food intake) and protein efficacy ratios (weight gained/protein intake) were determined and compared to a standard chow on the same protein intake and calorific basis. The giant grasshopper protein resulted in 80–100% higher weight gain, feed efficiency and protein efficiency values compared to control chow.

5.1.4 Antinutritional factors – nutritional limitations

Antinutritional factors in locust meal (grasshoppers and crickets)

Pesticides

Locusts and grasshoppers are considered as agricultural pests and therefore may be sprayed with insecticides as a control programme. This can cause bioaccumulation of pesticides residues in consumed insects. However, this is a risk when traditional harvesting and consuming of insects in the wild is practised and there is no control over chemical applications (van Huis et al. 2013). For instance, after the epidemic in Kuwait in 1988/89, substantial levels of pesticide residues from organophosphorus chemicals were found in locusts that were harvested for food (Saeed et al. 1993). Traditional grasshopper eating in Korea decreased in the 1970s due to the required use of pesticides in rice fields, but it returned in the 1990s with the rise of organic rice cultivation. Children in rural regions of Mali consumed less grasshoppers as a result of the increased usage of pesticides in cotton farming, which had an adverse effect on the amount of protein intake of these kids (van Huis et al. 2013). Broiler chickens fed locusts that were treated with an insecticide had a lower feed intake than chickens given untreated locusts, according to reported study (Gibril 1997).

Lead contamination

An incident of lead poisoning in the Mexican community in California in 2000 was linked to the intake of chapulines grasshoppers (*Sphenarium*) that were brought into the country from Mexico. Up to 2500 ppm of lead is thought to have bioaccumulated in the insects from the tailings of Oaxacan silver mines (Handley et al. 2007).

Presence of spines

Large spines on the tibia of grasshoppers and locusts may result in intestinal constipation, which has occasionally required surgery in humans and has been proved to be lethal in monkeys when experienced in the wild. Therefore, it is advised to grind or remove the wings and legs before ingestion (van Huis et al. 2013).

Chitin content

Chitin has two completely opposite effects, as it provides health effects such as antimicrobial, immunological and antitumor activities, but it also can trigger allergic reactions. On the other hand, it is like an insoluble fibre, reduces energy and protein density, and dilutes nutrient content for monogastric animals. Chitin content varies significantly between common mealworm and other species. For other species, the difference between the species has not been confirmed. Chitin is considered an indigestible fibre with protective effects. The removal of chitin improves the digestibility of insect protein.

Table 120 The content of chitin for each species of edible insects

Species	Chitin g/100g
Giant mealworm larva	6 ± 0.8
Common mealworm pupa	12 ± 0.2
Common mealworm larvae	13 ± 0.4
Field cricket nymph	7 ± 0.7

(Adámková, et al. 2017)

A variety of factors have an impact on the bioavailability of edible insect-related nutrients, including insect rearing (quality of the substrate, environmental conditions, development state) and food processing (physical, chemical and/or biological changes).

5.1.5 Insect meal in the laying hen diet

Among the different types of insect meal, black soldier fly seems to be an ideal protein-rich alternative for soybean meal in poultry feed as it has a similar amino acid profile to soybean meal (Newton et al. 2005). The use of insect meal in laying hens' feeding has been poorly investigated. The potential of black soldier fly larvae on food- and farm-waste was recently rediscovered after the problem had already been extensively studied and reported in the early 70s and 80s (e.g. Hale 1973; Newton et al. 1977; Sheppard 1983). Early studies focused more on the waste management side rather than feed production, but today's top concern is how to use waste resources in a framework of nutrient recycling and sustainability (Popa & Green 2012; Van Zanten et al. 2015).

In a study by Wang et al. (1996), it was reported that dried ground mealworms can successfully replace fishmeal in the laying hen diet and improve egg production by 2.4%. Agunbiade et al. (2007), in a study on 50-week-old laying hens, showed that maggot meal could replace 50% of fishmeal protein (5% of the diet) without adverse effects on egg production and shell strength, but 100% replacement of fishmeal with maggot meal decreased egg production.

Table 121 Standardised ileal digestibility of amino acids of black soldier fly Larvae in laying hens

Indispensable amino acid	**Insect meal (black soldier fly larvae)**
Arginine	86.9
Histidine	79.4
Isoleucine	88.4
Leucine	83.2
Lysine	78.5
Methionine	81.4
Met+Cys	-
Phenylalanine	86.1
Threonine	79.4
Tryptophan	94.8
Valine	85.4
Dispensable amino acid	
Alanine	86.0
Aspartic acid	74.1
Cysteine	66.4
Glutamic acid	80.3
Glycine	-
Proline	85.4
Serin	79.2
Tyrosine	91.6

(Source: Kaewtapee et al. 2023)

Maurer et al. (2016) conducted a feeding trial with Lohmann Selected Leghorn laying hens where partly de-fatted dried *Hermetia illucens* larvae meal (Hermetia meal), which was reared on vegetarian by-products of the pasta and convenience food industry, replaced soybean meal in the control diet. Experimental diets contained 12 and 24 g/100 g Hermetia meal replacing 50 or 100% of soybean cake

used in the control feed, respectively. The experiment lasted 3 weeks and no significant differences were observed between the experimental and the control groups with regard to performance (egg production, feed intake). Albumen weight tended to decrease with 24 g/100 g of Hermetia meal inclusion (100% soybean meal replacement), however, yolk and shell weights did not differ. No mortality and no sign of adverse effects on health were found. Their overall conclusion emphasised that Hermetia meal can be a valuable component of layer diets, although its production needs to be scaled up and costs need to be reduced.

Marono et al. (2017) studied the effect of the use black soldier fly larvae (*Hermetia illucens*) as a complete replacement of soybean meal on the productive performance and blood profiles of Lohmann Brown Classic laying hens, from 24 to 45 weeks of age. The soybean meal in the basal diet was completely replaced with black soldier fly larvae (17.0% total inclusion), however, the two diets were isonitrogenous and iso energetic. The replacement of soybean meal with black soldier fly larvae improved the feed conversion ratio, however, lay percentage, feed intake, average egg weight and egg mass were higher in hens fed the control (soybean meal) diet. Blood parameters were analysed, and hens fed with black soldier fly larvae had a higher level of globulin and lower level of cholesterol and triglycerides.

In a study conducted by Brah et al. (2017), the potential effects of gradually substituting fishmeal by grasshopper meal in laying hens' diets were investigated using 140 ISA Brown laying hens from 20 to 36 weeks of age. Layers were fed 5 experimental diets in which fishmeal was gradually replaced by grasshopper meal at the proportions of 0, 25, 50, 75 and 100%. The results demonstrated that the inclusion of grasshopper meal in layers' feed had no significant effects on the laying rate, daily feed intake, feed efficacy and efficiency, egg weight and shape index, albumen height and eggshell thickness. The egg quality parameters, such as egg yolk colour and Haugh unit, were improved by replacing fishmeal with grasshopper meal. The use of grasshopper meal enhances the commercial quality of eggs by improving the yolk colour, due to the carotenoids found in the grasshopper meal (Finke 2015).

The data on the optimum inclusion rate of insect meal, especially black soldier fly larvae in layer nutrition, are limited and due to the variation in the composition of the insect meal, which was discussed earlier, the results are controversial, and it is difficult to make solid conclusions. For grasshopper meal, we found only one paper. It seems that a high-quality black soldier fly larvae may successfully replace at least 50% of the soybean meal in layer feed. Further research is required to identify the potential of full soybean meal replacement by black soldier fly larvae in laying hens.

5.1.6 Insect meal in the pig diet

Table 121 below summarises the findings of the existing literature on different types of insect meal fed to pigs at different stages of growth. Driemeyer (2016) evaluated the effect of black soldier fly larvae inclusion as an alternative protein source in pig creep diets on growth performance, blood and microbiology of manure. In their study, black soldier fly larvae were included at 3.5% rate replacing fishmeal in pig creep diet, and the experimental and control diets were fed to 315 pure bred Large White and Landrace piglets from 10 to 28 days of age. Cumulative feed intake and average dairy weight gain were not affected by the experimental diet, and it was concluded that black soldier fly larvae can sustain normal growth and development of piglets after weaning. The second phase of the study evaluated the blood immunology of the piglets and the mineral bioavailability of the black soldier fly larvae. The haematological and biochemical concentrations were not different between the control and the black soldier fly larvae groups, however, the experimental diet increased haemoglobin and haematocrit levels over the trial. They concluded that black soldier fly larvae could be regarded

as a safe protein source that can be included at 3.5% to partially replace other traditional sources, maintaining piglet performance with no adverse effects.

Ao and Kim (2019) studied the inclusion of dried mealworm powder (*Ptecticus tenebrifer*) at 0, 1 and 2%, replacing fishmeal in weaned piglets from 21 to 56 days of age. Body weight at 1% inclusion rate of mealworm powder was lower than the control diet at 56 days of age (21.0 vs. 21.8 kg, respectively). The feed conversion ratio at 1 and 2% mealworm powder inclusion was also higher than the control diet (1.24 and 1.23, respectively) from 21 to 28 days of age.

Inclusion of 5 or 10% mealworm (*Tenebrio molitor*) in the diets for weaned piglets from 35 to 63 days of age did not affect performance parameters including feed intake, weight gain and feed efficiency (Meyer et al. 2020). Only daily weight gain was lower in pigs fed diets with 10% mealworm compared to pigs fed the control diets and the 5% inclusion level (573 vs. 636 and 614 g/d, respectively). The authors stated, however, that the number of pigs in the study was rather limited for a classic performance trial.

In another study by Jin et al. (2016) dried mealworm (*Tenebrio molitor*) larvae were included at 0, 1.5, 3.0, 4.5 and 6.0% as a substitute for soybean meal, and the growth performance of weaned piglets was studied from 28 to 63 days in two split phases. Feed intake, body weight and average daily gain improved linearly when the piglets were fed increasing levels of dried mealworm larvae in feeding phase I (28–42 days of age). Body weight tended to increase linearly as dried mealworm levels were increased during phase II (42–63 days of age). The overall feed conversion ratio tended to improve by increasing dried mealworm levels up to the highest inclusion level at 6%. They concluded that, adding dried mealworms to weaned pigs' diets at up to 6% as a replacement for soybean meal enhances growth performance and nutrient digestibility without impairing immunological responses.

Biasato et al. (2019) reported that the growth performance of the weaned piglets fed black soldier fly larvae (*Hermetia illucens*) included at 0, 5 and 10% inclusion rates in a two-phase experiment was not affected except for feed intake in the second phase. A linear response of feed intake to increasing black soldier fly larvae meal was observed (940, 950 and 970 g/d, respectively). These authors concluded that partially defatted BSF larva meal can be used as a feed ingredient in weaned piglet feeding with no adverse effects on growth performance, nutrient digestibility, blood parameters, and gut morphology traits.

Spranghers et al. (2018) also evaluated the growth performance of weaned piglets fed experimental diets including 4% and 8% full-fat and 5.4% defatted black soldier fly larvae from 21 to 36 days of age. All the experimental diets including full-fat and defatted black soldier fly larvae and the control diet were isonitrogenous and isoenergetic. Black soldier fly larvae were included in the diet at the expense of toasted soybeans. Growth performance was not affected by dietary treatment. The apparent fecal digestibility of the control feed did not differ significantly to that of the insect-containing feed (protein digestibility between 77 and 78% for all treatments). Whereas the ileal protein digestibility of the 8% full-fat black soldier fly larvae diet (67.4%) was lower than that of the control (69.7%), the values for the 4% full-fat and the defatted black soldier fly larvae diets were higher (73.3%). In conclusion, the trial with piglets showed that a substantial amount of soybean products (meal and/or toasted beans) can be replaced by black soldier fly larvae without adverse effects on performance.

In a study by Chia et al. (2019), pigs were fed experimental diets where black soldier fly larvae gradually replaced fish meal at 5 inclusion rates (0%, 25%, 50%, 75% and 100%). Black soldiers fly larvae was included at 18.5% at to fully replace fish meal. Partial or full replacement of fish meal by black soldier fly larvae did not negatively affect growth performance and feed efficiency. Dietary black soldier fly larvae inclusion at all levels did not influence blood cholesterol levels (Chia et al. 2019).

The inclusion of housefly larvae at 10% to replace an equal level of fishmeal in growing pig diets, from 11 to 29 kg, resulted in a higher average daily gain (290 vs. 250 g/d, respectively) and a lower feed conversion ratio (3.29 vs. 3.64, respectively), compared to pigs fed the control diet (Dankwa et al. 2000). Experimental diets with 10% housefly larvae had a similar crude protein to the control diet with 10% fishmeal, however, the crude fat content in the experimental diets was higher. Dressing percentage, fat measurements and eye muscle area were not significantly affected. The carcass fat contents were, however, higher in the housefly larvae meal-fed pigs. Housefly larvae meal could, therefore, be used to replace dietary fishmeal completely without compromising growth performance or the economics of pig rearing.

In finishing pigs (76–115 kg) inclusion of 4% dried black soldier fly larvae powder at the expense of soybean meal resulted in a higher final body weight (120 vs. 116 and 115 kg, respectively) and average daily weight gain (980 vs. 890 and 860 g/d, respectively) and a lower feed conversion ratio (2.85 vs. 3.21 and 3.24, respectively), compared to 0 and 8% inclusion rates (Yu et al. 2019). Feed intake was not affected by the dietary inclusion of black soldier fly larvae powder. The authors suggested that the underlying mechanism for the improved gain and feed conversion ratio may be associated with the up-regulated expression of genes related to the lipogenic potential and muscle fibre composition. The greater level of chitin in the black soldier fly larvae diet may be the cause of the positive response of the finishing pigs to the diets containing 8% black soldier fly larvae.

Based on the reported data and the existing literature, it seems that black soldier fly larvae and mealworm larvae can potentially replace traditional protein sources such as fishmeal and soybean meal in pig diets at varying inclusion rates, depending on the age and growth stage of the pig. Young pigs after weaning can be fed with up to 4% full-fat and 5% defatted black soldier fly larvae with no adverse effects on growth or development. Grow-finisher pigs can handle slightly higher inclusion rates of up to 6%, with enhanced effects of the black soldier fly or mealworm on the production performance and gut health. Additional refinement, such as removing the cuticle and rendering, may be helpful to increase the inclusion of insect meal in pigs' diet, however, further research is required to confirm these findings and identify better processing methods.

Table 122 Summary of the literature on different types of insect meal in pig feed and nutrition

Pig species/type	Age/BW (d)	Insect product	Target replacement	Insect meal inclusion %	Results	Reference
Nursing piglets (Large White and Landrace)	10-28	Milled and sieved (3 mm) black soldier fly larva	Fishmeal	0, 3.5	Growth performance was not affected.	Driemeyer (2016)
Weaned piglets	21-36	Full-fat black soldier fly larva and defatted BSF	Toasted soybeans	0, 4, 8	Growth performance was not affected.	Spranghers et al. (2018)
Weaned piglets ([Duroc×Yorkshire]×Landrace)	21-56	Dried mealworm powder	Fishmeal	0, 1, 2	Final body weight at 1% inclusion was lower than the control diet. FCR at 1 and 2% inclusion was higher than the control diet. BWG at 1% inclusion was lower than the control diet during 29-42 and 21-56 d of age.	Ao and Kim (2019)
Weaned piglets (Topigs)	21-61	Partially defatted black soldier fly larva meal	Soybean meal	0, 5, 10	FI increased linearly with increasing inclusion levels of black soldier fly larvae.	Biasato et al. (2019)
Weaned piglets	21-61	Black soldier fly larva oil	Corn oil	0, 2, 4, 6	BW and BWG increased linearly and FCR decreased linearly with increasing inclusion levels of BSFL.	Van Heugten et al. (2019)
Weaned piglets ([Yorkshire× Landrace] × Duroc)	28-63	Dried Mealworm (*Tenebrio molitor* larva	Soybean meal and soy oil	0, 1.5, 3.0, 4.5, 6.0	FI, BW and BWG increased linearly at increasing inclusion levels during phase I (28-42 d).	Jin et al. (2016)
Weaned piglets (Piétrain× [German Landrace×German Edelschwein])	35-63	TM larvae	Soybean meal	0, 5, 10	BWG at 10% inclusion was lower than the 0% and 5% inclusion.	Meyer et al. (2020)
Growing pigs (Large White)	11-29 kg	Ground sun-dried HF larvae	Fishmeal	0, 10	BWG was higher and FCR was lower for HF larvae-fed pigs compared to fishmeal-fed pigs.	Dankwa et al. (2000)
Growing pigs (Large White× Landrace)	18-53 kg	Dried BSF larval meal	Fishmeal	0, 9, 12, 14.5, 18.5	Growth performance was not affected.	Chia et al. (2019)

Finishing pigs ([Duroc× Landrace] ×Large White)	76-115 kg	Dried BSF larvae powder	Soybean meal	0, 4, 8	BW and BWG at 4% inclusion were higher and FCR was lower than the 0% and 8% inclusion.	Yu et al. (2019)

BSF – Black soldier fly (*Hermetia illucens*).
BW – Body weight.
BWG – Body weight gain.
FCR – Feed conversion ratio.
FI – Feed intake.
HF – Housefly (*Musca domestica*).
PT – Mealworm (*Ptecticus tenebrifer*).
TM – Mealworm (*Tenebrio molitor*).

5.1.7 Carbon footprint and sustainability of Insect meal production

In a study by Vauterin et al. (2021), it was reported that in most cases insect feed reduces GHG emissions (67.8% lower) and global warming potential (GWP) while producing protein under different scenarios (Vauterin et al. 2021).

Smetana et al. (2016) also mention that, in general, insect application for livestock feed is more environment-friendly than traditional protein sources. The study produced the information summarised in the table below, to show diet variations under multiple scenarios in the spectrum of environmental impacts recalculated for 1 kg of protein powder. The table shows varied results, which could be explained by the variations in production designs, diets and insect species (Smetana et al. 2016).

Table 123 Comparison of impact results for midpoint categories with literature sources

LCA studies	Midpoint impact categories		
	GWP, kg CO_2 eq.	**Energy use, MJ**	**Land use, m^2 arable**
HL[A] (van Zanten et al. 2015)	0.77	9.3	0.032
HL[B] (Roffeis et al. 2015)	-	159.85–288.15	2.79–5.32
BSF[C] (Komakesh at al. 2015)	1.24	1.512	-
BSF[D] (Muys et al. 2014)	-	13.4–64.06	0.01–0.04
MW[E] (Oonincx & de Boer 2012)	3.5	44.32	4.68
MW[F] (Smetana et al. 2015)	7.1–7.55	80.0–101.0	3.75–3.8
BSF[G] (Salomone et al. 2016)	2.1	15.1	0.05
BSF model[G] (Smetana et al. 2016)	1.36–15.1	21.2–99.6	0.032–7.03

LCA – Life cycle assessment.
HL – Larvae of *Musca domestica*.
BSF– Larvae of *Hermetia illucens*.
MW– Larvae of *Tenebrio molitor*.
GWP – Global warming potential.
Diets – [A] Poultry manure and house waste; [B] Pig manure; [C] Waste; [D] Brewery wastes; [E] Mixed diet; [G] Food wastes; [H] Variety of diets; (recalculated for FU 1 kg of insect protein meal).

5.2 Silkworm pupae meal

Silkworms are the caterpillars of the moth species raised for silk production. The silkworm (*Bombyx mori*) is a protein-rich insect meal, which is produced in large scale for livestock feed, notably for monogastric animals. Ninety per cent of silk production comes from mulberry silk, *Bombyx mori* L. (Bombycidae), although a few other species such as *Antheraea assamensis*, *Antheraea mylitta*, *Antheraea paphia*, and *Samia cynthia ricini* (Saturniidae) also produce silk. Silkworms and their metabolites are nutritionally, medicinally and economically valuable.

The silkworm lifecycle is divided into four separate stages: ova, larva, pupa and imago. When silkworms mature from larvae to pupae, they produce silk in the cocoon (Yang et al. 2010). The silkworm makes a protective cocoon out of raw silk as it enters the pupa stage. The pupa produces an enzyme that causes a hole in the cocoon to open, allowing the moth to emerge. The pupae are killed before they produce the enzyme that produces silk by boiling, drying, or soaking in NaOH (Govorushko 2019). In Asian countries such as Japan, Korea, India and, particularly, China, silkworm pupae are commonly consumed as food, although only the pupae of two silk-producing moths are edible. Silkworm pupae are also used in traditional Chinese medicine to alleviate hypertension and fatty liver (Zhou & Han 2006).
After reeling silk from the cocoons, the fresh spent silkworm pupae are normally thrown nearby without proper disposal. This may cause environmental pollution and unpleasant odour in the surrounding areas of silk-producing factories. Using the silkworm pupae, which is the by-product of silk production, to feed poultry and livestock or to produce valuable biological compounds such as chitin, protein, oil, and fatty acids (α-linolenic acid), is a better strategy to lessen the silk industry's environmental impact (Wu et al. 2014).

As an animal feed supplement, silkworm pupae have positive effects on moulting time, antioxidant capacity and nutrient digestibility. The hydrolysed peptides of silkworm have several physiological functions, including improving immunity, and antitumor and antioxidant activity.

However, further research is required to develop and enhance extraction methods, purification and structural identification. In addition, the mode of action and the underlying mechanism of silkworm pupae's pharmacological functions need to be studied further. Current enzymatic hydrolysis methods for extracting peptides from silkworm pupae provide low yields. As a result, enzymatic hydrolysis must be optimised in order for this technology to be commercialised (Battampara et al. 2020). For every 1 kg of raw silk approximately 8.014 kg wet silkworm pupae is used for extraction, and 2 kg of dry silkworm pupae is produced as a waste by-product. Silkworm pupae may replace fishmeal in poultry and fish species (Rahimnejad et al. 2019), which helps reduce other sources of protein in livestock and fish farming.

Silkworm pupae meal production globally and in Australia

In 2011, global production of silkworm cocoons suitable for reeling was approximately 485,000 tons. Given that raw silk output was 161,000 tons, it can be estimated that 324,000 tons of fresh pupae (equivalent to 65,000 tons when dried) were produced that year (FAO 2012). However, these FAO estimates are significantly lower than China's official statistics, which reported 440,000 tons of dry pupae production in 2009 (Wei ZhaoJun et al. 2009). The leading silk-producing countries include China, India, Uzbekistan, Brazil, Thailand, and Vietnam (FAO 2012).

About 91,765 tonnes of raw silk were produced by the world's silk industry in 2020. After China, India was the second-largest producer of raw silk (35,820 tonnes in 2019–2020; 33 770 tonnes in 2020–2021). China produced roughly 788,000 tonnes of silkworm cocoons in 2020.

5.2.1 General characteristics

Silkworm pupae in general are a good source of protein, fat, minerals and vitamins, being an energy-dense animal feed ingredient offering up to 230 Kcal energy per 100 grams (Melgar-Lalanne et al. 2019). Based on the literature, silkworm pupae have a balanced nutritional profile, that makes them a suitable protein-rich ingredient for animal feed. Silkworm meal is much cheaper compared to soybean meal, and it is a good alternative to replace soybean meal, although its quality is lower than fishmeal.

On a dry matter basis, silkworm pupae have 49–54% protein, however, it can reach to 80% in defatted meal (Nowak et al. 2016). The amino acid profile of the protein is very balanced and contains all essential amino acids. In fact, silkworm contains all of the amino acids required by the human body and in the appropriate proportions, based on the recommendations of the FAO/World Health Organization (WHO) (Köhler et al. 2019).

Insect meals are also a great source of fat. Silkworm pupae have 25–30% crude fat on a dry matter basis (Kouřimská & Adámková 2016). The fat content of the silkworm pupae is high in monounsaturated and polyunsaturated fatty acids (70%–80% of the fatty acid content) and low in saturated fat content (Payne et al. 2016), while about 1% is unsaponifiable matter in oil, including campesterol, β-sitosterol and cholesterol. Silkworm pupae, in particular, contain about 71% α-linolenic acid. Functional fatty acids are abundant in silkworm pupae. Furthermore, their total lipid content has a high oxidative stability, as the synergistic effect of tocopherol and phospholipids prevents lipid oxidation (Wang, Hu et al. 2016).

Saturated fat is abundant in some insect species, such as weevil larvae and termites, but not in silkworm pupae (Payne et al. 2016). This is particularly important, as high dietary intake of saturated fat is associated with higher risks of cardiovascular diseases (World Health Organization (WHO) 2015). The lipids of silkworm pupae have medicinal properties. Studies have shown that feeding silkworm pupae oil to rats for approximately 18 weeks leads to a significant increase in high-density lipoprotein (HDL) cholesterol levels, while notably reducing triglyceride and total cholesterol levels. In addition, silkworm pupae oil has regulated the plasma lipid and lipoprotein levels in the serum of rats by activating the apoproteins and lipid-metabolising enzymes. This function makes silkworm oil a potential drug to treat hyperlipidemia (Wu et al. 2021).

Insect meals have abundant mineral levels such as phosphorus, calcium, potassium, sodium, iron, zinc, magnesium, copper and manganese (Kouřimská & Adámková 2016). Furthermore, the heavy metal concentration of silkworm pupae (lead, arsenic, cadmium and mercury) is below the maximum permitted limit for human consumption and animal feed (Köhler et al. 2019). However, there is a great variation in the reported values for the mineral content of silkworm pupae in the literature. The variation could be explained by geographical location, seasonality and diet.

Insect meals have a variety of vitamins; however, they are deficient in vitamin A. Silkworm pupae has fair levels of vitamin B members such as thiamine, riboflavin and niacin. Importantly, the mineral and vitamin content of farm-bred silkworm pupae can be adjusted by manipulating their diet (Kouřimská & Adámková 2016).

5.2.2 Nutritive value for animal feed

As it is mentioned before, Silkworm pupae meal has been used to feed livestock, mostly monogastric species (poultry, pigs, and fish), but also ruminants, due to its high protein content (Makkar et al.

2014). Fresh spent silkworm pupae have a high moisture content, and are easily perishable, therefore spent pupae are generally sun-dried and ground. Defatted silkworm pupae meal is less perishable and has high protein content than intact meal. After drying, the spent silkworm pupae should be ground properly to assure more uniform mixing in rations (Sheikh et al. 2018).

Table 124 Nutrient composition of non-defatted and dried silkworm pupae

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	91.4	4.4	81.1	97.5
Crude protein	% DM	60.7	7.0	51.6	70.6
Crude fibre	% DM	3.9	1.1	2.5	5.8
Ether extract	% DM	25.7	9.0	6.2	37.1
Ash	% DM	5.8	2.4	3.3	10.6
Gross energy	MJ/kg DM	25.8			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Silkworm pupae's crude protein content ranges from 50% DM to more than 80% DM (for defatted meal). However, the true protein (calculated as the sum of amino acids) in silkworms was found to correspond to only 73% of the crude protein content (Finke 2002). This is due to the presence of chitin, as chitin contains nitrogen. However, the chitin content of pupae meal is only 3–4% DM, which is relatively low (Finke 2002; Suresh et al. 2012). The presence of chitin and insoluble protein may also explain the presence of fibre, and values of 6–12% DM of ADF have been reported (Finke 2002; Ioselevich et al. 2004). Silkworm pupae are a good source of calcium and iron and have high potassium content (34.0 mg/g), with a low Na/K ratio (0.08) and a high zinc content (36 µg/g), all of which are important for health and nutrition. They have a tocopherol content of roughly 10 mg per 100 g, which is substantially greater than most typical foods.

Table 125 Mineral composition of non-defatted and dried silkworm pupae

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	3.8	3.0	0.7	8.4
Phosphorus	g/kg DM	6.0	2.4	1.9	8.5
Magnesium	g/kg DM	3.7	2.5	1.9	6.5
Manganese	mg/kg DM	18		9	28
Zinc	mg/kg DM	224	126	79	310
Copper	mg/kg DM	15	12	2	25
Iron	mg/kg DM	326	67	262	395

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The lysine (6–7% of the protein) and methionine (2–3% of the protein) contents are particularly high. Overall, silkworm pupae have a highly digestible protein. The amino acid score and protein digestibility-corrected amino acid score of silkworm pupae are 100 and 86, respectively. The digestibility of amino acids is reported to be 94% for lysine and 95% for methionine (Penkov et al. 2002).

Table 126 Amino acid content of non-defatted and dried silkworm pupae

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	5.8		5.5	6.1
Arginine	% protein	5.6		4.4	6.8
Aspartic acid	% protein	10.4		9.9	10.9
Cystine	% protein	1.0		0.5	1.4
Glutamic acid	% protein	13.9		12.9	14.9
Glycine	% protein	4.8		4.6	4.9
Histidine	% protein	2.6		2.5	2.7
Isoleucine	% protein	5.1		4.4	5.7
Leucine	% protein	7.5		6.6	8.3
Lysine	% protein	7.0		6.5	7.5
Methionine	% protein	3.5		2.3	4.6
Phenylalanine	% protein	5.2		5.1	5.2
Proline	% protein	5.2		4.0	6.5
Serine	% protein	5.0		4.7	5.3
Threonine	% protein	5.1		4.8	5.4
Tryptophan	% protein	0.9			
Tyrosine	% protein	5.9		5.4	6.4
Valine	% protein	5.5		5.4	5.6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Non-defatted pupae meal is rich in fat, typically in the 20–40% DM range. Defatted meal contains less than 10% oil in the DM. Silkworm oil contains a high percentage of polyunsaturated fatty acids, notably linolenic acid (18:3), with reported values ranging from 11 to 45% of the total fatty acids (Ioselevich et al. 2004; Rao 1994; Usub et al. 2008). Compared to other animal by-products, silkworm pupae meal is relatively poor in minerals (3–10% DM).

5.2.3 Antinutritional factors – nutritional limitations

Novel protein ingredients such as silkworm pupae may create food allergies, which is the major concern in the feed and food industry (Pali-Schöll et al. 2019). Many examples of allergic reactions to silkworm pupae, such as acute allergies and anaphylactic shocks, have been recorded in recent years (Araujo et al. 2014). The antinutritional factors of silkworm pupae include phytate (72.89–110.16 mg/g) and phytin phosphorus (20.54–31.03 mg/g), as well as tannic acid, alkaloid, flavonoids, saponin and oxalate. However, the level of these antinutritional factors is reported to be lower than the human/animal tolerance threshold, and therefore silkworm pupae are considered a safe food and feed ingredient (Omotoso 2015).

No toxic compounds have been identified in silkworm pupae. Studies with silkworm pupae as a feed ingredient in poultry diets have reported a similar mortality rate as the control/standard diet.

5.2.4 Silkworm pupae meal in the laying hen diet

Silkworm pupae meal is a valuable protein source that can be used in poultry feeding, though it is of slightly lower quality than fishmeal. Compared to broiler chickens, less research has been conducted

on laying hens, however, they appear to accept silkworm meal well (Saikia et al. 1971; Joshi et al. 1979; Joshi et al. 1980).

Table 127 Metabolisable value of silkworm pupae for poultry

Poultry nutritive values	Unit	Avg
TME poultry	MJ/kg DM	10.2

Avg: average or predicted value.
(Source: Feedipedia.org)

Solomon and Yusufu (2005) and Ji et al. (2016) stated that silkworm meal's amino acid profile is almost similar but superior to soybean meal for better performance. In particular, silkworm meal contained higher contents of the essential amino acids (g/100 g of total amino acids) such as lysine (7.52), methionine + cystine (4.85), arginine (6.31), phenylalanine (5.58) and valine (5.70). However, the ratio of leucine and isoleucine (7.04:4.73) was lower than that of soybean meal (7.5:4.6). As leucine and isoleucine have antagonism, meaning that an excess of one can negatively impact the utilisation and/or absorption of the other, it is necessary to include their ratio in the formulation of poultry ration (Ospina-Rojas et al. 2020). One study on breeder roosters discovered that reproductive ability was negatively impacted by eating silkworm pupae meal (Mahanta et al. 2004).

Table 128 Summary of existing data in the literature regarding feeding silkworm pupae to laying hens

Country	Trial	Results	Reference
India	Layer chicks: substitution 0-100% of fishmeal (6% diet)	Reduction of intake and weight gain in diets based on 50-100% silkworm meal.	Deshpande et al. 1996
India	Layer chicks: substitution 0-100% of fishmeal	Deoiled silkworm meal replaced 100% fishmeal.	Virk et al. 1980
India	Laying hens: comparison to other alternative feeds	Better technical and economic performance for silkworm meal compared to other feeds (feed-to-egg conversion ratio, egg size, shell thickness, grading, light yellow yolk, no mortality, feed cost, cost per dozen eggs).	Saikia et al. 1971
India	Layer chicks: 6 to 8% silkworm meal replacing a protein concentrate	Profitability, growth, and egg production performance higher with 6% silkworm meal.	Khatun et al. 2005
Bangladesh	Breeder males: Substitution 0-100% of fishmeal	Detrimental effects of Muga silkworm meal on some breeding performance indicators (ejaculate volume, quantity and quality of spermatozoa).	Mahanta et al. 2004
Pakistan	Laying hens. Substitution 0-100% of soybean meal (1-year)	No adverse effect on performance, nutrient digestibility, blood profile and egg quality. Replacement of soybean meal with silkworm meal at 50% replacement in the ration achieved better results.	Ullah et al. 2017

In a recent study conducted by Ullah et al. (2017), the effects of replacing soybean meal with silkworm meal on production performance, apparent total tract digestibility of nutrients, blood profile and egg quality traits in white leghorn layers were examined. Five experimental diets that included silkworm

pupae at increasing ratios replacing soybean meal at 0, 25, 50, 75, and 100% were fed to 150 white leghorn layers from 52 to 58 weeks. All diets were iso-nitrogenous and isocaloric. The weight of the bird, daily feed intake (g/day/bird), hen-day production (%), average egg weight (g) and feed conversion ratio were not negatively affected by the inclusion of silkworm pupae at all levels.

Apparent total tract digestibility of nutrients was not different in the control group compared to silkworm pupae-fed groups. Blood profile and egg quality parameters also showed no significant differences among dietary groups. Silkworm inclusion at all levels did not have any adverse effects on the egg weight, albumen height, yolk weight or shell thickness. The authors concluded that silkworm meal can be effectively used as an alternative protein source to fully replace soybean meal without any adverse effects on layer production performance.

Further research is required to study the optimum inclusion level of silkworm pupae in laying hen rations. It seems that silkworm pupae together with other protein sources such as sunflower meal, cottonseed meal and crystalline amino acids have the potential to fully replace soybean meal in feed.

5.2.5 Silkworm pupae meal in the pig diet

Limited information is available on the utilisation of silkworm pupae for pigs. Some experiments showed that silkworm pupae meal was a good replacement for traditional protein sources. Non-defatted silkworm meal was able to substitute up to 100% of the soybean meal in diets for growing and finishing pigs in Brazil without having any negative effects on growth efficiency or carcass traits. When the substitution rate exceeded 50%, there was a negative impact on intake, which was attributed either to the diet's higher calorie density or its reduced palatability. However, a higher lysine content in silkworm pupae diet compensated for lower intake and improved feed conversion rate (Coll et al. 1992). Some studies in India, have reported 100% of replacement of fishmeal with silkworm pupae meal with no adverse effects on growth and production performance (Medhi 2011; Medhi et al. 2009a; Medhi et al. 2009b).

In a study conducted by Kumar (2017), unconventional silkworm pupae were used as an economic substitute for protein concentrate in grow-finisher pigs at 0, 50, and 100% of fishmeal replacement. Feed intake was reduced by the inclusion of silkworm pupae at 50 and 100% replacement levels, Feed conversion ratio was the lowest for the 50% diet (2.15 ± 0.16) followed by the control (2.63 ± 0.34) and 100% (2.68 ± 0.22) replacement rates. Body weight gain was not different for the 3 experimental groups; however, it was numerically higher in the control group (77.75 ± 4.34) followed by 50% (72.75 ± 4.57) and 100% (66.08± 5.76) replacement groups. Full replacement of fishmeal with silkworm pupae reduced the cost per kg body weight by nearly 10%, and hence it was concluded that silkworm pupae meal may be an economic alternative protein ingredient to replace traditional protein sources in grow-finisher pigs.

Similar to the conclusion regarding laying hens, fresh experiments are required to revisit the optimum inclusion rate of silkworm pupae in pigs' diet, especially for grow-finish pigs where old studies reported full replacement of fishmeal. As soybean meal inclusion is much higher in pig rations, therefore it might be possible to replace 40–50% of the soybean meal with silkworm pupae.

5.2.6 Carbon footprint and sustainability of silkworm pupae meal production

Research on LCAs of edible insects is in its infancy stage and more data on GHG emissions of farmed insect species are required to record the overall environmental and carbon footprint of insect production systems (Halloran et al. 2016).

5.3 Slaughterhouse/animal by-products

In the meat industry, great quantities of waste are generated during the slaughtering process. Slaughterhouse waste is the portion of a killed animal that cannot be sold as meat or used in human consumption; nevertheless, the eating habits of individuals in a certain geographic area distinguish between edible and inedible by-products. Dress percentage is the edible part of the carcass and deducting it from 100 determines the amount of animal by-products (Adhikari et al. 2018). Bones, flesh viscera, blood, feathers, tendons, skin and the contents of the gastro-intestinal system, blood, and internal organs are examples of animal by-products. By-products were previously a popular cuisine in Asia, but health concerns have shifted the focus to non-food applications such as pet food, pharmaceuticals, cosmetics, and animal feed (Muduli et al. 2019). Animal by-products can also include expired/out-of-date food products, such as former foodstuffs that are no longer intended for human consumption but may contain elements of animal origin (fat, milk, eggs and gelatine).

Animal by-products consist of adequate, if not exceptional, nutritional value that can be fed to farm animals as a cost-effective alternative to traditional feedstuffs and/or valuable supplements. According to reports, around a third to a half of the entire weight of killed animals is wasted as by-products of the livestock and poultry industries.

About 50–54% of each cow, 52% of each sheep or goat, 60–62% of each pig, 68–72% of each chicken and 78% of each turkey (dress percentage) is utilised for human consumption, and the remainder is not usable in human food chain. A solid waste of 27.5% of the animal weight (i.e. 275 kg/ton of total live weight killed) is generated by the bovine slaughterhouse. This figure is equal to 2.5 kg/head of sheep or goat equivalent to 17% of the animal weight. Pigs are more efficient meat producers, and every slaughtered pig produces about 2.3 kg/head waste, equivalent to 4% of animal weight. Dress percentage in chickens is about 65%, and on average 35% of by-products are produced in the poultry abattoir, with the waste composition consisting of 57.37% feathers and skin; 20.35% intestines; 14.8% legs and others (< 1%) (Mozhiarasi and Natarajan 2022).

The poultry industry produces massive amounts of solid waste. Poultry by-product meal is made of the remaining chicken parts from poultry processing plants and slaughterhouses. Poultry by-product meal is defined by the Association of American Feed Control Officials (AAFCO; US) as the ground, rendered, clean sections of the carcass of killed poultry (excluding feathers) such as necks, heads, feet, undeveloped eggs, gizzards and intestines. Culled laying hens can also be used to make whole poultry carcass meal (spent hen meal), especially in regions where there is no market for culled laying hens (Malher et al. 2015). Poultry by-product meal can be added to chicken, fish, and pet food such as for dogs and cats.

Animal by-products must be used to keep the livestock business economically competitive with vegetable protein sources, according to the economics of the global meat industry. Furthermore, every industry must transform waste into value-added products and recycle nutrient to assure sustainability (Irshad & Sharma 2015).

5.3.1 Slaughterhouse by-products production globally and in Australia

Solid waste generation rises in tandem with population growth, urbanisation, and industrialisation. Furthermore, rising living standards, disposable incomes, and consumption of goods and services all contribute to increased solid waste output. According to the World Bank, the majority of the world's waste is generated in East Asia and the Pacific region, as shown by the worldwide waste generation trend and projections from 2016 to 2050. In 2009, over 55.5 billion broilers were slaughtered worldwide, yielding around 16.5% offal. With an average slaughter weight of 1.8 kg, each broiler

should yield 0.3 kg offal. Broiler offal production was then expected to be at 17 million tonnes per year, excluding laying chickens that have already laid eggs (FAO 2011). The use of poultry by-product meal for livestock feeding was banned in 2002 in the European Union (Regulation (EC) No 1774/2002) (European Community 2002).

The total meat production had reached 350 million tons in 2022 with the breakdown of different meat types – Beef and buffalo (22%), sheep and goat (5%), pigs (35%) and poultry (40%) (FAO 2023). Overall, slaughterhouse/abattoir processes generate a large amount of organic waste with significant quantities of suspended solid, liquid and fat.

Here is a summary of the livestock products In Australia, in the September quarter 2022:

- Cattle slaughtered increased by 1.9% to 1.5 million tonnes.
- Beef production increased by 2.3% to 475,628 tonnes.
- Sheep slaughtered decreased by 5.2% to 1.7 million tonnes.
- Chickens slaughtered increased by 1.0% to 178 million tonnes.
- Pigs slaughtered increased by 0.8% to 1.4 million tonnes.
- Pigs slaughtered increased by 0.8% to 1.4 million tonnes.

Considering the dress percentage of 50% in cattle to 70% in chicken, it can be estimated that massive quantities of animal by-products are generated per year.

5.3.2 General characteristics

Animal by-products are very rich in essential nutrients. Some may contain compounds that have medicinal properties or are nutritionally vital such as amino acids, hormones, minerals and vitamins. Some of the animal by-products such as blood, kidneys, lungs, brains, spleen and other organs have a high moisture content, and some other organs consist of high proportions of carbohydrates such as liver (Jayathilakan et al. 2012).

Among the animal by-products, pork tail has the highest fat content and lowest moisture. The protein content of cattle's liver, tail, ears and feet is similar to that of lean meat tissue, although the ears and feet contain a lot of collagens. Mechanically deboned beef and pork contain at least 14% protein and up to 30% fat. As the animal by-products contain higher quantities of connective tissues, their protein content has a different amino acid profile and is very rich in proline and hydroxyproline but lower in tryptophan and tyrosine.

Organ meats have a higher nutrient content than lean meats. The most riboflavin is found in the kidney and liver (1.697–3.630 mg/100 g), which is 5–10 times more than lean meat. Niacin, vitamin B12, B6, folacin, ascorbic acid and vitamin A are all found in abundance in the liver. Vitamin B6, B12 and folacin are also abundant in the kidney. Lamb kidneys, pork, liver, lungs and spleen are all excellent sources of iron and vitamins.

Beef, lamb and veal livers have the highest copper levels. They provide 90–350 per cent of the copper RDA (2 mg/day). Manganese levels are highest in the liver (0.128–0.344 mg/100 g). The thymus and sweetbreads, on the other hand, have the highest levels of phosphorus (393–558 mg/100 g) and potassium (360–433 mg/100 g) in meat by-products. Except for the brain, kidney, lungs, spleen and ears, most other by-products have sodium levels that are similar to or lower than those observed in lean tissue. The maximum calcium concentration is seen in mechanically deboned pork (315–485 mg/100 g) (Seong et al. 2014; Devatkal et al. 2004b; Jayathilakan et al., 2012).

Organ meats have a higher proportion of polyunsaturated fatty acids than lean tissue. Monounsaturated fatty acids are found in the smallest amounts in the brain, chitterlings, heart, kidney, liver and lungs, while polyunsaturated fatty acids are found in the highest amounts. Organ meats contain three to five times as much cholesterol (260–410 mg/100 g) as lean meat, as well as substantial amounts of phospholipids. When compared to other beef by-products, brain has the highest quantity of cholesterol (1,352–2,195 mg/100 g) and the highest quantities of phospholipids.

Animal blood is an important by-product with a high protein and heme iron content (Wan et al. 2002). A healthy animal's blood is normally sterile. It contains a high protein content (17.0%), as well as an excellent amino acid balance. Blood makes up a large portion of an animal's body mass (2.4–8.0% of its live weight). Pigs, cattle and lambs have average blood recovery percentages of 3.0–4.0, 3.0–4.0, and 3.5–4.0%, respectively. However, the use of blood in feed may result in a dark-coloured, unpalatable final product. Because of its functional qualities and absence of colour, plasma nutritionally, is the most interesting part of blood (Lynch et al. 2017).

The most important and common animal protein sources used in the feed industry are poultry by-product meal, meat and bone meal, blood meal, feather meal and fishmeal (Webster et al. 2016).

5.3.3 Nutritive value for animal feed

Poultry by-product meal

The composition and nutritive value of poultry by-product meal varies greatly depending on the substrate that is used for processing and the processing conditions (Frempong et al. 2019). The protein content of poultry by-products is about 60% on average, however, it can be as high as 75–90%, with ash and fat contents less than 10 and 15%, respectively. Other poultry by-products are of lower quality, with protein levels ranging from 55 to 75% and greater levels of ash (up to 15%) and fat (between 15 and 30%) (Srour et al. 2016).

Table 129 Nutrient composition of poultry by-product meal

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	92.3	2.4	85.3	97.8
Crude protein	% DM	60.2	7.3	47.3	86.1
Ether extract	% DM	27.9	6.9	8.6	38.7
Ether extract, HCl hydrolysis	% DM	24.4	6.4	12.1	35.0
Ash	% DM	10.6	4.6	2.7	23.8
Gross energy	MJ/kg DM	24.4	2.5	19.9	27.4

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia)

Although the protein content of poultry by-product meal is higher than that of soybean meal, its amino acid digestibility coefficients are lower, and this should be taken into account in commercial feed formulation practices (Çenesiz et al. 2020).

Table 130 Mineral composition of poultry by-product meal

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	20.3	9.6	6.7	55.8
Phosphorus	g/kg DM	10.1	4.8	2.0	28.3
Potassium	g/kg DM	4.1	0.8	2.9	5.5
Sodium	g/kg DM	2.7	0.6	1.6	4.8
Magnesium	g/kg DM	0.7	0.2	0.5	0.9
Manganese	mg/kg DM	18	9	11	34
Zinc	mg/kg DM	67	41	10	126
Copper	mg/kg DM	41	59	5	157
Iron	mg/kg DM	5107	4872	212	13825

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Extruding poultry by-products with cereal grains produces a protein-rich component that outperforms meat and bone meal. There are processing techniques that help improve the digestibility of poultry by-product meal, including enzymatic or NaOH treatment of spent hen meal. Treatment of spent hen carcass with sulphite liquor has reported to reduce the protein digestibility (Mirzakhani et al. 2018). Poultry by-product meal is rich in calcium at 2–5% and phosphorous at 1–2%.

Table 131 Amino acid profile of poultry by-product meal

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	5.5	0.3	5.1	6.2
Arginine	% protein	6.6	0.4	5.5	7.1
Aspartic acid	% protein	6.9	0.3	6.6	7.8
Cystine	% protein	2.5	0.9	1.2	3.4
Glutamic acid	% protein	10.9	0.6	10.3	12.4
Glycine	% protein	8.8	0.8	7.9	11.5
Histidine	% protein	1.8	0.5	1.1	2.5
Isoleucine	% protein	3.9	0.3	3.5	4.4
Leucine	% protein	7.0	0.3	6.2	7.5
Lysine	% protein	4.4	1.3	0.8	6.3
Methionine	% protein	1.4	0.3	1.0	1.9
Phenylalanine	% protein	3.9	0.3	3.2	4.6
Proline	% protein	8.0	1.8	6.3	14.0
Serine	% protein	6.3	1.4	3.8	7.8
Threonine	% protein	3.9	0.2	3.6	4.5
Tryptophan	% protein	0.7	0.2	0.5	1.2
Tyrosine	% protein	2.6	0.3	2.2	2.9
Valine	% protein	5.4	0.6	4.5	6.6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value.
Max: maximum value.
(Source: Feedipedia.org)

Meat and bone meal

With a well-balanced amino acid composition, meat and bone is a great source of supplementary protein. The protein fraction typically has a high degree of digestibility, between 81 and 87%. (Kellems et al. 1998).

Table 132 Nutrient composition of meat and bone meal

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	95.8	1.5	90.1	98.8
Crude protein	% DM	54.9	3.4	45.6	68.6
Ether extract	% DM	11.4	1.9	6.8	17.2
Ether extract, HCl hydrolysis	% DM	12.1	1.9	8.0	18.2
Ash	% DM	30.5	3.6	15.7	40.6
Gross energy	MJ/kg DM	10.7			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Meat and bone meal typically contain 28 to 36% ash, 7 to 10% calcium, and 4.5 to 6% phosphorus. The mineral content of meat and bone meal may prevent it from being used in some diet formulations as the main source of supplemental protein.

Table 133 Mineral composition of meat and bone meal

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	101.1	16.8	42.1	148.2
Phosphorus	g/kg DM	48.7	7.7	22.1	68.9
Potassium	g/kg DM	4.6	0.7	3.5	6.1
Sodium	g/kg DM	7.5	1.3	5.2	11.5
Magnesium	g/kg DM	2.2	0.2	1.9	2.3
Manganese	mg/kg DM	26	13	8	47
Zinc	mg/kg DM	114	11	98	142
Copper	mg/kg DM	21	11	6	42
Iron	mg/kg DM	615	402	268	1390

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Meat and bone meal is a great source of calcium, phosphorus and certain other minerals (K, Mg, Na, etc.) in addition to the protein with a balanced amino acids profile. Like other animal products, meat and bone meal is a good source of vitamin B-12. Excessive heating during processing will reduce the digestibility of the protein fraction.

Table 134 Amino acid profile of meat and bone meal

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	7.6	0.6	6.4	8.9
Arginine	% protein	6.9	0.4	6.0	8.1
Aspartic acid	% protein	7.4	0.5	6.4	8.5
Cystine	% protein	1.1	0.3	0.6	1.8
Glutamic acid	% protein	11.9	0.6	10.5	13.3
Glycine	% protein	12.7	1.3	10.3	15.3
Histidine	% protein	2.1	0.4	1.4	2.8
Isoleucine	% protein	2.9	0.2	2.3	3.4
Leucine	% protein	6.0	0.5	5.2	7.3
Lysine	% protein	5.0	0.4	4.1	5.9
Methionine	% protein	1.3	0.1	1.0	1.6
Phenylalanine	% protein	3.4	0.2	3.0	3.9
Proline	% protein	8.1	0.6	6.9	9.1
Serine	% protein	4.0	0.5	3.2	5.1
Threonine	% protein	3.3	0.3	2.7	4.1
Tryptophan	% protein	0.6	0.1	0.4	0.9
Tyrosine	% protein	2.2	0.2	1.9	2.7
Valine	% protein	4.4	0.4	3.6	5.6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

5.3.4 Antinutritional factors – nutritional limitations

Multiple factors and criteria affect the inclusion rate of the poultry by-products in feed including price, nutritive value, palatability, potential contamination with pathogens or chemical compounds, antinutritional factors, and effects on digestion dynamics. It is widely known that improper use of animal by-products can create challenges and spread diseases. The outbreak of some diseases such as classical swine fever, avian influenza, bovine spongiform encephalopathy (BSE) or contamination with chemicals (dioxins) in the past years and decades have been proof that animal by-products should be closely monitored and regulated to eliminate economic impacts and jeopardise public health safety.

To ensure the safety of using animal by-products in the feed industry, appropriate protection measures and legislative quality controls have been in place for many years. These include Good Manufacturing Practices (GMP), Hazard Analysis Critical Control Points (HACCP), and alert systems like the Rapid Alert System for Food and Feed, which help manage potential risks associated with rendered animal products and food waste in feed. (Jedrejek et al. 2016).

Dioxins, such as polychlorinated dibenzodioxins and polychlorinated dibenzofurans, are potential pollutants of animal feed that may be linked to the usage of animal by-products. Human actions, such as the burning of plastics and the widespread use of chlorinated chemicals in industry, are significantly linked to their existence in the environment. Because dioxins are highly lipophilic chemicals, they bioaccumulate in fat tissues when contaminated plant-based feeds are used in animal feed industry.

By-products such as offal from healthy birds are considered to be safe, however, offal from dead or unhealthy birds can spread infections and diseases to animals and humans. Therefore, when processing bird carcasses, a robust monitoring system should be used to avoid the mixing of offal from healthy and sick birds, unless this risk is otherwise managed by an energy-intensive rendering process (Williams 2010). In addition, high-fat poultry by-product meal (16% fat) is susceptible to rancidity, which can cause diarrhoea, reduced feed intake (anorexia), poor animal performance, myopathy, hepatomegaly, steatites, haemolytic anaemia, and vitamin A and E deficiencies (Srour et al. 2016). It should be noted that poultry by-product meal is still prohibited in the European Union for livestock feeding (2011).

Prohibition of meat and bone meal in livestock feeding

In Western Europe between the 1980s and 1990s, the bovine spongiform encephalopathy (BSE) epidemic was spread by meat and bone meal and other processed animal proteins (EFSA 2022)). Because of this, many nations have banned the feeding of meat and bone meal to ruminant animals, while others only permit the feeding of meat and bone meal from monogastric species. Notably, Regulation (EC) No. 1774/2002 in the European Union outlawed the use of meat and bone meal for cattle feeding in 2002 (European Community 2002).

5.3.5 Slaughterhouse by-products in the laying hen diet

Sahraei et al. (2012) reported the chemical composition of poultry by-product consisted of 92% dry matter, 69.63% crude protein, 16.53% crude fat, 1.30% Ca and 0.56% P in their study, which was different from NRC (1994) values except for the dry matter. They also reported that the chemical composition, mineral content and protein quality of poultry by-product meal may vary greatly and need to be evaluated continuously.

Table 135 Apparent metabolisable energy content of poultry by-products for poultry

Poultry nutritive values	Unit	Avg	SD	Min	Max
AMEn cockerel	MJ/kg DM	15.2	2.8	11.7	20.0

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

In laying hen diets, poultry by-products have no detrimental effects on performance and egg quality up to an incorporation level of between 5% (Senkoylu et al. 2005) and 7.5% (Hosseinzadeh et al. 2010). In the study by Hosseinzadeh et al. (2010), the optimum inclusion rate of poultry by-product was estimated when Hy-Line laying hens were fed experimental diets including 0, 2.5, 5 and 7.5% of poultry by-product meal added to the control diet. Production performance including feed intake, egg production, egg mass, egg weight, and feed conversion ratio were not affected by the experimental diets.

The egg quality parameters (egg shape index, eggshell thickness, eggshell weight, Haugh unit and yolk colour score) of hens fed poultry by-product meal at different inclusion rates were measured and, except yolk colour score, there were no effects of poultry by-product meal (up to the highest inclusion rate) on the studied traits. The yolk colour score was less for the control group, and it was improved

by the inclusion of poultry by-product meal. The authors concluded that up to 7.5% poultry by-product meal can be safely included inlaying hens' diet (Hosseinzadeh et al. 2010).

Table 136 Standardised ileal digestibility of amino acids of meat and bone meal in laying hens

Indispensable amino acid	Meat and bone meal
Arginine	75.2
Histidine	68.5
Isoleucine	72.7
Leucine	74.7
Lysine	70.7
Methionine	72.8
Met+Cys	65.3
Phenylalanine	78.7
Threonine	68.3
Tryptophan	-
Valine	72.7
Dispensable amino acid	
Alanine	72.3
Aspartic acid	60.4
Cysteine	51.9
Glutamic acid	71.1
Glycine	66.9
Proline	61.4
Serin	67.2
Tyrosine	-

(Source: Adedokun et al. 2014)

The effect of the inclusion of meat and bone meal in the diet of old laying hens on their egg production and the quality of their eggs has been also reported by Bozkurt et al. (2004). In their study, meat and bone meal was included at levels of 2%, 4%, and 6% in the 84-week-old laying hens' diet for 20 weeks. The results showed that a 2% inclusion of meat and bone meal improved hen-day egg production in laying hens, whereas 4% and 6% inclusion rates had no additional benefits. Feed intake, egg weight, and feed efficiency were not affected by the experimental diets. The Haugh unit value of eggs in the 6.0% meat and bone meal diet was significantly higher than with the other treatments. There were no significant effects of MBM inclusion on yolk colour score, yolk height, eggshell thickness, eggshell weight, and eggshell strength. However, MBM inclusion in a diet had a significant beneficial effect on eggshell quality.

Senkoylu et al. (2005) studied the effects of poultry by-product meal and feather meal, incorporated separately and in combination in the diet, on laying hens and concluded the following:

1. The feather meal and poultry by-product meal can be incorporated at up to 5% separately and at up to 8% (4 + 4%) in combination with minimal adverse effect on laying performance and egg quality.
2. Nutrient, especially amino acids, variability in poultry by-products can lead to lowered Haugh Unit when its dietary inclusion is high.
3. The inclusion level of feather meal could be increased in laying hens due to its high metabolisable energy content, but the quality of the amino acids of feather meal must be considered during feed formulation practices.

5.3.6 Slaughterhouse by-products in the pig diet

By-product meal may be utilised similarly to meat meal in pig rations. It is generally palatable and can be fed to all classes of pigs without major problems. Its amount of digestible lysine (about 2.5% DM) is comparable to that of soybean meal. The amino acid composition is similar to that of meat meal or meat and bone meal, but of slightly lower quality than that of fishmeal. The amino acid digestibility seems to be lower than for soybean meal, and quite variable according to the processing method (Kerr et al. 2019).

The DE and ME values of poultry meal vary from 16.3 to 18.5 MJ/kg and from 14.9 to 17.2 MJ/kg, respectively. The NE value of poultry meal can be calculated from ME values using a NE/ME ratio of 70% (Rostagno et al. 2005).

Table 137 Slaughterhouse by-products nutritive value for pigs

Pig nutritive values	Unit	Avg	SD	Min	Max
Nitrogen digestibility, growing pig	%	87.0	1.4	85.0	88.0
Digestible Energy (DE)	MJ/kg	16.3			
Metabolisable Energy (ME)	MJ/kg	18.5			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Some old studies have reported that poultry offal meal can replace 50% of soybean meal (equal to 14% of the diet) with no depression in growth performance or carcass characteristics in growing-finishing pigs (Van Lunen et al. 1991; Van Lunen et al. 1990). A different study concluded that chicken offal meal also replaced 33% of fishmeal in pig diets, maintaining performance or carcass characteristics to the same level as the control diet (Fanimo et al. 1997). Previous reports show that poultry by-product meal can be added to starter diets at up to a 10% inclusion rate with no negative impact on growth performance of piglets (Veum et al. 1999; Keegan et al. 2004; Keegan et al. 2003).

Orozco-Hernandez et al. (2003) conducted a trial from weaning to slaughter and concluded that up to 7.5% poultry by-product meal can be safely added to the diet with no adverse effects on the production performance. Kannan et al. (2008) have reported that for young piglets with a growth rate of ≤ 350 g/day from 10 to 45 kg of body weight, poultry by-product meal can fully replace the protein component of the diet. This is in contrast to the results of Shelton et al. (2001), who reported a decrease in daily feed intake when soybean meal in the control diet was fully replaced with poultry by-product. Based on the existing data, it seems that poultry by-product meal can successfully replace a minimum of 50% of conventional protein sources such as soybean meal in pigs' diet (inclusion rate of up to 10% of the total diet), while no effects on the growth performance will be observed.

5.3.7 Carbon footprint and sustainability of slaughterhouse by-products

From the farm gate, cattle are transferred to slaughterhouses and then slaughtered – these two activities result in additional GHG emissions apart from the farming phase. A study (Desjardins et al. 2012) shows that the GHG emissions linked to shipping to the slaughterhouse and slaughtering processes were 0.18 kg CO_2e per kg shrunk live weight (0.17 kg CO_2e per kg live weight at the farm), or nearly 2% of on-farm GHG emissions.

Likewise, other by-products of cattle slaughtering, such as hides, edible offal and inedible materials further treated at the extracting plants (mainly tallow, meat bone meal and blood meal) can be attributed to individual carbon footprint (Desjardins et al. 2012). The study reported that the carbon footprint of cattle by-products at the slaughterhouse was 12.9 kg CO_2e per kg of product on a mass basis in Canada in 2006. The carbon footprints of meat, hide, offal and fat, bones and other products were 19.6, 12.3, 7 and 2 kg CO_2e per kg, respectively, based on economic allocation (Figure 21).

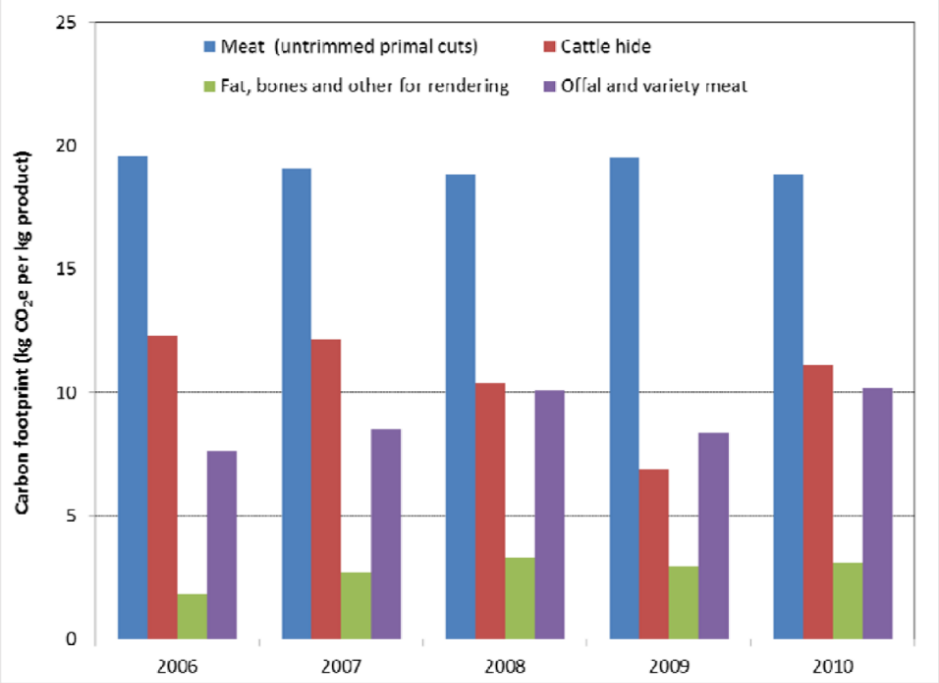


Figure 21 Estimated carbon footprint of beef products in Canada

(Source: Adeyemo et al. 2018)

5.4 Hatchery by-products

Hatchery waste, which comprises solid waste like hatched eggshells, infertile eggs, dead embryos, and dead or culled chickens, is produced in large quantities by commercial hatcheries. Traditionally the solid hatchery waste was disposed of in landfills or composting for fertiliser production and rendering, which release methane into the environment (Galtz et al. 2011). When an enormous amount of animal manure is put directly into the soil, it pollutes the ecosystem, particularly ground water. Hatchery waste is a high-protein waste that, with the right treatment, might be turned into high-protein/nutrient-dense feeds, other value-added products, or be used as an organic fertiliser

The use of hatchery by-product meal is also regulated, however, in some countries its use is prohibited due to the biosecurity risk (Al-Harthi et al. 2010). Pathogens can be effectively destroyed with heat treatments followed by appropriate drying (Chen & Jiang 2014). The most typical method for turning hatchery wastes into animal feed is rendering, which involves cooking the wastes, removing the fat (or not), and drying and grinding the final product in large quantities in a dedicated facility, as low volumes might make rendering uneconomic (El Boushy et al. 2000). Ensiling/fermentation is another processing technique that can be used if a rendering facility is not available. Other heat treatments, such as boiling, autoclaving, or extruding with soybean meal, maize, or eggshells, have been proposed (Glatz et al. 2011). A common reported ensiling method includes storing fresh hatchery waste for two weeks mixed with a source of carbohydrate and lactic acid bacterial culture, to produce a microbiologically safe, spoilage-free product that could be extruded into palatable and useful poultry feed (Yitbarek & Tamir 2014). Glatz et al. (2011) ensiled hatchery waste with 7% of a 1:1 mixture of formic acid and propionic acid and reported a high-quality meal with good microbiological results and high retention of nutrients.

5.4.1 Hatchery by-products production globally and in Australia

In 2009, 55.5 billion head of poultry including chickens, ducks, turkeys, geese and guinea fowl was produced worldwide (FAOSTAT 2011). Considering a hatchability percentage of 50–80% and average egg weight of 60 gr, a total of 0.8 to 3.3 billion tonnes of hatchery waste is estimated to have been produced back then. The volume of poultry production in 2022 almost doubled since 2009, and hence the quantity of hatchery waste.

The most prevalent elements of hatchery solid waste in Australia are empty shells, infertile eggs, dead embryos, late hatchings and dead chickens. A weekly average of 10.4 tonnes of waste is produced by chicken meat hatcheries in Australia. The average cost of disposal is A$127 per tonne. The majority of hatcheries don't treat waste before disposal. Most waste from hatcheries is disposed of in landfills or compost piles, however, some is rendered to be used in the pet food industry. Most wastewater from hatcheries is either used for irrigation or dumped directly into the sewer.

The accessibility of locations for the disposal of hatchery waste is a new problem for hatcheries. Additionally, it is important to reduce methane emissions from landfills into the environment. To create valuable products and lessen environmental issues, hatchery waste must be treated using economical and environmentally friendly methods.

5.4.2 General characteristics

Hatchery waste is composed of 53% ± 9.4% total solids, giving it a high liquid content. The waste has a neutral pH of 7.0 ± 0.5. Proper processing of hatchery waste can turn it to a protein-rich feed ingredient or other value-added products such as organic fertiliser (Glatz et al. 2011). In addition, it has a high calcium content originating from eggshells. The calcium bioavailability of hatchery by-

product meal is similar to that of bone meal or limestone, and it can be used as a source of dietary calcium in poultry diets (Badmos et al. 2016). Due to the potential high variability of final product composition, the inclusion of hatchery waste meal in feed formulation should be done carefully, and after detailed lab analyses, to control for the correct nutrient and chemical input.

Autoclaving or extruding followed by temperature disinfection and drying, or pressure boiling, are common methods to kill bacteria and produce a pathogen-free product that can enter feed manufacturing. If the hatchery waste is stored on-site, the pH should be reduced to an acidic pH to prohibit bacterial pathogen growth. This is done mostly by ensiling the waste with formic acid or propionic acid to produce an acidic environment, slowing spoilage, and supporting positive lactic-acid bacteria growth as stated before (Glatz et al. 2011). Waste treatment can happen off-site; however, some pre-processing is essential such as separating the solid waste into different categories and storing them in different recycling bins to control the pathogenic load and reduce the variation in the nutrient composition of the final product (Jayasinghe et al. 2020).

Technical challenges such as seasonal or irregular supply, bulkiness, wetness, processing requirements, drying and detoxification, and a lack of R&D activity can all be overcome with the help of solid waste management strategy plans (Jayathilakan et al. 2012; Srour et al. 2016).

5.4.3 Nutritive value for animal feed

Hatchery waste is a high protein waste with 43–71% moisture (Hamm & Whitehead 1982; Vandepopuliere et al. 1977). Dried hatchery waste contains 33.1% crude protein (CP), 29.0% ether extract, 12.1% crude fibre, 21.5% ash and 28.8 MJ/kg of gross energy (Sharara et al. 1992a). The apparent metabolisable energy (AME) of the hatchery waste by-product meal is 23.9MJ/kg (Sharara et al. 1992b) and the apparent amino acid availability (measured in Dandarawi cockerels) of the hatchery waste by-product meal is 73.5% (Sharara et al. 1993). Hatchery waste could be developed into high protein feedstuffs, other value-added products or utilised as an organic fertiliser after appropriate treatment.

Table 138 Nutrient composition of hatchery by-product

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	99.3	0.8	96.4	99.9
Crude protein	% DM	22.9	4.1	18.1	37.2
Crude fibre	% DM	2.1	2.2	0.0	6.1
Ether extract	% DM	11.3	3.0	7.8	21.7
Ash	% DM	61.4	6.8	36.0	65.5
Gross energy	MJ/kg DM	9.8			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Hatchery by-product meal, in addition to providing energy and protein, is a good source of calcium (17.2–24.6%), while it is low in phosphorus (0.3–0.6%). Gross energy can be as high as 28.8 MJ/kg due to the fat content (Glatz et al. 2009). The apparent metabolisable energy (AME) is 23.9MJ/kg, while the apparent amino acid availability is 73.5% (Talwar et al. 2019).

Table 139 Mineral composition of hatchery by-product

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	191.4	25.6	155.0	221.1
Phosphorus	g/kg DM	3.1	1.8	1.2	6.5
Sodium	g/kg DM	2.4	0.1	2.2	2.6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The amino acid balance of hatchery by-product is better than fishmeal. The protein biological value, net protein utilisation and nitrogen retention efficiency have been improved in chickens when hatchery by-product meal has replaced fishmeal. The apparent and standardised ileal digestibility of amino acids of mixed hatchery by-product meal range between 78.7 (for histidine) to 87.1 (for phenylalanine). Among the essential amino acids, hatchery by-product contains a high concentration of total arginine, leucine, lysine and valine, but has a low concentration of total histidine and tryptophan. The amino acid composition is likely similar to that in eggs and other animal by-products. The balance of amino acid makes hatchery by-product a potential alternative for conventional protein components in poultry diets.

Table 140 Amino acid profile of hatchery by-product

Amino acids	Unit	Avg	SD	Min	Max
Arginine	% protein	4.8			
Cystine	% protein	1.1			
Glycine	% protein	5.5			
Histidine	% protein	2.0			
Isoleucine	% protein	3.6			
Leucine	% protein	6.1			
Lysine	% protein	4.2	0.4	3.6	4.8
Methionine	% protein	2.2	0.5	1.4	2.8
Phenylalanine	% protein	3.5			
Threonine	% protein	3.4			
Tryptophan	% protein	1.3			
Tyrosine	% protein	2.4			
Valine	% protein	5.0			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

5.4.4 Antinutritional factors – nutritional limitations

Commercial hatcheries, as stated before, create a tremendous amount of waste, and the handling and disposal of this waste can be difficult. Recycling nutrients from the hatchery waste and incorporating it into the animal feed is a great way of reducing environmental pollution caused by agricultural activities (Freeman 2008). However, due to the high moisture content in hatchery by-product, it needs to be processed (i.e. dried) quickly to avoid bacterial growth and spoilage, and heated or fermented to get rid of pathogens (Iji et al. 2017).

Variability in nutrient quantity and quality, presence of naturally occurring antinutritional and toxic substances, presence of pathogenic microorganisms, and the problem of rancidity due to formation of free fatty acids are among the most important nutritional limitations of hatchery by-product meal. However, by employing suitable processing techniques, these can be reduced. For example, fat removing processing can manage the issue of fat rancidity (Saima, 2001).

Avidin is a biotin-binding protein found in raw eggs that causes biotin deficiency in chickens. A lack of biotin leads to skin and hair abnormalities (alopecia and hair colour loss), as well as locomotor and reproductive issues. It lowers feed intake and, as a result, growth. Biotin deficiency in chickens might result in abrupt death. Avidin can be deactivated by heat treatment at about 73.3°C and 125.6°C (Durance et al. 1992).

5.4.5 Hatchery by-products in the laying hen diet

It has been reported in multiple studies that hatchery by-product meal can replace fishmeal, soybean meal, and meat and bone meal in laying hens' diet (Abiola et al. 2004; Vandepopuliere et al. 1977; Wisman et al. 1965, cited by Al-Harthi et al. 2010).

In an old study by Vandepopuliere et al. (1977), to evaluate the optimum inclusion rate, hatchery by-product meal was incorporated at 2 levels of 8 and 16% in laying hens' diet replacing soybean meal, meat and bone meal, wheat middlings and ground limestone. The egg production performance and egg quality parameters at both inclusion levels were similar or better than the control diet. Apparent amino acid and energy digestibility were also comparable to the control diet, concluding that hatchery by-product meal can replace soybean meal, meat and bone meal and other protein components in laying hens' diet.

Table 141 Standardised ileal digestibility of amino acids of hatchery by-products in broilers

Indispensable amino acid	**Hatchery by-products**
Arginine	85.6
Histidine	83.7
Isoleucine	90.6
Leucine	90.8
Lysine	88.8
Methionine	87.4
Met+Cys	-
Phenylalanine	91.7
Threonine	84.6
Tryptophan	83.7
Valine	88.6
Dispensable amino acid	
Alanine	88.6
Aspartic acid	86.1
Cysteine	76.4
Glutamic acid	87.7
Glycine	83.0
Proline	73.3
Serin	83.6
Tyrosine	88.9

(Source: Kim et al. 2022)

In an experiment conducted by Abiola et al. (2004), fishmeal in layer diets was replaced by hatchery by-product at 0%, 33%, 66% and 100% rates. Their results showed that the feed intake and protein intake was improved by replacing fishmeal with hatchery by-product. Egg weight and egg length were also superior in hatchery by-product included diets. The hen-day egg production rate was greatest at the 33% replacement rate of fishmeal with hatchery by-product. Hatchery by-product improved eggshell thickness by 0.01 mm and the highest values of egg yolk weight and albumen weight were recorded in hens fed diets with 100% replacement of fishmeal with hatchery by-product. The authors conclude that hatchery by-product can fully replace fishmeal in layers' diet and improve egg quality traits.

Al-Harthi et al. (2010) evaluated the hatchery by-product inclusion in the diets for 25–41-week-old laying hens. The hatchery waste was cooked for 30 minutes and dried for 55 minutes in their trial, then included at 3 levels of 0, 5, and 10% in layers' diet. The hatchery by-product that was processed in their study contained 36.5% crude protein, 28.5% crude fat, 1.2% crude fibre, 27% ash, 18% Ca, 0.75% available P, and 2850 kcal metabolisable energy per kg. They reported that laying hens can consume up to 10% of hatchery by-product without any negative impacts on egg production performance, the quality of their fresh and stored eggs, or internal organs or lipid metabolism.

Alaba and Ekeocha (2012) conducted a trial where fishmeal was replaced with poultry hatchery by-product at 0, 25, 50, and 100% rates. There were no negative effects of poultry hatchery by-products on life performance and the quality of birds. They concluded that poultry hatchery by-product can replace fishmeal completely in pullet and layers diets without adverse effects on performance and egg quality characteristics. Since poultry hatchery by-products are considered a more affordable alternative to imported fishmeal, they can help lower the overall cost of egg production.

5.4.6 Hatchery by-products in the pig diet

Hatchery by-products are processed together, generating a mixture that is used in pig diets rather than a single hatchery by-product. However, to our knowledge, data on the evaluation of hatchery by-product mixture on growth performance in nursery pigs are very limited (Adeniji & Adesiyan 2007). Lack of data makes it challenging for the pig industry to recommend the optimum inclusion rate of hatchery by-product mixture in pig feed.

Table 142 Nutritive value of hatchery by-product meal

Pig nutritive values	Unit	Avg
Energy digestibility, growing pig	%	86.7
DE growing pig	MJ/kg DM	8.5
MEn growing pig	MJ/kg DM	7.9
NE growing pig	MJ/kg DM	5.7

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Considering that hatchery by-products contain approximately 32% to 67% of crude protein (Sung et al. 2019), they are regarded as an alternative protein ingredient which can replace widely used animal protein sources in nursery pig diets (Adeniji & Adesiyan 2007). Hatchery waste meal was incorporated into the experimental diets at 0, 7.5, 15, 22.5, and 30% as part of an experiment to determine the feeding value of the material in the diets of early-weaned piglets (Adeniji & Adesiyan 2007). Experimental diets were fed to 30 pigs after weaning for a period of 8 weeks. The increasing level of hatchery by-product meal had a negative impact on weight gain, nitrogen intake and nitrogen

digestibility, although feed conversion ratio was similar when pigs fed experimental diets were compared to the control. Adeniji and Adesiyan (2007) attributed the compromised growth performance to the unpleasant odour of the hatchery by-product mixture used in their study. Moreover, even though the inclusion rate of the hatchery by-product increased in diets, the inclusion rates of fishmeal (4.5%), bone meal (2.5%) and oyster shell (1.0%) were constant, resulting in excessive Ca concentration in diets. Excessive dietary Ca over the Ca requirement may negatively affect mineral digestibility and growth performance (Lagos et al. 2019; Wu et al. 2018), and therefore when hatchery by-products are included in pig diets, inorganic Ca sources such as limestone should be reduced in order not to exceed the Ca requirement. The authors reported that hatchery by-product meal can be included in the early-weaned piglets' diet at up to 22.5% with no detrimental impact on their growth performance.

Table 143 Standardised ileal digestibility of amino acids of hatchery by-products in pigs

Indispensable amino acid	**Hatchery by-products**
Arginine	73.8
Histidine	71.5
Isoleucine	71.8
Leucine	74.9
Lysine	79.5
Methionine	83.4
Met+Cys	-
Phenylalanine	71.6
Threonine	70.0
Tryptophan	69.4
Valine	70.9
Dispensable amino acid	
Alanine	75.0
Aspartic acid	62.6
Cysteine	52.5
Glutamic acid	74.2
Glycine	59.8
Proline	36.3
Serin	56.3
Tyrosine	63.5

(Source: Sung et al. 2020)

Sung JungYeol & Kim BeobGyun (2020) studied the effects of a hatchery by-product mixture on growth performance and estimated digestible energy concentrations at various inclusion rates. Pigs were fed graded concentrations of hatchery by-product meal at 0%, 3.33%, 6.67% and 10% for 14 days. The growth performance of nursery pigs was not impaired, and hence hatchery by-product meal can be included at up to 10% in nursery pig feed. The digestible energy content varied from 2772 to 3887 kcal/kg as-is basis, depending on the different types of hatchery by-product that were included in the mixture. In another study, Sung JungYeol & Kim BeobGyun, 2020 (2020) concluded that a hatchery by-product mixture can fully replace fishmeal and spray-dried plasma protein in nursery pig diets without negative effects on growth performance. As the energy utilisation of hatchery by-product mixtures is variable in pigs, different energy values should be used for each hatchery by-product mixture.

In a different study, Sung et al. (2019) estimated the energy concentrations and standardised total tract digestibility of phosphorus in hatchery by-products using 2 x 20 nursery barrows in 2 trials. Four experimental diets, each including 25% of infertile eggs, unhatched eggs, culled chicks, or a

combination of the three hatchery wastes, were compared to a base diet made up of maize and dried whey. The second trial, which included the same 4 experimental diets (25% of infertile eggs, unhatched eggs, culled chicks, or a combination of the three hatchery wastes) as the only source of phosphorous, was compared to a phosphorous-free control diet. Among the different hatchery by-products, culled chickens had the greatest metabolisable energy content (4560 kcal/kg as-is basis), and infertile eggs had the lowest metabolisable energy value (2645 kcal/kg as-is basis). The standardised total tract digestibility of P in infertile eggs (81.7%) was greater than that in unhatched eggs, culled chicks, and the mixture (61.6, 53.9, and 47.4%, respectively).

The composition of hatchery by-product mixtures varies depending on hatchery facility conditions. To ensure precise feed formulations, each batch should be thoroughly evaluated for its nutrient content, amino acid profile, and energy concentration before use. (Son et al. 2017), although information on available energy in various hatchery by-product mixtures is very limited. Further research is required to develop regression models to estimate the available energy and standardised amino acids digestibility values of different hatchery by-products based on nutrient composition, which can be obtained by simple lab analyses.

To sum up, existing reports show the potential of hatchery by-products as a protein ingredient that can replace conventional protein ingredients in pigs' feed. However, due to the variability of the hatchery by-product mixtures, the outcomes are inconsistent, and it is difficult to recommend optimum inclusion rates. One solution would be to conduct further research to develop regression models where the nutritive value and energy availability of the by-product can be estimated by simple lab analytical work.

5.4.7 Carbon footprint and sustainability of hatchery by-products

The bulk of hatchery waste goes to landfill or composting, with some processed as animal feed. Disposing hatchery waste to land fill causes environmental pollution as it releases methane and spreads microbial contamination. Again, the disposal cost for hatchery by-products is high in developed nations; for instance, it is $127.30/tonne in Australia (Glatz & Miao 2009). Hence, processing hatchery wastes into livestock/animal feed is a smart way to lessen the environmental footprint (Freeman 2008). Recent research shows hatchery has the minimum carbon footprint (0.12 kg CO_2 eq/kg chicken meat) in the chicken meat supply chain (Figure 22; Tetteh et al. 2022), and processing of the hatchery by-products even can improve the net carbon footprint of the chain.

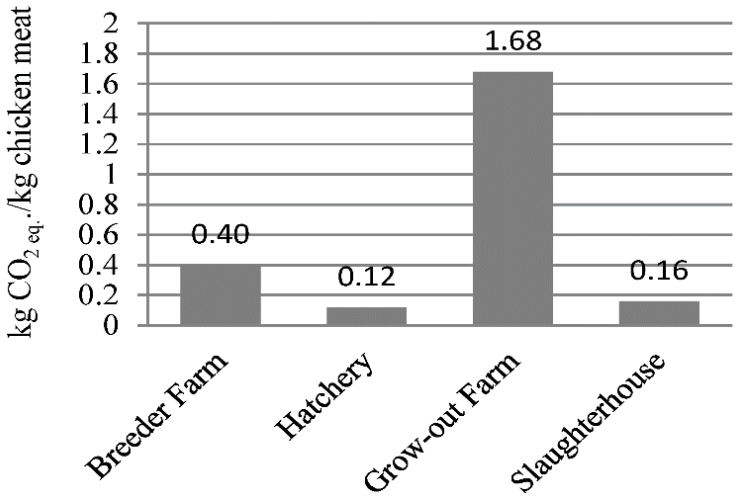


Figure 22 GHG emissions from life cycle stages within the chicken meat supply chain

There is a dearth of research specifically looking at the carbon footprint of the hatchery by-product meal; however, a study reports that ruminant by-product meal and fat contribute a massive percentage of emissions (79%) compared to poultry by-product meals. Hence, swapping ruminant by-product meal and fat with poultry-derived ingredients reduces emissions per tonne of feed by 69% (Pelletier et al. 2013). Figure 23 shows the carbon footprint for feeds originating from ruminant, porcine, or poultry by-product meals or crops only.

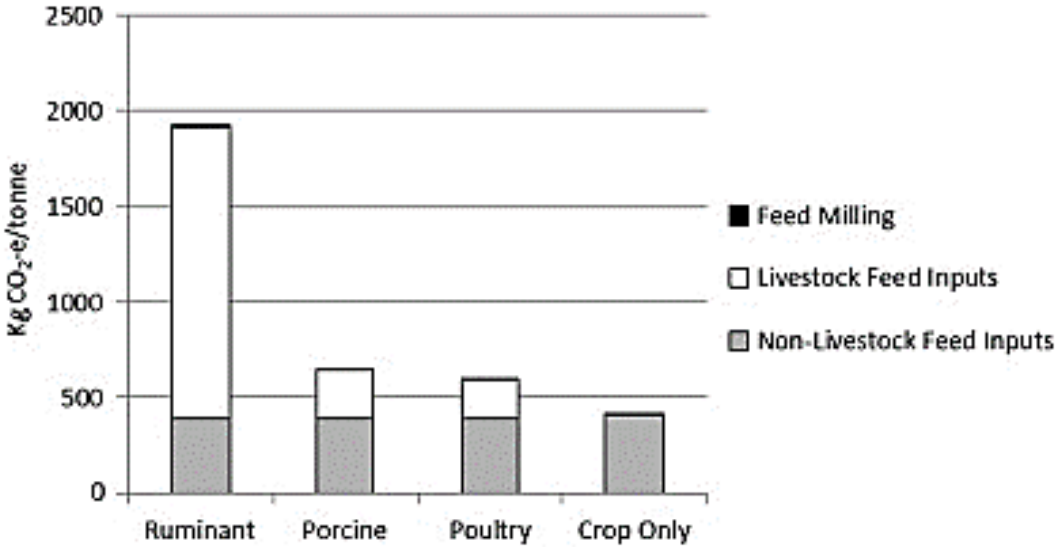


Figure 23 Carbon footprint for ruminant, porcine, or poultry by-product meals and fats

6 Aquaculture protein sources

6.1 Seaweed

Thousands of species of macroscopic, multicellular marine algae are classified as seaweed. Seaweed or marine algae grow in the ocean, rivers, lakes and other aquatic environments, and provide nutrients and sustenance for marine life. They are classed as algae taxonomically, and they constitute a food group that is rarely consumed in its natural state in Western countries (Del Cortona et al. 2020). Brown algae (Phaeophyta), red algae (Rhodophyta), green algae (Chlorophyta) and blue-green algae (Cyanophyta) are all four main classification categories of macroalgae. Kelps and other seaweed species provide vital nursery habitats for fisheries and other marine creatures, protecting food sources. Other species, such as planktonic algae, play a significant role in sequestering carbon, creating at least 50% of the Earth's oxygen. Many seaweed species are edible, and many are also valuable commercially. Some are utilised as fertilisers or as polysaccharide sources (Michalak & Chojnacka 2015).

The caloric load of seaweed is low due to a low-fat content. Its proteins and carbohydrates have a low digestibility rate in humans (Costa-Pierce et al. 2021). For thousands of years, seaweeds have been used to feed animals and are described in ancient texts. Seaweeds were dried and stored in barns, and in the early 1900s, seaweeds were preserved as silage and used as winter feed for sheep and cattle (Makkar et al. 2016). There are numerous records of seaweeds being used to feed livestock in France (Brittany), the Scottish islands, and Scandinavia (Gotland, Norway, Finland) in the 19th and early 20th centuries, mostly to ruminants (including calves) and pigs (Delaney & Frangoudes 2016).

There has been an interest to revisit seaweed’s potential as a feed ingredient in the past few decades. Seaweeds are sources of vital nutrients, particularly chelated micro-minerals, which are more readily available than inorganic ones; complex carbohydrates with prebiotic properties; pigments and polyunsaturated fatty acids that are favourable to consumer health (Monagail & Morrison 2020). Seaweeds include two types of polysaccharides: structural and storage. Celluloses, hemicelluloses, and xylenes are structural polysaccharides that are similar to those found in terrestrial plants. Carrageenans and other storage polysaccharides have textural and stabilising characteristics, thus they are used in food industry (Kumar et al. 2015).

Seaweed farming, often known as kelp farming, is the cultivation and harvesting of seaweed. In its most basic form, it entails the management of naturally occurring batches, however, its most advanced form entails complete control of the algae's life cycle (Wei et al. 2013).

6.1.1 Seaweed production globally and in Australia

Seaweed is consumed all over the world, particularly in East Asia (Asian cuisine), such as Japan, China, Korea, Taiwan and Southeast Asia (Delaney & Frangoudes 2016).

Collection of wild seaweed and its cultivation contributed equally to a volume of 2.2 million tonnes of production in 1969. While wild production stayed at 1.1 million tonnes in 2019 after half a century, cultivated production surged to 35.8 million tonnes in 2019, accounting for 97 per cent of global seaweed production (Cai et al. 2021). Between 1950 and 2019, the world's seaweed farming volume increased by 1000 times, from 34.7 thousand tonnes to 34.7 million tonnes. Currently, the global seaweed industry has a production value of USD $11 billion (AUD $16.8 billion) (Chopin & Tacon 2021). The global average wholesale price of seaweed is roughly USD $3.60/kg dry weight (AUD $5.40/kg) based on a global production of 30 million tonnes (wet). Industrial extracts such as alginate and

carrageenan, which are utilised in everyday food and personal care products, account for the majority of market value (Chopin & Tacon 2021). Many invertebrates that are prey for arthropods and marine birds live in seaweeds, and excessive seaweed harvest rates have been found to disrupt the balance of coastal ecosystems. In Norway, for example, wild kelp harvesting was found to be deleterious to fish quantity and bird feeding efficiency (Makkar et al. 2016).

Thousands of native seaweed species thrive in Australian coastal waters, many of which have a great potential for value-added products. The native genus of red seaweeds, *Asparagopsis* spp., lowers methanogenesis when put into ruminant animal feed and potentially revolutionises the world's approach to reducing livestock emissions. The scope of the opportunity in developing the full supply chain from production to processing and the consumption of seaweed products has the potential to generate jobs in regional areas and enhance Australians' diets and health, and conserve Australian ecosystems (Kelly 2020).

Currently, the Australian seaweed industry has a gross value of $3 million, of which the majority comes from Kelp Industries Pty Ltd on Tasmania's King Island. It is projected that the Australian seaweed industry will reach $100 million gross value of production (GVP) by 2025. This will generate 1200 direct jobs, and a 3% reduction in greenhouse gas emissions. Ideally following all recommendations, this will increase to $1.5 billion (GVP), 9000 direct jobs and a 10% reduction in greenhouse gases emissions by 2040. Seaweed exports from Australia are valued at $1.5 million for non-human consumption, according to ABS data, and it is thought that this is entirely from Kelp Industries Pty Ltd exports. Australia, on the other hand, is a nett importer of seaweed. In 2017/18, annual imports to Australia totalled over AUD $40 million, with 85 per cent of that being for human consumption. Imports have been rising at a rate of 15% per year on average, up from AUD $17 million in 2008/09. (Lee 2010). Imported seaweed food products from China and South Korea are expensive per unit in Australia.

Australia has no commercial ocean seaweed farms at the moment, and there are only two small-scale (less than 5 hectares of seaweed under production) land-based operations for *Ulva* spp. cultivation including Shoalhaven, NSW (Venus Shell Systems) and Ayr, QLD (Pacific Biotechnology) (Kelly 2020). Considering the projected growth, there is a massive opportunity for the seaweed industry here in Australia to reach the targets in regional coastal communities. The Australian Seaweed Industry target for 2025 is $100 million (GVP), 1,200 direct jobs and a domestic greenhouse gas emissions reduction of 3%.

6.1.2 General characteristics

The chemical composition of seaweeds including proteins, minerals, lipids and fibre content varies greatly depending on the species, time of collection and habitat, as well as external conditions such as water temperature, light intensity and nutrient concentration in water. Fresh seaweed has a high moisture content (about 70–90%), thus it needs to be dried in order to be stored (Makkar et al. 2016).

Brown algae have a lower protein content and a higher mineral content, and therefore its nutritive value is less than red and green algae, however, it contains some bioactive compounds with functional properties (Lafarga et al. 2020). Algae contain protein-free nitrogen such as free nitrates, causing an overestimation of the crude protein content.

A coefficient of 5.38, 4.92, and 5.13 nitrogen to protein conversion have been proposed for brown, red and green algae, respectively. The amino acid profile of some algae species such as the brown seaweed *U. pinnatifida* and the red seaweed *P. palmata*, are beneficial in nutrition. The essential amino acid index of red seaweed *P. palmata* was 103.7% of the standard protein for humans, while for brown seaweed *U. pinnatifida* it was 95.9% of the standard protein for humans (Makkar et al.

2016). The *M. pyrifera* and *Ulva* species are very rich in sulphur-containing amino acids, with significantly greater methionine plus cystine levels than soybean meal. This makes these two seaweeds suitable feed for wool-producing animals, and their high sulphur amino acid content makes them good candidates for overcoming toxicity because the liver requires methyl donors to detoxify poisonous elements. The amount of methionine in *A. nodosum* is comparable to soybean protein. The three seaweeds have lower quantities of lysine than soybean meal. *A. nodosum* and *Ulva* species had lower levels of phenylalanine and tyrosine than soybean meal, while *M. pyrifera* had lower levels of these amino acids than soybean meal. Arginine, an important amino acid for chickens, was shown to be lower in the three seaweeds (Tanna et al. 2019).

For thousands of years, seaweeds' medicinal properties including anti-inflammatory and antimicrobial properties, have been known; the ancient Romans used them to cure wounds, burns, and rashes. Certain seaweed species contain functional compounds that fight cancer, and it is hoped that these compounds can be extracted and used to treat and cure malignant tumours and leukaemia in humans. While dietary soy has long been linked with Japan's low cancer rate, dietary seaweed is now being credited with this sign of good health as well (Sithranga Boopathy & Kathiresan 2010). Algae and other adaptable marine plants are effective binding agents and emulsifiers that are used in commercial products such as toothpaste and fruit jelly, popular softeners (emollients) in organic cosmetics and skin-care products, among their many uses in manufacturing (De Luca et al. 2021).

Seaweeds are a great source of organic iodine, iron and calcium. Some varieties may contain high levels of vitamin B12. They are also a good source of omega-3 fatty acids. Antioxidants found in seaweed include vitamins A, C and E, as well as carotenoids and flavonoids (Cabrita et al. 2016). Seaweed includes moderate levels of fibre and carbohydrates with prebiotic function, that encourage the colonisation of beneficial bacteria in the gut (Jandhyala et al. 2015).

6.1.3 Nutritive value for animal feed

On a dry matter basis, seaweed has on average 8% crude protein, 5.5% crude fibre with 20.9% of it being NDF and 13.1% ADF, a relatively high lignin content of 13%, crude fat 3.9% and ash 22.5%. Seaweeds have a high mineral content (8–40%), which is higher than that of land plants (5–10% on a dry matter basis) and animals. This variation in mineral content, which is not common in edible land plants, is linked to factors like seaweed phylum, geographical origin, seasonal, environmental and physiological variations. There is a positive correlation between each mineral element concentration and seaweed oceanic residence time, according to studies.

Table 144 Nutrient composition of dried brown seaweed (*Ascophyllum nodosum*)

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	88.0	2.7	85.4	91.8
Crude protein	% DM	8.0	2.7	5.6	12.1
Crude fibre	% DM	5.5		4.1	6.8
NDF	% DM	20.9		19.8	22.0
ADF	% DM	13.1			
Lignin	% DM	13.8		6.2	21.4
Ether extract	% DM	3.9	1.6	2.9	5.8
Ash	% DM	22.5	2.1	18.9	25.0
Gross energy	MJ/kg DM	14.7		14.5	14.7

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Mineral concentration is also affected by the type of seaweed processing and mineralisation techniques utilised (Tabarsa et al. 2012). Some of these trace elements are non-existent or extremely modest in land crops; edible marine seaweeds may be an essential source of minerals (Cian et al. 2014).

Table 145 Mineral composition of brown seaweed (*Ascophyllum nodosum*)

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	20.0			
Phosphorus	g/kg DM	1.0			
Potassium	g/kg DM	24.0			
Magnesium	g/kg DM	8.0			
Manganese	mg/kg DM	12	3	7	17
Zinc	mg/kg DM	181	114	74	403
Copper	mg/kg DM	28	16	8	63
Iron	mg/kg DM	134	36	101	198

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Brown seaweeds are rich in potassium (2–3% in *Ascophyllum nodosum*, 1.3–3.8% in *Laminaria digitata*), sodium (3–4% in *Ascophyllum nodosum*, 0.9–2.2% in *Laminaria digitata*) and particularly iodine (up to 0.1% in *Ascophyllum nodosum* and 1.1% in *Laminaria digitata*) (Rodriguez-Montesinos et al. 1991; Guiry 2014). Indeed, *Laminaria* has the capacity to accumulate iodine by more than 30,000 times the iodine concentration in seawater (Mišurcová 2012).

Table 146 Amino acid profile of brown seaweed (*Ascophyllum nodosum*)

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	5.4		5.3	5.4
Arginine	% protein	6.0		4.0	8.0
Aspartic acid	% protein	8.4		6.9	9.8
Cystine	% protein	0.9		0.0	1.8
Glutamic acid	% protein	11.6		10.0	13.1
Glycine	% protein	4.8		4.5	5.0
Histidine	% protein	1.4		1.3	1.5
Isoleucine	% protein	3.1		2.8	3.4
Leucine	% protein	5.3		4.6	6.0
Lysine	% protein	4.6		4.3	4.9
Methionine	% protein	1.3		0.7	1.9
Phenylalanine	% protein	3.2		2.3	4.0
Proline	% protein	3.0		2.6	3.4
Serine	% protein	3.5		3.0	4.0
Threonine	% protein	3.6		2.8	4.3
Tyrosine	% protein	0.9			
Valine	% protein	4.1		3.7	4.4

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The protein content of seaweed ranges from 5% to 47% on a dry matter basis. The species and environmental factors affect the protein content. All amino acids, particularly glycine, alanine, arginine, proline, glutamic and aspartic acids, are found in seaweed protein. Essential amino acids make up over half of all amino acids in algae, and their protein composition is similar to that of egg protein. For non-essential amino acids, the amounts in the three categories of seaweeds (green, brown, and red) are comparable. Red seaweed has a rating of 47%, which suggests that it is a rich source of protein.

Seaweed supplementation is linked to the prebiotic activity coming from its complex carbs. A dietary macroalgae inclusion rate of 2% of dry matter, can exert substantial prebiotic action which is reported to be 5 times more powerful than the commercially known prebiotics, such as fructo-oligosaccharides or inulin. The prebiotic effects of microalgae are reflected in improved gastrointestinal tract health, stress resistance, immune system competency, increased productivity and decreased gut pathogenic bacterial load. Along with these advantages, increases in whole ration digestibility have been reported, which are likely as a result of changes in the gut bacteria. In addition, microalgae supplementation in the feed has shown to be beneficial to promote gut health in an antibiotic-free production system.

Seaweeds' nutritive value in livestock feed depends on the species, chemical composition regarding protein, minerals, carbohydrates and fibres, and tannins and the animal's adaption to this specific meal. Seaweeds have a low cellulose content (about 4%), but are high in particular polysaccharides (alginate, laminarin, and fucoidan), as well as mannitol. Inclusion of seaweed at 1–5% in poultry feed improves immune status, reduces pathogenic bacterial load in the digestive tract and improves meat and egg quality (Ribeiro et al. 2021).

Compared to the other common feed ingredients used in the commercial feed industry, seaweed provides just a fraction of the potential energy value, as evaluated by total digestible nutrients, or carbohydrate content. The addition of even moderate amounts of seaweed to the diet clearly reduces the energy content. As the seaweed content in diets increased above 10%, this most likely accounted for decreasing animal performance (Ead et al. 2011).

6.1.4 Antinutritional factors – nutritional limitations

Marine algae can biofortify and enrich nutrients that are present in their environment, therefore heavy metals and inorganic pollutants may be present in marine algae. As a result, national and international laws are in place governing the content of trace elements in seaweeds for food and feed apply (Smith et al. 2010). In the European Union, calcareous marine algae must contain less than 10 mg/kg arsenic, 15 mg/kg lead, and 1000 mg/kg fluorine; seaweed meals and seaweed-based feed materials must contain less than 40 mg/kg total arsenic, and less than 2 mg/kg inorganic arsenic (all values relative to a feed with moisture content of 12%).

High levels of arsenic have been detected in brown algae *S. fusiforme* (Harvey) Setchell (synonym *Hizikia fusiformis* (Harvey) Okamura) (Rahikainen & Yang 2020). If seaweed is the sole feed ingredient available to an animal, then it may consume large quantities of arsenic. This is the case with the Orkney sheep of North Ronaldsay Island, where the arsenic levels in their wool and tissues are 100 times higher than with un-exposed animals. The mineral overload of algae can lead to health issues such as dental problems caused by tartar deposits, and significant mineralisation of the kidney medulla in exposed animals (Makkar et al. 2016).

Seaweeds, particularly brown algae, are high in iodine, which can affect thyroid function and induce iodine poisoning if consumed over a long term. The maximum iodine concentrations proposed in

complete diets in the European Union are 2 mg/kg (dairy ruminants), 3 mg/kg (laying hens) and 3 mg/kg (pigs/horses). The degradation of poisonous seaweeds on beaches could be a source of intoxication for grazing animals (Reboleira et al. 2019).

6.1.5 Seaweed in the laying hen diet

Seaweeds offer interesting nutritional characteristics for laying hens. Carrillo et al. (2008) recommended that including *Macrocystis pyrifera* at up to a 10% inclusion rate in laying hens' diet, was an effective way of increasing omega-3 fatty acids content the albumen height, and yolk colour however, egg weight was not improved. In their study, egg flavour did not deteriorate by inclusion of seaweed in the diet. The authors suggested that levels higher than 10% inclusion should be avoided as this could affect acceptance of the feed, lower the egg production, or cause aqueous faeces in the birds because of the high mineral content in the seaweed (Carrillo et al. 2002).

Table 147 Standardised ileal digestibility of amino acids of brown and green seaweed

Indispensable amino acid	Brown seaweed	Green seaweed
Arginine	-	-
Histidine	-	-
Isoleucine	45.8	56.8
Leucine	73.2	59.1
Lysine	-	-
Methionine	77.5	54.2
Met+Cys	-	-
Phenylalanine	63.5	68.0
Threonine	56.7	56.2
Tryptophan	-	
Valine	62.1	59.7
Dispensable amino acid		
Alanine	55.8	60.8
Aspartic acid	60.1	57.7
Cysteine	-	
Glutamic acid	65.5	62.6
Glycine	-	
Proline	71.9	49.2
Serin	64.8	56.8
Tyrosine	54.0	57.3

(Source: Azizi et al. 2021)

Laying hens were fed the brown seaweed *Sargassum* spp. from the shore of the Red Sea during the course of 23to 42 weeks at a percentage of 0, 3, 6, 9, or 12% of their diet without or with enzyme preparations. No negative effects of dietary algae on body weight, egg weight, egg production, egg mass, feed intake, feed conversion rate, and egg quality were observed (El-Deek et al. 2009).

In another study, egg quality was improved when *Sargassum dentifolium* was fed at two inclusion levels of 3 and 6%, and in 3 types of processing including sun-dried, boiled and autoclaved. The beneficial effects consisted of reduced yolk cholesterol, triglycerides, and n-6 fatty acids, while raising omega-9 fatty acid (palmitic acid), carotene and lutein plus zeaxanthin levels. High density lipoproteins, a desirable characteristic in cholesterol, were improved by boiling as well (Al-Harthi et al. 2012).

Egg production and quality were enhanced when the green seaweed *Enteromorpha prolifera* was added at a concentration of 1, 3, and 3%; this resulted in an increase in weight, shell thickness and yolk colour, as well as a decrease in yolk cholesterol. Additionally, the green seaweed supplementation lowered feed conversion ratio and resulted in a lower *E. coli* burden in faeces, indicating improved animal health (Wang, Jia et al. 2013).

Stupart et al. (2019), conducted two trials where in the first trial the effect of short-term inclusion of red seaweed (Chondrus crispus) in 70-week-old laying hen diets were evaluated and in the second trial the effects of dietary inclusion of two seaweed species – namely, *Chondrus crispus* and *Ascophyllum nodosum* – with two processing methods (i.e. ground and extruded) on laying hen production performance under thermoneutral and heat stress conditions were investigated. Experimental diets in trial 1 included 0% seaweed (control); 1%, 2%, 3%, 4% extruded *Chondrus crispus*, and 4% ground *Chondrus crispus*. Birds fed the 3% extruded *Chondrus crispus* had significantly higher egg weight and albumen height (7.8) compared to birds fed the other experimental diets. There were no differences between 4% extruded vs. 4% ground seaweed diets regarding egg production and quality traits, indicating that the extrusion process had no positive effects on performance or egg quality traits. In second trial, laying hens at 70 weeks of age fed *Chondrus crispus* and *Ascophyllum nodosum* either ground or extruded at inclusion levels of 0, 0.5, and 3% while exposed to heat stress. There was no effect of the diet on any of the egg production parameters, feed intake, or feed efficiency. The authors reported no negative effects of heat stress on layers either, and therefore there were inconclusive results considering the effects of seaweed on alleviating the consequences of heat stress on layers, although could be concluded that up to3% seaweed inclusion has no negative impact on the egg production performance.

Based on the existing data, an inclusion rate of 6% brown or green seaweeds (potentially up to 10% of brown seaweed) might be beneficial to laying hens, however, this may vary depending on the seaweed species and their chemical composition. Further research is required to determine the standardised ileal digestibility coefficients of different seaweeds for laying hens, and to conduct feeding trials where amino acids are balanced following an ideal protein profile and the energy to amino acids ratio is well-maintained.

6.1.6 Seaweed in the pig diet

Very old studies indicate that in 19th and early 20th centuries, pigs in ancient Sweden were fed with a mixture of boiled brown algae (*Fucus vesiculosus)* and cereal meal (Sauvageau 1920). Similarly, in Loch Feochan (Scotland), oatmeal was given with either raw or boiled brown algae (*Pelvetia* spp.) to fatten pigs (Chapman et al. 1980).

Research reports suggest that consuming moderate to large amounts of brown seaweeds may have adverse effects on pigs. A 10% *Ascophyllum nodosum* meal inclusion rate in the pig diet for several weeks caused weight loss, however, this had no negative impact on blood parameters (Jones et al. 1979).

As stated earlier, seaweed can accumulate high concentrations of iodine, and this can be used as a feeding strategy to improve iodine deficiency in regions where people suffer from lack of iodine in common food ingredients. The organic iodine present in seaweeds like *Laminaria* or *Ascophyllum* is easily metabolised and stored in the pig muscle, as opposed to inorganic iodine (Banoch et al. 2010). Pigs fed 2% dried *Ascophyllum nodosum* (the seaweed-based diet contained 10 mg/kg of iodine compared to 1 mg/kg for the control diet) in their ration had an increase in iodine content in their meat of 2.7 to 6.8% depending on the tissue. It was discovered that this feeding method for producing meat that was iodine-enriched could easily be controlled, and did not pose a risk of overdose or need

a change in eating habits, but this contribution was deemed insufficient to address Belgium's national iodine shortfall (Dierick et al. 2009).

There are two main reasons to use seaweed in pig feed, gut health and performance improvements including meat quality. The use of seaweed and seaweed extracts have been shown to have prebiotic effects and to enhance immunologic function in pigs and have been assessed to replace antibiotics in pig farms (Lopez-Santamarina et al. 2020). Additionally, an inclusion level of 1–2% seaweed as an additive improves pig health and meat quality.

A plethora of studies have reported the prebiotic effects of seaweeds and seaweed extracts in pigs, improving immune response and having the potential to replace antibiotics as growth promoters. Corino et al. (2019) have reviewed the biological functions of seaweed and seaweed extracts in pig nutrition, including prebiotics, antimicrobial, antioxidant, anti-inflammatory and immunomodulatory effects, promoting intestinal wellbeing and improving digestibility.

Table 148 below summarises the reported average daily gain of pigs when different species of seaweeds or seaweed extracts are included at different rates into the pigs' diet. Additionally, 24 studies have been published in the last 10 years on the effects of supplementation with brown seaweeds, or their extracts, on gut health. Most of the studies were carried out on weaned piglets (14 trials), considering that the weaning phase is a critical period with a high incidence of enteric pathologies. Some studies were carried out on growing pigs ranging between 14 and 65 kg live weight (LW), and some others on gestating and lactating sows.

In general, the compounds present in brown seaweeds (in 20 trials the supplement was titrated in laminarin and/or fucoidans) stimulated the growth of Lactobacilli and reduced the enterobacteria population or *Escherichia coli*. Brown seaweed supplements supported the growth of *Bifidobacteria* species in the ileum in piglets. Gut health is modulated by laminarin and/or fucoidans, with the microbial production of short–chain fatty acids (SCFAs), in particular butyrate (Wan et al. 2016; O'Doherty et al. 2010; Dillon et al. 2010; O'Shea et al. 2014; Walsh et al. 2013; Gardiner et al. 2008; Murphya et al. 2013; Lynch et al. 2010; Mukhopadhya et al. 2012; Reilly et al. 2008).

Table 148 Summary of literature – effects of seaweed supplement on average daily gain in pigs

Algae Supplement	Dose	Age	ADG, kg/day control	ADG, kg/day supplemented	Diff. %	Reference
A. nodosum	Dried seaweed 2.5–5–10 g/kg	Weaning to 28 d	0.220	0.209 0.198 0.213	−5.0 −10.0 −3.18	Michiels et al. 2012
A. nodosum	Dried seaweed 10–20 g/kg	Weaning to 11 d	0.027	0.054 0.040	+100 +48.14	Dierick et al. 2009
Brown seaweed	Alginic acid oligosaccharides (50–100–200 mg/kg)	Weaning to 14 d	0.216	0.248 (50) 0.304 * (100) 0.301 * (200)	+14.81 +40.78 +39.35	Wan et al. 2016
Brown seaweed	Alginates oligosaccharides (100 mg/kg)	Weaning to 21 d	0.441	0.516	+17.01	Wan et al. 2017
Ecklonia cava	FUC = 0.05 – 0.10 – 0.15 g/kg	Weaning to 28 d	0.344	0.347 0.368 * 0.360 *	+0.87 +6.98 +4.65	Choi et al. 2017
Laminaria digitata	LAM + FUC (0.314 –0.250 g/kg) – lactose 15 or 25%)	Weaning to 25 d	0.275 0.287	0.293 (15% lact.) 0.350 **(25% lact.)	+6.55 +21.95	O'Doherty et al. 2010
Laminaria spp.	LAM (1 g/day)—sows, 109 d until weaning at 20 d LAM (0.3 g/kg)—piglets	20 d lactation Weaning to 26 d Challenge *Salmonella* Typhimurium at 10 d post weaning	0.340 0.410	0.450 ** 0.370	+32.35 −16.13	Bouwhuis et al. 2017
Laminaria spp.	LAM + FUC (0.18 + 0.34 g/kg)	30.9 kg pigs for 28 d Challenge *Salmonella* Typhimurium at 10d	0.620	0.720 ***	+16.13	Bouwhuis et al. 2017
Laminaria spp.	LAM (0.112 g/kg) [y] FUC (0.089 g/kg) [z]	Weaning to 25 d	0.281	0.322 **	+14.59	Dillon et al. 2010
Laminaria spp.	LAM + FUC (1 g + 0.8 g day) − sows LAM + FUC (0.3 + 0.24 g/kg) − piglets	Weaning to 126 d	0.760 0.800	0.850 **(lactation effect) 0.810 (weaning effect)	+11.84 +1.23	Draper et al. 2016

Laminaria spp.	Extract (1–2–4 g/kg) [x] LAM = 0.11–0.22–0.44 FUC = 0.09–0.18–0.36	Weaning to 21 d	0.249	0.274 ***(1 g/kg) 0.313 *** (2 g/kg) 0.303 ***(4 g/kg)	+10.04 +25.70 +21.69	Gahan et al. 2009
Laminaria spp.	LAM (0.30 g/kg)	Weaning to 32 d	0.280	0.353 *	+26.07	Heim et al. 2014
Laminaria spp.	LAM + FUC (0.30 + 0.24 g/kg)	Weaning to 40 d	0.356	0.374	+5.06	McAlpine et al. 2012
Laminaria spp.	LAM (0.3 g/kg) FUC (0.36 g/kg) LAM + FUC (0.3 + 0.36 g/kg)	Weaning to 21 d	0.288	0.319 * LAM 0.3 0.302 FUC 0.36 0.328 LAM + FUC	+10.7 +4.86 +13.89	McDonnell et al. 2010
Laminaria spp.	LAM + FUC (0.30 + 0.24 g/kg) [k]	Weaning to 21 d 21–40 d	0.235 0.489	0.239 0.523	+1.70 +6.25	O'Shea et al. 2014
Laminaria spp.	LAM (0.15–0.30 g/kg) FUC (0.24 g/kg) LAM + FUC (0.15 + 0.24 and 0.30 + 0.24 g/kg)	Weaning to 35 d	0.340	0.351 FUC 0.24 0.334 LAM 0.15 0.347 FUC 0.24 LAM 0.390* LAM 300 0.358 FUC 0.24 LAM 0.3	+3.24 –1.76 +2.06 +14.71 +5.29	Walsh et al. 2013
Ocean feed swine	Seaweed extract (5 g/kg)	21 to 56 d 56–160 d	0.401 0.798	0.380 0.824 *	−5.24 +3.26	Ruiz et al. 2018

ADG – Average daily gain.
Means marked with *, **, *** showed a significant effect of supplement for $p < 0.05$, $p < 0.01$ and $p < 0.001$ respectively.
LAM – Laminarin.
FUC – Fucoidan.
y – 990 g/kg Laminarin.
z – 720 g/kg Fucoidan.
x – 112 g/kg Laminarin, 89 g/kg Fucoidan and 799 g/kg ash.
k – 455 g/kg Laminarin and 360 g/kg Fucoidan.

Brown seaweeds have biological properties that enhance the health and wellbeing of pigs. Laminarin's and fucoidans' prebiotic properties, as well as their antibacterial properties, may help post-weaning pigs better digest their diets and prevent gastrointestinal disorders. Additionally, laminarin contains anti-inflammatory properties that lessen the pro-inflammatory cytokine response. Antioxidant status and meat oxidative stability are improved by the antioxidant compounds found in seaweed. Brown seaweed consumption may benefit the immune system by increasing the production of immunoglobulin and reducing the generation of cytokines.

In conclusion, the use of brown seaweeds in pig diets appears to be a viable way to improve the health of their immune systems, antioxidant status and guts. It seems that a 1–2% inclusion has the maximum beneficial effect after weaning. There are currently few studies on the dietary supplementation of green seaweeds in pigs, which requires further research.

6.1.7 Carbon footprint and sustainability of seaweed production

As stated before, through photosynthesis, seaweeds and microalgae absorb carbon dioxide and extract nutrients like nitrogen and phosphorus from surrounding waters. This process helps mitigate eutrophication, treat wastewater, reduce ocean acidification, and capture or sequester carbon. (Cai, Lovatelli, et al. 2021). A study reports that seaweed cultivation may reduce net climate change factors, i.e. −0.1·102 kg CO_2 eq per ha of seaweed grown (Seghetta et al. 2016). Studies in Australia also found that native seaweed significantly reduces methane emissions and has the potential to boost livestock productivity (CSIRO 2022). Machado et al. (2016) and Roque et al. (2021) report that adding just 2% of specific seaweed species to the cattle diet could decrease the methane emission from livestock production by 99%.

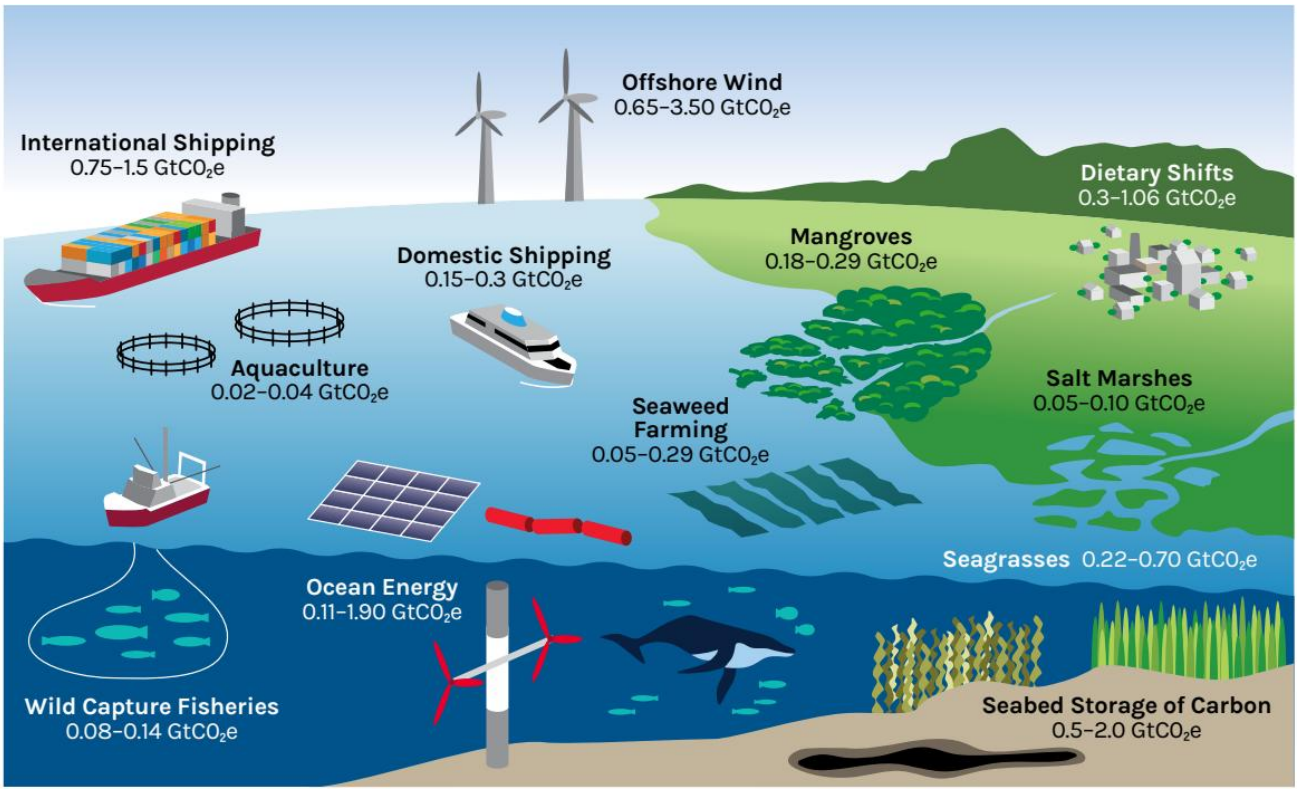


Figure 24 Ocean-based mitigation options (annual mitigation potential in 2050)

6.2 Microalgae

Microalgae are unicellular photosynthetic microorganisms that live in saline or fresh water, and convert sunlight, water and carbon dioxide into algal biomass containing proteins, carbohydrates and lipids, as well as microelements such as minerals, vitamins, polyphenols, flavonoids and carotenoids (Caron et al. 2010). They lack roots, vascular systems, leaves and stems, and are autotrophic and photosynthetic. These phytoplankton can be grown in huge quantities in photobioreactors and open ponds, then harvested and processed into functional feed supplements for livestock (Slegers et al. 2013). They are important components of the maritime environment and could help to meet global strategic concerns such as climate change, pollution (including chemicals and waste), land degradation, deforestation, and marine pollution. Microalgae play crucial roles in the ecosystems in which they live, such as uptake of dissolved nutrients from their surrounding environment, coastal defence against dangerous waves, and carbon sequestration (Teagle et al. 2017).

Microalgae are typically eukaryotic organisms. Although cyanobacteria, like spirulina, are prokaryotes they are considered to be microalgae because of their photosynthetic and reproductive abilities (Ravishankar et al. 2012). There are 200,000 to 500,000 microalgae species that exist in nature. Spirulina is one the many organic blue-green algae that is considered a great source of protein. The crude protein level of some of the microalgae species is comparable to that of meat, egg, soybeans and milk (Gouveia et al. 2008).

Animal protein, in particular, requires 100 times more water than if the same amount of protein was produced from plant sources (FAO 2014). Algae do not require fresh water or arable land to grow, maximising resources that may be used for additional food production (Korczyński et al. 2015). Furthermore, algae's high development rate makes them a viable alternative to traditional crops that are restricted to agricultural land. Organisms like Dunaliella, Spirulina, or Chlorella provide up to 70% protein, as well as polyunsaturated fatty acids, vitamins, and β-carotene.

Microalgae are grown for their total biomass and their immense chemical diversity, which includes important compounds such as poly-unsaturated fatty acids, carotenoids, phycocyanin and nutraceuticals that are used in the food and feed (especially aquaculture) industry. Microalgae rich in lipids or carbohydrates are being used to create biofuel (Ravishankar et al. 2012).

Several hundred microalgal species have been tested as feed during the past few decades, but only about 40 species are currently produced in intensive production systems. Diatoms, flagellated and chlorococcalean green algae, as well as filamentous blue-green algae, especially spirulina, are some of these species (Becker 2013).

Among all the algae employed in commercial aquaculture, the cyanobacterium spirulina (*Arthrospira* sp.) has the broadest range of applications in human and animal nutrition.

6.2.1 Microalgae production globally and in Australia

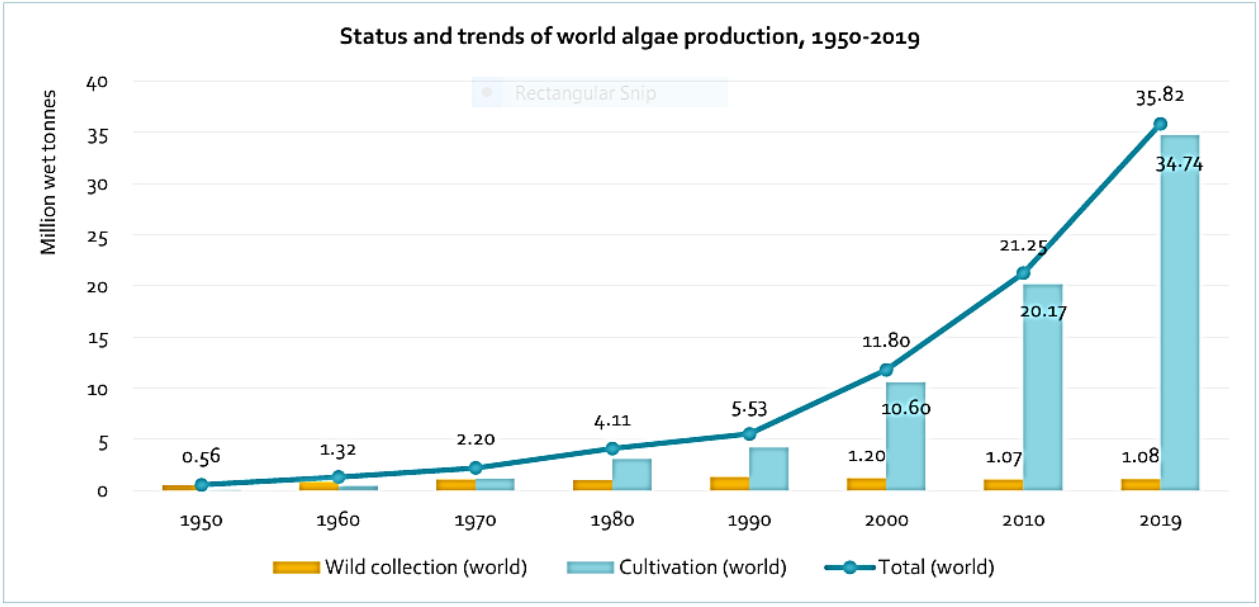
The commercial cultivation of microalgae in Japan started in the 1960s with the cultivation of Chlorella, which then was followed by spirulina farming in Mexico and the US in the 1970s. Microalgae industrial biotechnology has advanced significantly since that time. Microalgae species appeared in the FAO statistics in 2003 with the Chinese production of several species of spirulina, which was first recorded at 16,483 tonne and rose sharply to 97,104 tonne in 2010. As of 1999, aquacultural hatcheries used approximately one-fifth of the 5,000 tonne of yearly global microalgae production: 62% were molluscs, 21% were shrimp, and 16% were fish (Spolaore et al. 2006). It was estimated that of the 63 million t of aquacultural production in 2005, 35 million tonne were fed only on pond-grown

green water. In 2011, the total ingestion of green water microalgae by cultured fish and crustaceans via planktivory was estimated at 240 million t (Zmora et al. 2013).

Brown algae/*Saccharina japonica* is the most commonly produced seaweed in China, accounting for 51 per cent of total output (in 2015, China was the world's largest producer of seaweed with 13.9 million tonnes). Germany, Spain and Italy are the top three producers in terms of microalgae production units. France, Italy, Germany and Spain are the primary producers of spirulina.

Algae biomass output increased globally, reaching 32.67 tonne [Fresh weight (FW)] in 2016 (Araújo et al. 2021; based on data from FAO), of which 0.57% was generated in Europe (containing the EU 27 plus the United Kingdom, plus Iceland and Norway). While harvesting from wild stocks contributed to 98% of the total volume of algae production in Europe over the same time period, aquaculture provided 96.5% of the world's algal biomass in 2016 (Araújo et al. 2021). There are huge knowledge gaps with these data.

Global algae production (including cultivation and wild collection) increased over 60 times from 0.56 million (wet) tonnes in 1950 to 35.82 million tonnes in 2019 (Figure 25); nearly all of the growth was contributed by cultivation.



Data source: FAO 2021. FAO Global Fishery and Aquaculture Production Statistics (FishStatJ; March 2021; www.fao.org/fishery/statistics/software/fishstatj/en).

Figure 25 Status and trends of world algae production, 1950–2019

Australia produced 1923 tonnes (wet weight) of microalgae in 2019, which is about 0.01% of the total world's production (FAO 2021).

6.2.2 General characteristics

Microalgae have many strains, and a great variation among the strains that is mostly due to the growing conditions, temperature, geographical location and the availability of sunlight. They have a long history of use as a human food due to their high content of nutrients and biologically active components such as protein, amino acids, n-3 long-chain polyunsaturated fatty acids, microelements, vitamins, antioxidants, and carotenoids (Almela et al. 2002). Algae do not compete for space and resources with traditional food crops and for these reasons, they are gaining popularity.

Several countries have approved algae as a feed ingredient in poultry and livestock diets with no further testing required (Van der Spiegel et al. 2013). Bacillariophyta (diatoms), Chlorophyta (green algae), Chrysophyta (golden algae) and Cyanophyta (blue-green algae) are the most common microalgal strains. Microalgae biomass from species like the genera *Chlorella*, *Tetraselmis*, *Spirulina*, *Nannochloropsis*, *Nitzchia*, *Navicula*, *Chaetoceros*, *Scenedesmus*, *Haematococcus*, *Crypthecodinium*, *T. lutea* and *A. nodosum*, have been utilised as dietary supplements in the food and feed industry for a long period, delivering vitamins, highly digestible proteins, polysaccharides and lipids (Wells et al. 2016). *Saccharina latissimi* has been supplemented in livestock feed as well (Araujo et al. 2021). Approximately 30% of globally produced algal biomass from the mentioned species, is used for animal feed (Rando & Rene 2020).

Microalgae contain various active compounds including polyphenols, polysaccharides, lipids, peptides and proteins and pigments (Michalak & Chojnacka 2015). The majority of these bioactive compounds have been extensively studied and are known for their antioxidant, antibacterial and anti-inflammatory activities (Coudert et al. 2020). Algae include carotene (β-carotene) and carotenoid pigments (basically xanthophylls: fucoxanthin, lutein and zeaxanthin). Carotenoids are potent antioxidants that fix oxygen and deactivate peroxide-rich radicals in addition to pigmentation. Egg yolk colour is improved by adding carotenoid-rich algae to chicken diets.

Microalgae are high in vitamins A, B1, B2, B6, B12, C and E, as well (Becker 2013). Red algae have high levels of provitamin A and vitamin E; brown and green algae have high levels of vitamin C. Significant levels of B complex vitamins (especially B2 and B3) are present. The high quantities of vitamin B12 provide an advantage over land plants, which are very deficient in vitamin B complex (Rodriguez-Garcia & Guil-Guerrero 2007).

In red algae, the soluble polysaccharides (agar, carrageenan and xylan) are the most important portion (*Gracilaria verrucosa*, *Chondrus crispus*, Laver, *Palmaria palmata*). Sulphate galactose and anhydrous galactose polymers, respectively, are agar and carrageenan. Laminarans, alginates and fucans are soluble fibres found in brown algae (*Ascophyllum nodosum*, *Fucus vesiculosus*, *Himanthalia elongata*, *Undaria pinnatifida*) (Mišurcová, 2012). Alginates are polymers of mannuronic and glucuronic acids which are derived primarily from two sources: marine plants and bacteria (Umoren et al. 2022).

Algal lipid content varies widely. Microalgae can produce up to 50% or even more lipids (w/w) on a dry matter basis, depending on the strain and cultural conditions (Mata et al. 2010). Polyunsaturated fatty acids such as eicosapentaenoic acid, alpha-linolenic acid, arachidonic acid, docosahexaenoic acid and linoleic acid make up the long-chain fatty acid profile of certain microalgae (López et al. 2019). These are precursors of gamma-linolenic acid, prostaglandins, leukotrienes and thromboxane. Green algae have a fatty acid profile similar to that of land plants, with higher levels of oleic acid (C 18: 1) and alpha-linolenic acid (C18: 3).

Red algae contain polyunsaturated fatty acids with 20-carbon units, which is a very rare characteristic for plants as these are common fatty acids found in animal tissues. The quantity of linolenic acid is high in brown algae; however, the distribution of fatty acids is similar (Zbinden et al. 2013).

Beside great metabolites with bioactive functions, microalgae provide a rich source of other compounds with fascinating properties and applications, such as lipoproteins, sterols and alkaloids (Jacob-Lopes et al. 2019).

The protein yield of microalgae per unit area (4–15 tons/Ha/year) is greater than that of soybean (0.6–1.2 tons/ha/year) and wheat (1.1 tons/ha/year; Van Krimpen et al. 2013).

6.2.3 Nutritive value for animal feed

Algae species have been used widely in human nutrition since the 1970s. It is referred to 'superfood' due to its nutritional properties and being important sources of specific components such as antioxidants, pigments, oils and vitamins (Jung et al. 2019). The amount of protein in algae varies. On a DM basis, it varies between 30 and 40% in red algae.

Table 149 Nutrient composition of dried spirulina (*Arthrospira* spp.)

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	92.3	2.2	89.3	96.4
Crude protein	% DM	63.8	5.6	54.2	72.6
Crude fibre	% DM	2.9	2.8	0.1	6.4
NDF	% DM	0.1			
ADF	% DM	0.0			
Ether extract	% DM	6.1		1.2	10.9
Ash	% DM	8.9	2.6	4.1	13.9
Insoluble ash	% DM	0.1		0.1	0.2
Gross energy	MJ/kg DM	21.3	0.7	20.3	23.2

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The protein content of green algae can reach up to 20% on a dry matter basis at certain times of the year. Spirulina with 70% protein on a DM basis, contains the highest protein level among different microalgae strains. Algae's total fibre content ranges from 32 to 50%. In green and red algae, the soluble fibre fraction accounts for 51 to 56% of total fibre, while in brown algae it accounts for 67 to 87%.

Minerals such as sodium, calcium, magnesium, potassium, chlorine, sulphur and phosphorus, as well as essential micronutrients like iodine, iron, zinc, copper, selenium, molybdenum and other trace elements like fluoride, manganese, boron, nickel, and cobalt can account for up to 36% of the dry matter in algae (Becker 2013).

Table 150 Mineral composition of dried spirulina (*Arthrospira* spp.)

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	0.8	0.2	0.7	1.0
Phosphorus	g/kg DM	6.6	4.2	0.3	8.9
Sodium	g/kg DM	7.0		2.9	11.0
Chlorine	g/kg DM	1.4		0.1	2.7
Iron	mg/kg DM	560		530	590

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Microalgae are usually rich in protein, which may amount to more than 60% of DM. Spirulina (*Arthospira*) contains a high amount of protein, between 55 and 77% of DM (Garofalo 2011). As noted above, there are considerable variations due to genetic or culture conditions. For instance, some

Chlorella strains contain less than 30% protein in the DM, whereas regular *Chlorella* exceeds 50% protein. The protein content was found to be more susceptible to medium-induced variation than the other cellular constituents (Becker 2013b). The amino acid composition of microalgal proteins is quite similar between species, and relatively unaffected by intrinsic and extrinsic factors (Becker 2013b). For example, cultures grown over a range of light intensities were identical in amino acid composition, as were those grown in stationary phase and logarithmic-phase cultures (Brown et al. 1993). In general, aspartic acid and glutamic acid occur in the highest concentrations, and cysteine, methionine, tryptophan and histidine occur in the lowest concentrations (Becker 2013b). Spirulina protein contains all essential (for humans) amino acids, though reduced amounts of methionine, cysteine and lysine when compared to animal proteins. It is superior to a typical plant protein, including that of legumes (Garofalo 2011).

Table 151 Amino acid profile of dried spirulina (*Arthrospira* spp.)

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	7.0	0.7	5.9	8.0
Arginine	% protein	4.6	2.7	1.4	7.6
Aspartic acid	% protein	9.2	0.6	7.6	10.0
Cystine	% protein	0.9	0.2	0.4	1.1
Glutamic acid	% protein	13.7	1.6	11.4	16.1
Glycine	% protein	4.8	0.3	4.0	5.2
Histidine	% protein	3.7	2.5	1.2	6.9
Isoleucine	% protein	5.8	0.7	3.8	6.5
Leucine	% protein	8.5	0.6	7.4	9.3
Lysine	% protein	4.4	0.3	3.8	5.0
Methionine	% protein	2.2	0.6	1.1	3.0
Phenylalanine	% protein	4.3	0.3	3.8	5.0
Proline	% protein	3.6	0.4	3.0	4.3
Serine	% protein	4.9	0.5	4.2	5.7
Threonine	% protein	4.8	0.4	4.2	5.8
Tryptophan	% protein	1.4	0.1	1.3	1.6
Tyrosine	% protein	4.4	0.5	3.6	5.0
Valine	% protein	6.4	0.9	5.1	8.6

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Because microalgae are not widely consumed, there is a scarcity of studies on the ileal digestion of algae, which limits comparisons of algal protein quality between different algae species and other protein sources.

The differences in the chemical composition and nutritional value of microalgae depend on the algae type, classification (red, blue or green), and growing conditions. Numerous nutritional and toxicological studies have reported that algal biomass is an alternative protein-rich feed supplement to replace traditional protein sources such as soybean meal and fishmeal in animal feed (Ljubic et al. 2020).

Kotrbácek et al. (2015) found that combining a conventional feed ingredient with microalgae such as *Chlorella*, *Scenedesmus* and *Arthrospira* can improve growth, health, and product quality and quantity. In addition, microalgae inclusion in the feed has resulted in multiple positive effects including reduced

cholesterol and improved immune response (Raja & Hemaiswarya 2010); enhanced milk quality and yield in dairy cows (Altomonte et al. 2018); improved meat and egg quality in poultry (Madeira et al. 2017); increased resistance to disease and stress through antiviral and antibacterial action (Dewi et al. 2018); improved gut function and enriched the colonisation of probiotics (Camacho et al. 2019); and improved lipid metabolism and feed conversion (Tibbetts et al. 2018).

Poultry is the target domestic animal for microalgae inclusion in commercial applications (Becker 2007). Algae can be incorporated into the feed at a 5–10% inclusion rate partially replacing traditional protein-rich sources in chicken feed (Spolaore et al. 2006).

In pigs, it is assumed that up to 33% algae inclusion will not impair growth performance. However, ruminants are the most suitable species for algae biomass as they can digest the algae fibres by the microflora in their rumen (Gouveia et al. 2008). The pet food market seems to be a promising end-user of microalgae as well (Pulz & Gross 2004).

Microalgae can be used as a feed supplement to increase the quality of meat, eggs, and milk products, which will bring many health benefits to people when consumed, including anticancer, antioxidant and antiviral properties (Saadaoui et al. 2020).

6.2.4 Antinutritional factors – nutritional limitations

Some of the limitations with including microalgae in practical and commercial feed formulations include potential contamination with toxins and relevant biosecurity and safety issues, antinutritional factors such as saponin, phytic acid, and tannins and poor digestibility. Microalgae contain high fibre content including cellulose, which is not a digestible fraction for monogastric animals (do Carmo Gominho-Rosa et al. 2015). Furthermore, microalgae cells may adsorb and accumulate heavy metals due to the properties of the surface cell with a range of functional groups and negative charges. These toxic elements, if they exist in the water, will be biofortified by microalgae and will then accumulate in animal tissues when microalgae are used as a feed ingredient, and through the animal within the food chain, which will generate a potential risk for public health (Pavithra et al. 2020).

6.2.5 Microalgae in the laying hen diet

Microalgae have emerged as novel sources for monogastric animals' diets since they are rich in many nutrients, including proteins. *Arthrospira platensis* is particularly rich in proteins (up to 76% of dry matter), lipids, minerals and pigments (carotenoid), which are essential nutrients for production and improving the colour of chicken meat and eggs. However, its rigid peptidoglycan cell wall interferes with the digestibility and bioavailability of nutrients for monogastric animals (Spínola et al. 2022). Numerous nutritional studies have shown that different species/types of microalgae may be successfully incorporated into layer diets to produce a favourable performance and egg quality when compared to the conventional standard diet.

An inclusion level of 5–10% of microalgal biomass in the diet can safely substitute for a portion of a traditional protein source; however, feeding higher concentrations for longer periods may have negative consequences on production performance (Spolaore et al. 2006). Feeding laying hens during 29 to 40 weeks of age with 3g *S. platensis*/kg diet increased egg mass, egg weight and egg production by comparison with the control group (Samia et al. 2018). Zheng et al. (2012) showed that feeding laying hens with 1 and 2 g/kg fermented *Chlorella* improves the quantity and quality of produced eggs, although there was no effect on feed intake. Hepatic triacylglycerol level was linearly decreased with increasing dietary. Supplementing fermented *Chlorella* improved cecal bacterial population by increasing the lactic acid bacteria population in the intestine. Spray-dried or bullet milled *Chlorella*

vulgaris at a 2.5 g, 5.0 g or 7.5 g per kg inclusion rate was studied in breeding hens from 22–54 weeks of age. The results showed improved egg production, yolk colour and shell weight, as well as hatch percentage (Halle et al. 2009). Also, inoculation of liquid spirulina extract into quail eggs (*in ovo* injection) during the final stages of hatch improved the hatch percentages, the chicken survival rate, immunity and their antioxidant status (Aljumaily & Taha 2019). It was found that *Chlorella* increased lutein concentration in eggs, which prevents muscular degeneration (retinal structure) in elderly humans (An et al. 2014).

Halle et al. (2009) suggested that *Chlorella* improves intestinal microflora, which positively affects egg production performance and egg quality. Inclusion of 7.5% of *Staurosira* microalgae replacing soybean meal did not have any negative impact on laying performance, but replacement at a 15% inclusion rate adversely affected feed consumption, feed conversion ratio and egg production performance (Leng et al. 2014). In contrast, (Ekmay et al., 2015) conducted a 14-wk trial using two types of microalgal biomass as alternative protein sources in laying hen diets. Hens fed a defatted green microalgal biomass (*Desmodesmus* spp.) at 25% and a full-fatted diatom biomass (*Staurosira* spp.) at 11.7% inclusion with or without protease. The results showed that the addition of two species of microalgal biomass (25% of *Desmodesmus* and 11,7% *Staurosira*) in the diet of laying hens did not decrease laying performance and egg quality, despite a decrease in feed intake.

Table 152 Results of selected studies on the effects of spirulina inclusion in laying hens' diets

Dietary inclusion of algae	Birds/age/duration of trial/	Studied parameters	Results	Reference
1.5, 3, 6, 12%	Leghorn cockerel chicks, 1–21 day	Growth performance	No significant effect of spirulina on performance	Ross & Dominy 1990
0.001, 0.01, 0,1, & 1.0%	White Leghorns, and broiler chicken; 1–49 day and 1–21 day	Growth performance and immune response	No effect of spirulina on performance. Leghorn chicks in spirulina-dietary group, had increased total anti-SRBC titters; increased phagocytic potential of macrophages and NK-cell activity	Qureshi et al. 1996
1.5, 2.0, 2.5%	Laying hens, 63–67 wk	Laying performance, yolk colour	Spirulina increased yolk colour without any negative effect on production.	Zahroojian et al. 2011
1.5, 2.0, 2.5%	Laying hens, 63–67 wk	Laying performance, egg quality, yolk colour	No significant effect of spirulina on studied indices, except yolk colour, which was increased by dietary algae addition	Zahroojian et al. 2013

Kotrbáček et al. (2013) studied the effects of including *Chlorella* at 1% or 2% inclusion rates in laying hens' diet from 56–63 weeks of age on egg quality traits and blood parameters. *Chlorella* increased yolk carotenoids, lutein, β-carotene and zeaxanthin content and yolk colour score. However, feed intake was decreased when *Chlorella* was included at 2%. Table 152 above summarises a few studies on inclusion of microalgae (spirulina) in layer hens' diet.

Herber and Van Elswyk (1996) and Moran et al. (2019) demonstrated that the efficiency of DHA assimilation from microalgae to eggs was 42.6% in hens when they were provided with a 2.4% algal-blended feed. Compared to the control eggs, the DHA content increased 6-fold in eggs from hens fed with algae-based feed (Bourre et al. 2005). In general, microalgae inclusion improves poultry

performance in four different ways: supplying and improving the absorption of vitamins and minerals, supplying a good source of protein, balancing intestinal microflora, and improving nutrient digestion. The inclusion of microalgae improves egg yolk colour due to the accumulation of zeaxanthin pigments in spirulina, which is transferred to egg yolk (Mariey et al. 2014). The antimicrobial, anti-inflammatory, immune-modulatory and antioxidant capacity of *S. platensis* enhances the health status and immune response of birds (Christaki et al. 2013).

Based on the current existing data, it seems that spirulina can be included at up to 10% in laying hens' diet, not only with no adverse effects on egg production performance but also improving egg yolk colour, egg omega-3 fatty acids content, gut bacterial balance and gut health, and immune response. *Chlorella*, at an inclusion rate of 1% improves egg quality measures and immune parameters.

6.2.6 Microalgae in the pig diet

Microalgal biomass seems to be appealing to pigs, has a good nutritional profile, and can partially substitute fishmeal or soybean meal (Becker 2013a). It has been demonstrated that adding one or more PUFA-rich algae species such as *Arthrospira maxima* and *Arthrospira platensis* to the diet of pigs resulted in meat with a balanced lipid profile, (Samarakoon et al. 2012; Lum et al. 2013). In a recent study, inclusion of microalgae such as *Schizochytrium* sp. at 5% and 7% in growing pigs' diet, has improved the omega-3 fatty acid content in their meat and enhanced skeletal muscle phenotypic appearance and functionality (Kalbe et al. 2019).

Numerous studies on the incorporation of different dried microalgae in swine feeds have been conducted over the years. Simkus et al. (2013) incorporated 2 g of fresh microalga biomass with forage into the feed of pigs weighing from 30.6 to 96.4 kg, to study the use of spirulina as a supplement. Table 153 summarises the reports on the inclusion of different microalgae biomass in pigs' diet and their effects on performance or meat quality.

Table 153 Summary of studies evaluating different microalgae in pig diets as either ingredients (> 3%) or additives (< 3%).

Microalgae	Ingredient vs. additive	Inclusion level	Objective	Animal class/live weight	Main results	References
Arthrospira platensis and Chlorella vulgaris	Additive	1% (both)	Mitigate postweaning stress	Weaned piglets/9.1–20 kg	*Chlorella* increased feed:gain ratio in comparison to *Spirulina* Both microalgae increased villus height in the jejunum	Furbeyre et al. (2017)
	Additive	385 mg/kg LW (in drinking water)	Mitigate postweaning stress	Suckling piglets/4.9 kg Weaned piglets/9.04 kg	Spirulina increased weight gain in the suckling period and at weaning Spirulina lowered diarrhea incidence Chlorella increased diarrhea occurrence	Furbeyre et al. (2018)
Aurantiochytrium limacinum	Additive	3.12%	Replace fish oil as a source of n-3 PUFA with microalgae, to boost immune stats during postweaning stress	Weaned piglets/6.82–22.30 kg	After lipopolysaccharide challenge, algae-fed piglets had lower rectal temperature, less circulating cortisol but increased cytokine concentration Microalgae had no effect over animal performance	Lee et al. (2019a)
	Additive	3.12%	Enhance weaned piglet immune status through maternal supplementation	Multiparous sows/NA	Supplementation did not affect cortisol response in sows following a LPS challenge No effect on offspring	Lee et al. (2019b)
Aurantiochytrium limacinum	Additive	1%	Evaluate the use of the microalga as a source of DHA in finisher diets	Finisher 117.1–140.3 kg	No effect over animal performance Algae supplementation increased EPA, DHA and n-3/n-6 ratio in *Longissimus lomborum*	Moran et al. (2018)
Defatted microalgae biomass (unknown species)	Additive	0.5%–1%	Test the effect of defatted biomass supplementation on growth performance, ileal digestibility and total tract apparent digestibility	Weaned piglets 6.27 kg	Defatted biomass downregulated the urea cycle in the liver No influence of microalgae biomass dietary inclusion over animal performance	Urriola et al. (2018)

***Desmodesmus* sp. (defatted)**	Ingredient	10%	Determine the impact of using defatted biomass in piglet diets and the effect of protease addition	Weaned piglets 9.8 kg	Dietary microalgae with protease supplementation increased final live weights from 26.7–28.1 kg Biomass incorporation increased ingested N utilization	Ekmay et al. (2014)
***Chlorella vulgaris* (fermented)**	Additive	0.1% 0.2%	Evaluate the effect of fermented microalgae as prebiotic in the performance of growing pigs	Growers 26–53 kg	0.1% incorporation increased dry matter digestibility and ADG Microalgae incorporation benefited the gut's *lactobacillus* population	Yan et al. (2012)
Chlorella* and *Scendesmus	Ingredient	10% (grower) 5% (finisher)	Test the viability of feeding sewage-grown microalgae to fattening pigs	Growers 63 kg Finisher 90 kg	Thicker backfat in diets with algae and vitamin B supplementation Vitamin B supplementation improved ADG (866 g/d) vs. no supplementation (757 g/d) in algae-fed groups	Hintz and Heitman (1967)
***Schizochytrium* JB5**	Additive	0.5%–1%	Test the effect of microalgae supplementation on growth performance, nutrient digestibility and blood immune profile	Weaned piglets 6.25–10.52 kg	Supplementation of 1% microalgae improved gain:feed ratio vs. 5% Microalgae improved blood lymphocyte count Microalgae supplementation increased dry matter and N apparent total tract digestibility and ileal digestibility	Kibria and Kim (2019)
***Schizochytrium* sp.**	Ingredient	7% (piglets) 5% (growers)	Increase n-3 PUFA content in pig meat	Weaned piglets/9.46 kg Grower pigs/103.37 kg	Reduced feed intake No effect over animal performance	Kalbe et al. (2019)
	Additive	0.25% 0.5%	Evaluate the effect of microalgae as a source of DHA in the diet of Italian heavy pigs	Finisher 118 kg	No effects of microalgae dietary inclusion on animal performance	Sardi et al. (2006)
	Additive	0.06% 0.6% 1.6%	Evaluate DHA from *Schyzochitrium* sp. as a source to improve bacon fatty acid profile	Finisher 80 kg	Positive correlation between increased dietary microalgae and average daily gain	Meadus et al. (2010)

ADG, average daily gain; DHA, docosahexaenoic acid; EPA, eicosapentaenoic acid; LPS, lipopolysaccharide; LW, live weight; NA, not available; PUFA, poly unsaturated fatty acids.

Table 154 Summary of main effects of dietary microalgae inclusion on pork quality and nutritional value

Microalga	Inclusion level	Animal-initial weight LW-final weight LW or trial duration	Main findings	Reference
Arthospira platensis	0.2%	Grower pigs-30.6–96.4 kg	Microalga had no effect on protein, colour, pH, cooking loss, tenderness and backfat thickness; decreased the amount of intramuscular fat in meat.	Simkus et al. 2013
Arthrospira platensis	8.3 and 12.5% (1st period—25–50 kg LW), 6.6 and 9.9% (2nd period—51–75 kg LW) and 9.5% (3rd period—more than 75 kg LW)	Barrows-25–110 or 122 kg	Microalga influenced the FA composition of backfat with increased PUFA levels. Meat quality was not compromised.	Altmann et al. 2019
Arthrospira platensis	10%	Weaned piglets-12.0 kg-4 weeks	No significant effects on meat quality traits with the dietary microalga.	Martins et al. 2021a
Chlorella vulgaris	5.0%	Weaned piglets-11.2 kg-2 weeks	Microalga improved total carotenoids and n-3 PUFA content in meat.	Martins et al. 2021b
Chlorella vulgaris	5.0%	Grower pigs-59.1–101 kg	Microalga improved total carotenoids and n-3 PUFA content in meat.	Coelho et al. 2020
Schizochytrium sp.	0.250% (for 4 or 8 weeks) and 0.500% (for 4 weeks)	Barrows-118–160 kg	Microalga had no effect on backfat thickness; feeding 0.50% microalga over 4 weeks prior to slaughter increased the DHA content and decreased n-6/n-3 ratio.	Sardi et al. 2006
Schizochytrium sp.	0.300, 0.600 and 1.20%	Finisher pigs-75–110 kg	Microalga increased lipid peroxidation and EPA and DHA contents in dry-cured hams; no effect on proximate composition, colour, pH and TBARS values.	Vossen et al. 2017
Schizochytrium sp.	0.06, 0.60 and 1.6%	Finisher pigs-80–110 kg	Microalga increased DHA content and lipid peroxidation of bacon. Over 0.6% inclusion, consumer acceptability was reduced due to the development of off-flavours during and after cooking bacon	Meadus et al. 2011
Schizochytrium sp.	0.250 and 0.500%	Grower pigs-27.9 kg–17 weeks	Microalga increased DHA content of loin and backfat.	Moran et al. 2017
Schizochytrium sp.	1.00%	Finisher pigs-117–140 kg	Microalga increased EPA, DHA and n-3/n-6 ratio in longissimus lumborum muscle.	Moran et al. 2018

Schizochytrium sp.	0.900, 1.90 and 3.70%	Finisher pigs-50.7–115 kg	Microalga increased C20:4, C20:5 and C22:6n-3 contents in the tissues studied; DHA deposition depends on tissue location.	De Tonnac et al. 2017 & 2018
Schizochytrium sp.	0.940, 1.85, 2.74 and 3.61%	Finisher pigs-64.6–115 kg	Increasing dietary DHA reduced the activity of lipogenic enzymes in the liver and inhibited the expressions of genes involved in FA metabolism.	De Tonnac et al. 2016
Schizochytrium sp.	7.00% (piglet diet)/5.00% (grower pig diet)	Grower pigs-9.46–104 kg	Microalga increased DHA in longissimus thoracis and semitendinosus muscles.	Kalbe et al. 2019

The inclusion of microalgae biomass reduced the amount of intramuscular fat in the meat by 0.33%, but the ADG was 9.26% greater compared to the control group without affecting the thickness of the backfat (Simkus et al. 2013).

In weaned piglets, the main concern is to guarantee intestinal health during post-weaning stress, by avoiding diarrhoea or any factors that may delay the development and weight gain of such young animals. In growing and fattening pigs, studies on the use of microalgae have a different role and researchers commonly target them as an alternative source of proteins and carbohydrates (Valente et al. 2019). Older pigs have less susceptibility to infections, and for that reason the use of microalgae is more practical than in piglets. As it can be seen in the previous table, several authors have reported data for when microalgae have been included in the diet as an adequate protein source. Other effects that have been reported are increased linoleic acids in subcutaneous fat (Altmann et al. 2019), increased backfat thickness, without negatively influencing the animal's performance, improved nutritional properties of meat, namely the fatty acid profile in pork (Marriott et al. 2002; Moran et al. 2018; Sardi et al. 2006; De Tonnac et al. 2018). In addition, the prebiotic effects of microalgae have also been reported in several studies. Yan et al. (2012), for instance, reported an improvement in the microbiological profile of animal faeces with fermented Chlorella dietary supplementation.

To sum up, different microalgae strains can be included in pigs' diet to enhance performance and meat quality, as well as gut health. Based on available literature, the inclusion rate of microalgae as an additive or feed ingredient typically ranges from 1% to 10%, depending on the specific targets to achieve.

6.2.7 Carbon footprint and sustainability of microalgae production

Likewise, seaweed production and microalgae farming also provide significant environmental benefits and ecosystem services. Both seaweed and microalgae can be grown in marine water or freshwater and cultivated in peripheral land in the desert and barren fields (Winckelmann et al. 2015). Using the same bio-extraction of nitrogen and phosphorus, and photosynthetic process like seaweeds, microalgae can also help reduce eutrophication and ocean acidification, treat wastewater, and capture carbon (Cai, Lovatelli et al. 2021). All of these features make microalgal-based feed environmentally sustainable and, additionally, it has a high commercial ability owing to its high areal biomass productivity (Nagappan et al. 2021).

Earlier studies indicated how to reduce carbon emissions from microalgae production. According to one study, large-scale (more than 2.5 ha) microalgae-based feed production may lower the carbon footprint by 20 times. Further developments in biomass harvest, improved reactor design, climate-smart reactor systems, energy-efficient harvesting systems, and sustainable practices (e.g. the use of solar energy and waste by-products) may cut the carbon footprint (Taelman et al. 2013). Another study mentioned that when using hydrolysed food waste to acquire carbon in microalgal farming, the environmental benefit could be 4.5 times greater, making it much more eco-friendly among protein sources. (Ahmad et al. 2022).

6.3 Duckweed

Duckweed, or water lentils or *Lemna*, is a family of small flowering aquatic plants that float on the surface of water, such as in lakes. *Spirodela polyrhiza* is the most widely distributed duckweed species. Duckweed belongs to the botanical family Lemnaceae. They are known as macrophytes and are often confused with algae (Sońta et al. 2019). These little floating aquatic plants grow incredibly quickly, and they can be found everywhere except dry deserts and or frozen areas. They have a simple morphology; however, they are rich in protein (Santaeufemia et al. 2016). Tropical climates are the optimum environment for their growth, although they can tolerate harsh environments (Sońta et al. 2019). Open greenhouse pools or ponds are used to cultivate duckweed biomass in a controlled environment, where the produced biomass may also include microflora of bacteria, viruses, fungi algae, and potentially microscopic invertebrates (Vermeulen et al. 2012).

Overgrown duckweed on lakes is not desirable, although its potential as a cleanser when it accumulates toxic compounds, heavy metals and minerals from sewage water (such as effluent or wastewater originating from intensive livestock production or irrigated crop farming) has drawn research opportunities (Hegazy et al. 2009). Duckweed species can also uptake and transform phenols and pesticides, such as organophosphorus pesticides (malathion, demeton-S-methyl, and crufomate) (Gao et al. 2000); lipophilic compounds (De Carvalho et al. 2007); 3-methyl-4-nitrophenol, 3,5-dichloroaniline, 3-phenoxybenzoic acid (Fujisawa et al. 2006); dimethomorph (Olette et al. 2008; Dosnon-Olette et al. 2010); copper sulphate and flazasulfuron (Olette et al. 2008); and xenobiotics (chlorophenols) (Day et al. 2004). The main duckweed species are the following:

- *Lemna minor*
- *Lemna gibba*
- *Spirodela polyrhiza*
- *Wolffia arrhiza*

Duckweeds are consumed by domesticated and wild birds, fish, herbivorous animals and people in various regions of the world. One nutritionally important property of duckweed is its high protein content ranging between 25 and 40%, which makes it a great alternative novel ingredient to be used in animal feed (Sońta et al. 2019). This fodder plant was well-known and utilised in Poland in the 1960s and 1970s to feed pigs and ducks (Lassociski 1979). For farm animals and aquaculture, it has been acknowledged as a source of protein by numerous studies (Haustein et al. 1994; Bairagi et al. 2002; Goopy & Murray 2003; Moyo et al. 2003; Khandaker et al. 2007; Effiong et al. 2009; Hasan & Chakrabarty 2009; Akter et al. 2011; Mwale & Gwaze (2013); Appenroth et al. 2017.

6.3.1 Duckweed production globally and in Australia

There are no data available on duckweed global or regional production.

6.3.2 General characteristics

The natural green biomass of duckweed can provide 4 to 5 times more protein per hectare as soybean. Duckweed is not a genetically modified plant; it contains no gluten, and for production does not require arable land (Zawadzki 2016). It is a natural feed ingredient for ducks and geese when grown on ponds and lakes.

Protein content in some strains might reach 30 or 40 percent by dry weight. Duckweed leaves are small, less than 5 mm long and they can be found alone, or clusters of two or three. Although

duckweed grows fast, the nutrient content of the water affects its growth rate. Several factors are important in its growth including temperature, nutrient loading, nutrient balance, pH, sun exposure and day length, and wind speed.

Optimum conditions for duckweed growth include a pH of 5–9, and temperature ranging from 6 to 33°C. Water temperatures of 20 to 28°C and a pH of 6.5 to 7.5 are ideal growing conditions for high biomass output. Duckweed ponds should be at least 30–50 cm deep to minimise extreme temperature swings. Duckweed can use a variety of nitrogen compounds contained in the water. Ammonium ion (NH4+) with an optimal concentration of 10–15 ml/l is the major nitrogen source and precursor for duckweed growth. It is well known that nitrogen concentrations more than 60 ml/l in an aquatic environment are poisonous to duckweed, which is most likely owing to the high level of free ammonia in the water. Duckweed can grow well in either low or high phosphorous concentrations, and it will accumulate around 1.5% of phosphorus in dry matter.

As stated before, cultivation conditions and the nutrient/chemical/mineral content of the water can alter the nutrient and mineral profile of duckweed. Duckweed contains carotenoids and vitamins from the A, B and E groups, which is an added benefit (Sońta et al. 2019). Minerals including Ca, Cl, K, Na, Si, N, H, C, Fe, Mg, Mn, Al, Si, B, P, Cu and Zn are among the macro- and micronutrients that duckweed may absorb from water (Showqil et al. 2017).

Duckweed is capable of absorbing a wide range of substances from the aquatic environment, including hazardous heavy metals. Many heavy metals (cadmium, chromium and lead) accumulate in it, posing a risk to its natural growth as well as the health of poultry, cattle and humans, if consumed. The levels of heavy metals should be monitored during duckweed production for feedstuffs, to avoid their entry into the food chain. Natural freshwater resources, household sewage and wastewater from livestock production normally does not contain high volumes of heavy metals, and therefore the use of these resources may not pose a risk.

Duckweed has a good nutrient profile, and is rich in protein, minerals and vitamins. A quick literature search shows that it has been added to feed as a supplement, mostly to enrich diets and enhance animal development. Duckweed is widely utilised as a feed for fish (Yilmaz et al. 2004) and domestic animals such as chickens (Ahammad et al. 2003), ducks (Ngamsaeng et al. 2004), and pigs (Aguilera-Morales et al. 2005).

W. microscopica and *Wolffiella hyalina* were the most promising candidates in terms of nutritive value among the species chosen for livestock feed (Appenroth et al. 2017). *W. microscopica* is endemic to the Indian subcontinent, and *W. hyalina* has a similar distribution pattern. Some duckweed species have outstanding nutritional properties for human nutrition, such as *W. globose* which is very popular in Asia. This is because species of the genus *Wolffia*, unlike subfamily Lemnoideae, don't contain calcium oxalate crystals that might cause health problems in humans or animals (Hu et al. 2022). Duckweed is primarily produced in tropical regions on a commercial scale, where it is dehydrated and de-oiled before being processed into meal (Sońta et al. 2019).

6.3.3 Nutritive value for animal feed

The chemical composition of duckweed includes a dry matter content of 3–14% (high moisture content); protein ranging from 7–45% of the dry matter (most often 20–35%); 2–9% fat; fibre about 12–28%; and 14–44% carbohydrates (Hasan & Chakrabarty 2009). Despite having less crude fibre than terrestrial plants, duckweed does contain a sizable amount of it. In general, the crude fibre content of duckweed grown in nutrient-rich water (7–10% DM) is lower than that of duckweed produced in nutrient-poor water (11–17% DM).

Table 155 Nutrient composition of fresh duckweed

Main analysis	Unit	Avg	SD	Min	Max
Dry matter	% as fed	5.6	1.0	4.6	7.9
Crude protein	% DM	29.1	4.3	24.9	38.6
Crude fibre	% DM	12.5	4.6	6.9	18.7
NDF	% DM	40.1	8.2	33.9	58.2
ADF	% DM	18.5	4.5	12.4	23.4
Lignin	% DM	5.7	4.3	3.2	10.6
Ether extract	% DM	6.1	3.6	2.2	13.8
Ash	% DM	15.9	3.9	9.5	23.3
Gross energy	MJ/kg DM	18.2			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The amount of minerals present in the water directly affects the mineral content of duckweed, which can range from 0% to 30% DM. It could have significant calcium and potassium content (Leng et al. 1995). In a study by Appenroth et al. 2018, the mineral composition of duckweed is reported as below: Magnesium content ranged from 1.91 to 4.55 g/kg freeze-dry weight (FDW) (mean 2.85 ± 0.71 g/kg FDW); iron from 0.11 to 0.4 g/kg FDW (mean 0.23 ± 0.09 g/kg FDW); and the trace element manganese from 78.4 to 431 mg/kg FDW (mean 230 ± 98 mg/kg FDW). Interestingly, iodine ranged from 0.20 to 0.92 mg/kg FDW (mean 0.39 ± 0.19 mg/kg FDW), and cadmium content from 0.009 to 0.59 mg/kg FDW (mean 0.076 ± 0.145 mg/kg FDW).

Table 156 Mineral composition of fresh duckweed

Minerals	Unit	Avg	SD	Min	Max
Calcium	g/kg DM	23.3	14.2	7.1	33.1
Phosphorus	g/kg DM	5.7	0.7	4.9	6.2
Potassium	g/kg DM	42.9			
Sodium	g/kg DM	1.4			
Manganese	mg/kg DM	1723			
Zinc	mg/kg DM	75			
Copper	mg/kg DM	20			
Iron	mg/kg DM	0			

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

The amino acid profile is interestingly similar to the WHO recommendations, with 4.8% lysine, 2.7% methionine + cysteine, and 7.7% phenylalanine + tyrosine. Lysine and the aromatic amino acid histidine + phenylalanine are slightly limiting AA in duckweed. A very rich source of polyunsaturated fatty acids with a concentration ranging from 48 to 71%, and high n-3 fatty acid content has resulted in a favourable n6/n3 ratio of 0.5 or less. *W. microscopica*, the fastest growing angiosperm, has a phytosterol concentration of 50 mg/1g of lipid (Appenroth et al. 2017).

Duckweed is a good supplement for livestock, especially chicken, because it contains significant quantities of xanthophylls and pigments that can affect the skin and yolk colour of animals. The

literature reports carotene contents between 600 and 1000 mg/kg. The results of the studies using duckweed in poultry or ruminant feed show that its amino acids, such as lysine and methionine, have a better availability for animals than that of vegetables. Its protein is rich in leucine, threonine, phenylalanine, valine and isoleucine, which makes it an economically interesting ingredient for livestock feed (Goopy & Murray 2003). Previous studies have reported that duckweed can replace expensive protein-rich ingredients in conventional poultry diets such as alfalfa (Lucerne), as it has a high protein content (20–40%) and a low fibre and high mineral content.

Table 157 Amino acid composition of fresh duckweed

Amino acids	Unit	Avg	SD	Min	Max
Alanine	% protein	4.3	0.5	3.8	4.6
Arginine	% protein	4.4	0.7	3.8	5.3
Aspartic acid	% protein	6.8	1.0	5.6	7.6
Glutamic acid	% protein	7.1	1.2	5.8	8.0
Glycine	% protein	3.6	0.5	3.0	4.0
Histidine	% protein	1.7	0.5	1.2	2.2
Isoleucine	% protein	3.6	0.4	3.1	3.9
Leucine	% protein	6.6	0.7	5.8	7.2
Lysine	% protein	3.9	0.5	3.4	4.3
Methionine	% protein	0.8	0.0	0.8	0.9
Phenylalanine	% protein	4.1	0.4	3.6	4.5
Proline	% protein	2.9	0.4	2.4	3.3
Serine	% protein	2.6	0.3	2.3	2.8
Threonine	% protein	3.1	0.5	2.6	3.5
Tyrosine	% protein	2.7	0.5	2.2	3.1
Valine	% protein	4.3	0.7	3.5	5.0

Avg: average or predicted value.
SD: standard deviation.
Min: minimum value; Max: maximum value.
(Source: Feedipedia.org)

Dried duckweed would be preferred as an excellent supplement to any high-energy diet in poultry feed (Demann et al., 2022). Fresh duckweed can be used to replace all the soybean meal in fattening ducks (Men et al. 1995). Chickens given 10% dehydrated (dried) duckweed gained more weight than those given normal protein sources. However, depending on the nutrients in the growing medium, duckweed can be high protein/low fibre or low protein/high fibre, and this can create inconsistent outcomes when duckweed is used in animal feed.

More and more papers are being published on the topic as there is a growing interest in commercialising duckweed as a common feed ingredient in animal feed, however, optimum cultivation conditions, preparation methods and processing techniques (including drying), require further investigation. Methods to assure that heavy metals, phenols, pesticides and pathogens do not contaminate duckweed biomass should be developed (Ujong et al., 2024).

6.3.4 Antinutritional factors – nutritional limitations

Duckweed may contain a variety of dangerous pollutants that are accumulated in the produced biomass, raising questions regarding the safety of eating it. Heavy metals and metalloids, pathogens (bacteria, viruses and parasites) and xenobiotics (hormones, antibiotics, parasiticides, etc.) are the most common pollutants. Municipal and agro-industrial wastewater, such as wastewater from poultry, piggery and cattle farms, and food processing by-products (cheese whey, olive-oil mill wastes, etc.), as well as gaseous waste streams (like flue gases) have all been explored for nutrient recycling using duckweed production. However, besides rich nutrients, waste streams may contain a variety of other organic and inorganic substances that could contaminate the biomass, leaving it unfit for feed or food production.

Some other antinutritional factors present in duckweed include trypsin inhibitor (ranging from 1.1% to 1.5%), calcium oxalate concentration (ranging from 0.6% to 3.5%), tannin concentration (ranging from 0.25% to 0.93%) and phytate concentration (ranging from 0.004% to 0.005%).

Strategies should be identified, and processing and preparation methods need to be developed, to reduce the risks of bio-contamination of duckweed. These techniques may include, but not be limited to, pre-treating the wastewater streams, or manipulating the cultivation media, post-treatment, and processing of anaerobic digestates, precipitation, degradation, and biotransformation of organic pollutants by various mechanisms (Markou et al. 2018). A potential solution might be anaerobic digestion, which is a frequently utilised technique to treat wastewater. It is well-known that a vast majority of organic and biological pollutants are eliminated extensively during anaerobic digestion. Chemical precipitation, ion exchange, adsorption, membrane filtration, coagulation and flocculation, flotation and electrochemical treatment are some of the ways for removing heavy metals from media before cultivation. However, each of these approaches has both benefits and drawbacks (Fu & Wang 2011).

Environmental conditions that influence pathogen survival include pH, temperature, humidity, ionic and osmotic strength, competition with other flora, and light (ultraviolet – UV). Pathogens in the media can be deactivated using several mechanisms such as cell disruption, proteolysis, protein denaturation, antibiosis, antagonism and nutritional shortages.

6.3.5 Duckweed in the laying hen diet

It has been reported that *Lemna minor* (duckweed) can be an alternative ingredient in the laying hen diet due to its high protein content and pigments, which enhance the egg yolk colour. In a study, application of duckweed at 10, 30, 50, 80, 120 and 200 grams/kg as feed to laying hens showed that performance, egg production and egg characteristics were comparable to those layers in control groups, demonstrating the potential of duckweed to provide a source of amino acids and minerals, and yolk pigmentation (Goopy & Murray 2003).

Chantiratikul et al. (2010) studied *Wolffia* meal as an alternative ingredient to replace soybean meal in Rohman laying hens from 71 weeks of age. Experimental diets included crude protein of the control diet (soybean meal) replaced by crude protein of wolffian meal at 0, 25, 50, 75, and 100% rates. The results showed that when soybean meal was fully replaced by *Wolffia* meal, feed intake, metabolisable energy intake and egg production were all decreased, however, egg yolk pigmentation was increased. The authors concluded that duckweed can safely replace up to 75% of soybean meal in the layer diet without any adverse effects on production performance. Full replacement, however, is not recommended.

In a 16-week experiment, Akter et al. (2011) fed the laying hens diets in which the proportions of rice polish and fishmeal were decreased with increasing proportions of dried duckweed at levels of 0 g/kg (control diet) and 50, 70, 110, 130 and 150 g/kg of the diets. Duckweed was found to be a good source of protein for laying hens without any harmful effects on production performance at up to a 130 g/kg level, and on egg quality characteristics at up to a 150 g/kg level. The authors reported no significant differences in feed intake when *Lemna minor* meal was added to the laying diet at up to 20%.

Table 158 Standardised ileal digestibility of amino acids of duckweed in broilers

Indispensable amino acid	**Duckweed (*Spirodela polyrhiza*)**
Arginine	75.6
Histidine	54.7
Isoleucine	67.3
Leucine	69.1
Lysine	67.4
Methionine	68.5
Met+Cys	-
Phenylalanine	69.9
Threonine	61.4
Tryptophan	63.3
Valine	66.0
Dispensable amino acid	
Alanine	67.6
Aspartic acid	69.8
Cysteine	42.5
Glutamic acid	58.5
Glycine	55.6
Proline	50.2
Serin	60.3
Tyrosine	-

(Source: Demann et al. 2022)

In another study, Witkowska et al. (2012) replaced inorganic salt (control group) with dried duckweed enriched with trace elements in layers' feed. Duckweed inclusion improved egg quality parameters, such as shell thickness, the total concentration of trace elements in eggs, Co content in egg yolk and shell, Cr content in the yolk, and Cu and Zn contents in albumen and yolk. The authors suggested that duckweed can be a novel biological mineral supplement, which is a good and cheaper alternative to inorganic dietary additives.

Table 159 Summary of research done on the inclusion of duckweed in laying hens

Poultry type	Duckweed species	Trial	Results	Reference
Laying hens	*Spirodela polyrhiza*	Diet containing 12.6% *Spirodela* meal	Did not impair the performance of laying hens - means of enhancing Omega 3 levels in eggs.	Anderson et al. 2011
Laying hens	*Lemna gibba*	Dried duckweed included 0, 15, 25, and 40%	Egg production and weight maintained at all levels, optimal level was 15%. Eggs from hens fed 15 and 25% Lemna had higher protein content than control eggs. 15% Lemna = more egg pigmentation than in controls.	Haustein et al. 1990
Tau Vang hens, 19 weeks old	*Lemna minor*	Broken rice with roasted soybean partially or fully replaced with fresh duckweed *ad libitum*	Egg production, egg quality and feed conversion were highest at 75% substitution. 100% substitution showed the highest profit.	(Nguyen Thi Kim Khang & Ogle, 2004)

Table 159 above has a summary of a few reports regarding the use of duckweed in laying hen feed. Zakaria and Shammout (2018) reported that duckweed grown in good quality irrigation water can replace up to 10% of the soybean meal as a source of protein without adverse effects on hen performance or egg quality in addition to improving profitability.

To draw a conclusion, if duckweed is grown in clean water (with known chemical analyses), up to 25% of soybean meal can be replaced with duckweed in laying hens feed formula, with no negative effects on egg production performance, but also improving egg yolk pigmentation.

6.3.6 Duckweed in the pig diet

Duckweed contains a wide array of amino acids such as lysine and methionine, which are essential for pig nutrition. Apart from the favourable amino acid composition, other characteristics such as mineral content, vitamin A and dry matter yield, make duckweed appropriate ingredients for pig (Gwaze & Mwale 2015).

Piglets develop quickly, so it is critical to offer them a diet rich in nutrients that can keep up with their rapid growth. In a study, 0–10-day-old piglets were fed with 4 experimental diets including 44% of crude protein soybean meal, 20% replacement of soybean meal with duckweed, 40% replacement of soybean meal with duckweed, and 60% replacement of soybean meal with duckweed as the supplementary protein. Replacing soybean meal at a 60% rate created the poorest feed efficiency, however, pigs on the 40% replacement of soybean meal had the highest feed efficiency. Authors argued that perhaps at a high inclusion rate of duckweed, its antinutritional factors are hampering the nutrient utilisation of the duckweed. Authors concluded that duckweed can be included at up to a 40% rate with no negative effects on production performance (Moss et al. 1999).

According to Nguyen van Lai (1998), native piglets had a much higher feed consumption than Large White piglets and a faster growth rate (200 g/day vs. 87 g/day), which was attributed to the higher protein intake by the indigenous piglets compared to the Large White ones.

Feeding growing pigs with 10% duckweed (*Lemna gibba*), decreased dry matter digestibility but had no impact on performance or energy digestibility (Gutierrez et al. 2001). Du Thanh Hang et al. (2009)

conducted a trial where dried duckweed was added to pigs' ration at up to a 30% inclusion rate. The nutrient digestibility was relatively high (organic matter digestibility of 88%), which was similar or greater than dried cassava leaves or sweet potato vines at the same inclusion rate.

The nitrogen digestibility of duckweed has been reported to be 69.0% for fresh *Lemna* leaves (Nguyen van Ly and Preston 2001).
In a study growing crossbred pigs (Large White x Mong Cai -indigenous pigs of Vietnam origin) were fed the traditional diet with sweet potato vines (control), or experimental diets with ensiled cassava leaves or fresh duckweed. Eating duckweed at around 1.5 kg per day had a positive impact on pigs' growth in body weight. Animals in the duckweed group showed an 18.7% better feed conversion ratio, a 27.8% higher body weight, and a 26.8% greater liveweight increase when compared to the control animals. The improved performance of pigs fed duckweed was attributed to the high apparent ileal digestibility of organic matter (81.7%), crude protein (73.2%) and ether extract (59.8%) of the plant (Du et al. 1998).

In a study by Rodriguez and Preston (1996), the authors fed unconventional diets containing duckweed to three pig genotypes (Mong Cai, Large White, and Mong Cai x LW). Mong Cai pigs and the crosses utilised the duckweed efficiently. According to these authors, as the proportion of the N intake for duckweed increased, 50% of the N in duckweed consumed was stored in the tissues. These authors suggested that the protein of duckweed plants is readily utilised and has a higher biological value than meals such as those prepared from cassava leaves that are often fed to pigs in developing countries.

According to Gutierrez et al. (2001), when duckweed was incorporated in the diet at a 10% level, the nutrient digestibility and utilisation was not as effective as the sorghum/soybean meal-based control diet despite the fact that the pigs on duckweed group consumed more feed and developed faster. The scientists attributed this to the large amount of fibre (2.3%) present in the duckweed used. It suggests that the nutritional profile of duckweed should be established before feed-formulation practices, and any necessary modifications performed.

An investigation has evaluated the duckweed protein concentrate and assessed its nutritive value as a feed ingredient for young pigs. The concentration of the metabolisable energy of duckweed was slightly lower than that of soybean meal, however, the standardised total tract digestibility of phosphorous, and the standardised amino acid ileal digestibility of duckweed did not differ to those of soybean meal and fishmeal (Rojas et al. 2014).

In conclusion, it seems that duckweed has a great potential as an alternative to replace conventional protein sources in pig feed, however, to advocate for its use as a feed ingredient, studies need to be conducted to identify the ideal duckweed species and its optimum inclusion rate for various stages of pig growth and production. Additionally, it is critical to analyse chemical composition, amino acid profile, and test the presence of harmful compounds and heavy metals before feed formulation practices.

6.3.7 Carbon footprint and sustainability of duckweed

With a biomass production of nearly 55 dry tons/ha per annum, duckweed farming on nutrient-rich wastewater can yield five times more in biomass than corn (Zhao et al. 2012). If 10% of freshwater surfaces in China are used for duckweed cultivation, Zhao et al. (2012) estimated that it can remove 100 million tons of CO_2 from the air coupled with 0.12 million tons and 1 million tons of phosphorous and nitrogen from wastewater sources, respectively. This environmental benefit is a powerful incentive for adopting duckweed production for different purposes (Zhao et al. 2012). In addition to this benefit, duckweed can grow fast and does not require additional fertilisers or intensive care.

Therefore, the environmental footprint of duckweed is less, and for each kilogram of duckweed, some 0.4 kg of CO_2 equivalent is emitted (de Beukelaar et al. 2019).

7 Other sources

7.1 Protein-rich food wastage

Agriculture, horticulture and fisheries operations provide the majority of the world's food. The food sector has become progressively market-oriented due to rising population, urbanisation economic liberalization, and globalization (Dreher 2006). Food waste comprises food losses that occur at every stage of the food production and supply chain as well as the final consumption stages, although it can be incurred in the post-harvest and processing sectors as well. While the amount of food wastage fluctuates based on the product variety and production phase, the necessary infrastructure available in the location where the waste is generated, has a significant impact on the quantities of food being wasted/generated (Garcia-Herrero et al. 2018). The largest waste stream in developed countries is produced at the end of the food chain, including in the home, retail and food service, and it is primarily disposed of in landfills (ReFED 2016).

Roughly one-third of the worldwide foodstuff produced for human consumption in 2007 was wasted due to numerous factors, which was about 1.3 billion tonnes of food (Ishangulyyev et al. 2019). Food loss and waste cost the global economy US$936 billion in 2012 (FAO 2014). It is not just nutrients that are lost when foods are abandoned. Consider all the resources required to get food from the farm to the table: irrigation water, planting land, harvesting fuel and transportation vehicles. When a bunch of bananas falls from a truck or restaurant operators load their trash bins with unconsumed meals, all of those resources, along with the food, are ultimately wasted (Cicatiello et al. 2017).

A practical solution that has the ability to address waste management (landfilling), food security, resource constraints and environmental issues all at once is recovering food waste for animal feeding. Livestock will act as bio-processors where food materials that are not edible for humans anymore can be recycled by animals and their nutrients recovered. In the past, numerous cultures around the world have routinely fed livestock animals leftover food and by-products of food production (Westendorf 2000). However, with the development of intensive animal feeding facilities, which today operate with precision feeding using feed grains like corn and soybeans for maximum output, these traditional methods fell out of favour (Banhazi et al. 2012). A thorough examination based on scientific and practical evidence is required to establish the core viability, safety and sustainability implications involved in evaluating the use of food waste in animal nutrition. This could be the basis of a national and international strategy for solving difficulties in both waste management and sustainable food security, concurrently.

7.1.1 Food waste production globally and in Australia

According to current data, the worldwide output of all types of food is projected to continue to expand, both in production and demand. There is no clear and accurate data pattern between the amount of food produced and the amount wasted. However, specific investigations focused on food waste drivers indicate that food waste production sources are increasing based on annual global food production (Kamal et al. 2021).

Since 2014, moderate or severe food shortages worldwide have increased. The number of people in the world affected by hunger increased in 2020 under the shadow of the COVID-19 pandemic. Nearly one in three people in the world (2.37 billion) did not have access to adequate food in 2020 – that’s an increase of almost 320 million people in just one year (Dasgupta & Robinson 2022).

Based on the UN Food Waste Index Report of 2021, nearly 17 per cent of worldwide food production might be wasted, having 61 per cent of this waste originating from individuals, 26% from the food business, and 13% from retailers (Sharma, Vanapalli et al. 2021).

An estimated 102.5 million tonnes of food were wasted in the EU in 2015 (202 kg per person) (European Commission 2010), from four principal waste streams: households (42%), manufacturing (39%), the food service/catering industry (14%), and retail (5%).

The majority of food waste happens during supply and utilisation in high-income nations, with significant depletion also taking place through farming production of vegetable and animal goods. Crop harvesting also produces an inedible percentage of the biomass. Losses from harvested crops are also significant, with 44.0% of crop dry matter (36.9% of energy and 50.1% of protein) lost before reaching human consumption. The residue-to-crop-production percentage for most conventional staple foods ranges from 1 to 3. Losses are far more common in lower-income countries at every stage, especially post-harvest, but they are, substantially to a lesser extent, common at the consumption stage. In low-income regions, higher production losses are due to a lack of knowledge, skills, techniques, and infrastructure to accommodate the food supply chain compared to the industrialised world (Scarlat et al. 2010).

Food waste is estimated to be around 30% for cereals, 40–50% for root crops, fruits and vegetables, 20% for oilseed crops, meat and dairy, and 30% for fish globally annually.

Even though China and India contribute the greatest share of home food waste each year, the estimated amount produced per capita annually is less than 70 kg. On the other hand, in Australia it is an average of 102 kilograms of food waste per capita every year (Chen et al. 2020).

According to the National Food Waste Baseline, Australia currently produces 11.3 tonne per annum of food waste and diverts 3.9 million tonnes to animal feed. Of the remaining 7.3 tonne, up to 60% of the wastage is avoidable by directing it to food rescue and animal feed. Food waste costs the economy AUD $36.6 billion per year or AUD $2000 to AUD $2500 per family.

Australia's production and disposal of wastage produce 17.5 tonne of CO_2-eq per year (excluding emissions related to exported food), comparable to the yearly discharges from Australia's top emitting coal-fired power plant. Food waste is responsible for about 3 per cent of Australia's yearly greenhouse gas emissions. The quantity of water lost in growing food is proportional to the amount of five Sydney Harbours (2600 gigalitres). When the landmass utilised to cultivate food wastage in Australia is added together, it exceeds Victoria's 25 million hectares. A quarter of the water employed in agriculture is used to produce waste food. Implementing the strategy to meet our national goal of reducing food waste by 50% by 2030 will need all Australians to collaborate and take appropriate action.

7.1.2 General characteristics

Agro-industrial by-products and waste produce tens of billions of tonnes of waste annually. These leftovers can be solid, liquid, or gaseous, and they are one of the most abundant, inexpensive, and sustainable available resources of nutrients (Diwan et al. 2018). Given that food waste typically contains 30–60 % starch, 10–40 % lipids, and 5–10% protein (wet basis), millions of tonnes of protein from plant and animal sources is wasted which may be better utilised. (Kwan et al. 2016).
Food waste has a significant moisture concentration of 50 to 85 per cent, shortening its shelf life and complicating its collection and processing into livestock feed. It has been proposed that the heat treatment required to produce a safe food waste product can sufficiently dehydrate the product.

Bioactive substances including long-chain polyunsaturated fatty acids, peptides, vitamins, polyphenols, carotenoids, eicosapentaenoic acid, docosahexaenoic acid and arachidonic acid are abundant in meat and other animal products; therefore, food waste items from fish or meat may also contain relatively high quantities of bioactive compounds (Georganas et al. 2020).

Each tonne of food waste going to landfill is estimated to produce 1.9 tonnes of carbon dioxide equivalents in the form of methane. Some of the major categories of food waste include:

- fish offal
- spent brewers' grains/bakery leftovers
- restaurant leftovers
- vegetable and fruit waste.

7.1.3 Nutritive value for animal feed

Food waste, in general, is a valuable source of protein (Adhikari et al. 2018). To be considered a source of (valued) protein, food waste must meet three essential criteria: (a) high protein content, (b) high-quality protein (well-balanced necessary amino acid contents), and (c) harmful or allergenic compounds removed before use as feed ingredient (Kamal et al. 2021).

Based on available data from the literature, the nutrient composition of food waste includes dry matter 21.7% (CV 25.0%), crude protein 19.2% (CV 24.5%), crude fibre 6.2% (CV 44.1%), ether extract lipids 21.5% (CV 33.3%), nitrogen-free extract carbohydrates 38.6% (CV 24.4%), and Ca:P ratio 2.3 (CV 77.8%). A crude protein of 19.2% is nearly double the crude protein content of corn (8–10%). This indicates that every tonne of food waste can replace more than a ton of corn in livestock feed.

Table 160 Summary of literature for nutrient composition of food waste in animal feed

Reference	Sample type	*n*	DM%	CP%	EE%	NFE%	Fibre%
Chen et al. (2007)	Dried food waste	5	87.6	15.8	16.0	–	10.8
Chen et al. (2015)	Fermented food waste	60	20.2	25.5	28.1	31.6	7.3
	Dry-heat food waste	60	19.4	28.3	25.3	23.0	6.9
	Hydrothermal food waste	60	18.8	30.6	31.5	28.6	3.0
García et al. (2005)	Restaurant	28	39.6	27.5	28.8	26.9	2.3
	Household	34	33.1	16.3	11.3	41.8	12.4
Jin et al. (2012)	Restaurant	6	22.8	28.6	31.5	–	3.1

Based on crude protein accessibility and nutritional value, food waste protein sources can readily be divided into animal and plant sources. Pumpkin kernel meal, hop and sea buckthorn seed meal have a poor nutritional profile while having more significant crude protein (20%) content (Prandi et al. 2019). Likewise, soybean curd residue has been an excellent source of fat, fibre, protein, vitamins, and trace minerals. With 27% viable protein (dry basis), soybean crude residue has a great potential for value-added processing and utilisation. Mushrooms and sugar beetroot flake protein with 40%

necessary amino acids have also been investigated as a suitable feed component in mostly vegetal food scrap protein sources (Prandi et al. 2019).

In terms of the amount of protein in food waste, four independent investigations have found that the crude protein level of restaurant waste ranged from 15% to 23% on a dry basis (Myer et al. 2000). In a study by Fung et al. (2019) crude protein in food waste from a university residential dining hall was estimated to be around 18.9% on a dry matter basis – greater than corn but lower than solvent-extracted soybean meal (CP 47.2%). The crude protein in restaurant (kitchen) food waste was similar to the aforementioned values (18% - 20%). Additionally, the crude protein level in food waste is reported at 22% by (Chao et al. 2004). The mineral-ash level in two dehydrated restaurant food waste fluctuated from 3% to 6% (DM basis) in a few separate trials. It is described that ash content was about 5 per cent of college dining hall food waste collection, in agreement with the earlier reports (Myer et al. 2000).

Food waste has a significant ether extract content in general. According to four independent investigations, the amount of ether extract in restaurant garbage ranged from 17% to 24% on a dry basis. Earlier, it was reported that the ether extract content in food waste from a college dining hall was 13.58% on a dry basis (Myer et al. 2000).

In terms of the nutritive value of food waste for animal nutrition, little investigation has been done on the vitamin content. Thiamine and niacin concentrations were adequate to meet pig dietary needs, but pantothenic acid amounts were inadequate (Georganas et al. 2020).

7.1.4 Antinutritional factors – nutritional limitations

Food waste may have low digestibility values due to antinutritional components such as tannins, cyanogenic glycosides, oxalates and trypsin inhibitors, despite the high nutrient levels. This emphasises the need for new methods to eliminate these antinutritional components in food waste (Torres-León et al. 2018).

A number of treatment methods have been reported, which can be grouped into three categories: wet-based, dry-based, and ensiling/fermentation treatment. Wet-based methods typically include a simple heating step to provide a wet feed which has 70 – 80 per cent moisture. Wet-based methods require less preparation time compared to dry-based and the food can only last a few days without refrigeration, although shipping costs of wet-based feed is prohibitive. Dry-based approach entails drying food waste to less than 20% moisture, hence sterilise the raw waste material, rendering it safe for animals. In addition, dry feed has longer shelve-life and less expensive to store or transport. Fermentation is recognised as one of the efficient ecological processing methods to reduce antinutritional factors and improve protein digestibility. The most commonly used microbes in the fermentation process are lactic acid bacteria and filamentous fungi of Aspergillus and Rhizopus. One of the unique features of these microorganisms is that they are considered safe because they do not generate mycotoxins (Hasan & Lateef, 2024).

Some issues associated with feeding food waste include:

- spoilage
- chemical contamination
- biological contamination
- high variation in nutrient levels.

7.1.5 Food waste in the laying hen diet

Kojima (2005) conducted a trial where the dehydrated kitchen waste product was included as a feedstuff for laying hens at 4 inclusion rates of 0% control diet (diet 1), 12.5% (diet 2), 25.0% (diet 3) and 50.0% (diet 4). The product contained 12.24% moisture, 15.14% crude protein, 5.33% crude fat, 2.34% crude fibre, 5.26% ash, 2.82% Ca, 0.29% P and 0.31% Na. The study lasted for 5 weeks, and the results showed that body weight was significantly decreased for diet 4 (50% inclusion of kitchen waste). Feed intake was highest for diets 2 and 3, and lowest for diet 4. Egg mass was also highest for diet 3, and lowest for diet 4. Egg weight was highest for diets 2 and 3 and was depressed in hens fed diet 4 with 50% inclusion of dehydrated kitchen waste product. The comparison between the dietary treatment of the control and the experimental diets indicated that up to 5.0% dried kitchen waste product can be safely included in laying hens' diet with no adverse effects on egg production, however, higher inclusion levels negatively impacted the egg production.

Chung et al. (2015) studied the effects of multi-strain probiotics supplementation to diets containing 40% food waste product on egg production and quality in 40-week-old Lohmann Brown laying hens. Four experimental diets included a basal diet containing corn-soybean meal and food waste (at a 40% inclusion rate) with no probiotic supplementation, and 3 additional diets including 0.1, 0.2 and 0.4% probiotic supplementation. The body weight changes as well as feed intake were not different among the dietary treatments. The egg production was the highest with the basal diet without probiotic (85%) and the basal diet plus 0.2% probiotic. Egg production of the basal diet plus 0.4% probiotic supplementation was the lowest, although it was not different to the basal diet plus 0.1% probiotic supplementation. The basal diet supplemented with 0.4% probiotic showed greatest Haugh units compared to the other experimental diets. There was no significant difference in yolk colour among the experimental groups except for the dietary group with 0.4% probiotic in which the least Roche colour index was observed. The authors concluded that the addition of probiotics to diets containing 40% food waste products improved the egg protein quality and did not affect productivity of laying hens.

In an experiment Dao et al. (2022) evaluated food waste as a feed ingredient in 24-week-old Isa Brown laying hens. The experimental diets included a control diet (wheat-sorghum-soybean meal), a food-waste based diet, and a blend of 50-50 of control and food waste diet. The results are summarised in the Table 161 below.

Table 161 Egg production performance of laying hens fed food-waste based diets

Variable	Control	Food waste	50:50 blend	SEM	P-value
Egg weight, g	61.7	61.2	61.6	0.29	0.747
Hen day egg production, %	95.9	96.2	96.6	0.34	0.534
Egg mass, g/d	59.1	58.8	59.6	0.35	0.709
Feed intake, g/d	128[c]	114[a]	121[a]	0.84	<0.001
FCR, kg feed/kg egg	2.172[c]	1.948[a]	2.044[b]	0.015	<0.001

[a,b] Means within rows not sharing a common suffix are significantly different at the 5% level of probability.

(Source: Dao et al. 2022)

Food waste-based diets contained higher concentrations of crude protein, fat, fibre, available phosphorus and sodium compared to the control diet. The extra fat and protein in the 100% food waste treatment is a likely reason that hens consumed less feed and were more efficient in converting

feed to egg mass than the controls. Dry matter and energy digestibility were higher in hens fed the 100% food waste and 50:50 diets compared to the controls. This finding may explain the lower FCR/higher feed efficiency in hens fed the food waste diets compared to the controls. No differences in internal or external egg quality were detected among the experimental diets. Excreta moisture was increased in the 100% food waste and the 50:50 blend diets. The researchers concluded that food waste demonstrates a great potential to be used in laying hen feed, as feed efficiency and nutrient digestibility were improved, and this represents an opportunity for a sustainable and profitable poultry industry.

Based on the limited available data, food waste has a great potential to be used as an ingredient in laying hens' nutrition. Further research is required to identify the best processing solutions to eliminate antinutritional factors and pathogens and produce a safe product that can be fed to hens. In addition, strategies to create clear categories of food waste may reduce the variability of the final product. Last but not the least, additional feeding trials are required to determine the nutritive value and optimum inclusion rate (if not 100%) of food waste in laying hen feed production.

7.1.6 Food waste in the pig diet

Pig farmers seek to produce pork that is of the greatest quality possible while maintaining the highest levels of food safety, affordability and profit margin stability. Using food wastes as pig feed is not new but, for health and safety reasons, many states have banned the feeding of food wastes to pigs. Previous reports show that dehydrated food waste products, which were produced by dehydrating food wastes from food service operations and pelleting, were relatively high in protein and fat. *In vitro* and limited *in vivo* trials have indicated that pigs can effectively utilise the protein and fat in this product. Microbiological determinations indicated no apparent health threat for pigs or humans (Myer et al. 1994).

Various feeding trials investigated the incorporation of food waste in pig diets at inclusion rates ranging from 10% to 100%. Production performance in terms of animal weight gain and/or feed efficiency varied depending on animal species and physiological stage, length of the feeding trial, and type of food waste and substitution rate. Several studies reported no difference in the growth performance of pigs comparing diets with vs. without the inclusion of food waste products (Kwak & Kang 2006; Myer et al. 1999), whereas others have reported decreases in weight gain in pigs (Westendorf et al. 1998). Pigs fed a 50% food waste had 1.4% higher monounsaturated fat percentages and 13% greater meat marbling (zu Ermgassen et al. 2016b). Additionally, zu Ermgassen et al. (2016b) suggested a 13% lower growth rate for pigs with a 50% substitution rate and therefore farmers will need to fatten pigs for a 13% longer production period than the conventional system to reach slaughter weight. The authors have estimated all the costs associated with the change to 50% food waste inclusion and 13% longer production period (together with all other costs) to reach the market weight, and have concluded that food waste inclusion improves profitability, however, due to the high variability in nutrient profile, it may not suit the business model of all farming systems.

Myer et al. 1999 studied two dehydrated restaurant food waste (DFW) products and evaluated them as potential feedstuffs for finishing pigs. For each product, fresh food wastes were obtained from food service operations at a resort complex, which were and mostly leftover food and plate scrapings. The wastes were minced, blended with a feed stock (soy hulls and wheat flour (DFW1] or soy hulls and ground corn [DFW2]), pelleted and dried. The dried product was then blended with additional minced fresh food wastes and dried; this process was then repeated. The final products contained approximately 60% dried food wastes. Two feeding trials with 48 and 72 finishing pigs (56 to 112 kg) were conducted, comparing diets without (control) or with the food waste product included at 40% of the diet (DFW1) for Trial 1 and 40 or 80% of the diet (DFW2) for Trial 2. Pigs fed the DFW diets in

both trials had a similar average daily gain to the control pigs, however, average gain:feed ratios were superior to those for control pigs. Carcass lean content and lean quality scores were not reduced by feeding pigs the food waste diets in either trial. Carcass fat became softer with an increasing amount of DFW2 in the diet in Trial 2. The authors concluded that dehydrated restaurant food wastes have the potential to produce feedstuff with high nutritive value for pigs while offering a viable solid waste disposal option.
In another study, Chae et al. (2000) evaluated experimental diets containing 0%, 25%, or 50% food waste mixture against a corn-soybean meal control diet in pigs, and reported that the percentage of total saturated and unsaturated fatty acids, the monounsaturated/saturated fatty acid ratio, and the polyunsaturated/saturated fatty acids ratios of the longissimus muscle were not affected by the incorporation of the food waste mixture.

In the study of Márquez and Ramos (2007), food waste from fish and fruit shops was used as an alternative to the grain in grower-finisher pig (20–100 kg) diets. Two iso-nitrogenous and isocaloric diets were formulated (14 MJ/kg DE and 16% CP) to include no food waste or a mixture of 50 g of fish-shop waste per kg and 120 g of fruit-shop waste per kg. The authors reported that the inclusion of food waste in the diet had no significant effect ($P > 0.05$) on average daily feed intake (2.12 vs. 2.20 kg/day), average daily gain (0.74 vs. 0.78 kg/day) or gain/feed (0.35 vs. 0.35 kg body weight per kg feed intake). The findings of the sensory analysis showed that the bacon had a very light fishy aroma, while the organoleptic quality of meat from the food waste-fed pigs was acceptable. The authors concluded that food waste from the fish and fruit shops could be included in grower-finisher pig diets without any detrimental effect on growth performance, and only minor effects on carcass characteristics and meat quality.

Similar to the previous study, Westendorf et al. (1998) found that pork from pigs fed heat-treated food waste was comparable in flavour and quality to meat from pigs fed a corn-soybean meal diet. Sasaki et al. (2007) conducted a blind tasting and reported that panellists preferred lean meat from pigs fed liquid food waste-based feed compared to a standard diet, for greater tenderness. Using linear mixed models to determine the effects of the inclusion of food waste in pig diets, with the original data derived from a few studies, zu Ermgassen et al. (2016) demonstrated that feeding food waste had no effect on 16 of 18 pork quality parameters (e.g. juiciness, dressing percentage, meat colour, fat free lean percentage, flavour, overall palatability). The detected effects of two parameters (mono-unsaturated fats; marbling) were “weak and did not detrimentally affect pork quality or value”. The researchers concluded that the inclusion of food waste in diets produced pork of similar quality as that from animals fed conventional diets.

To sum up, food waste demonstrates a great potential as an alternative to substitute for conventional feed – fully or partially – in the pig feed industry. Possibly with regulated, centralised systems for safely recycling food wastes into animal feed, these products can enter the pig feed industry, although fresh research is required to identify best practices regarding processing, as well as optimum substitution rates for maximum profitability and sustainability.

7.1.7 Carbon footprint and sustainability of food waste

Food waste is a significant contributor to climate change, with roughly 1.3 billion tons (30% of the total food production) of food wasted yearly (Peydayesh et al. 2022). For one kilogram of food protein waste, there is 15 to 750 kg CO_2 emission in the atmosphere. Accordingly, this waste food is responsible for 8–10% of GHG emissions worldwide. The same study presents four sustainable practices to treat these food protein wastes (Figure 26), namely: (i) revalued food; (ii) bioplastics; (iii) water purification; and (iv) renewable energy. Here, revalued food is the only one that is considered

within the food-value chain and re-enters the chain by being reused for indirect human intake as animal feed (Peydayesh et al. 2022).

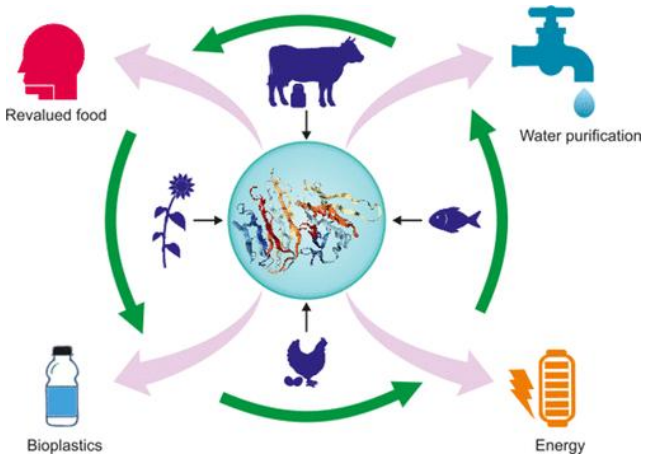


Figure 26 State of the art of food protein waste usage sustainably

Another study also mentioned six waste management scenarios (Figure 27; Eriksson et al. 2015). Feeding animals with proper treatment following local regulations is one of the waste management scenarios that can benefit the environment. When fed to farm animals, treated food waste could replace other feed with a high carbon footprint. For instance, when soybean is replaced with food waste in the animal feed, the substitution (based on protein content to replace soybean meal), produced a carbon footprint of 0.66 kg CO_2-eq/kg and reduced landfill emissions' impact (Eriksson et al. 2015). Utilizing food waste to produce poultry feed is anticipated to reduce carbon footprint and greenhouse gas emissions in chicken meat production by 35% and 25%, respectively, and in egg production by 75% and 76% (Almeida 2021). However, there is a lack of research reporting the net effect of using animal feed made from food waste.

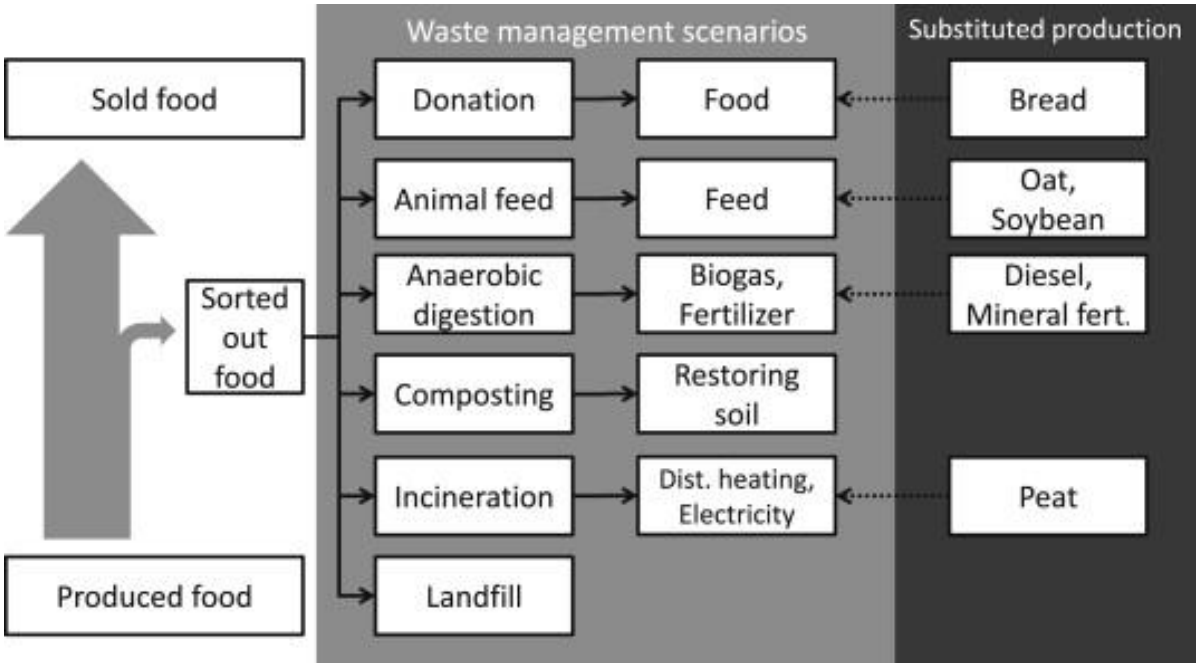


Figure 27 Schematic diagram of waste management scenarios

7.2 Microbial protein or single-cell protein

Single-cell protein is a term used to describe microbial protein. It refers to protein produced by cells of microorganisms such as yeast, fungus, algae and microbes grown on various carbon sources (Razzaq et al. 2020). Certain single-cell proteins are prepared as intact cells, while others have the cell wall broken down to make the protein more available. Single-cell protein has a good potential as a supplemental protein source for feeding livestock (Giec et al. 1988). Depending on population increase and the availability of plant-based protein sources, single-cell protein may replace other types of protein as the main source of protein for domestic animals in some areas. Bacterial fermentation on a vast variety of substrates makes single-cell production easy and scalable.

The world is interested in generating healthier food with an excellent amino acid content, minimal but high-quality fat, and socially sustainable manufacturing methods. These are primarily non-animal, ecologically friendly products. Protein can also be obtained by cultivating diverse microorganisms, ideally those with biomass that contains more than 30% protein and can offer a healthy balance of necessary amino acids. Microbes contribute to protein demand when they are used to improve the protein content or quality of fermented meals and their direct usage as single-cell protein (Bourdichon et al. 2012). Single-cell protein is currently made from a few microbial species, which can grow on a variety of materials including but not limited to whey, orange peel residue, sweet orange residue, sugarcane bagasse, paper mill waste, rice husks, wheat straw residue, cassava waste, sugar beet pulp, coconut waste, yam waste, banana pulp, mango waste, grape waste and sweet potato. Single-cell protein sources that are utilised in animal feed are more diverse than those permitted for human consumption, and the list is growing (Ritala et al. 2017).

Autotrophic development can create single-cell protein completely independent of agro waste sources (Bogdahn 2015). Autotrophic single-cell protein allows various alternative growth methods, diverse choices for biogeochemical cycles, and significantly higher efficiency than crops due to the enormous diversity of microbial metabolism. Photovoltaic-driven microbial protein production might utilise ten times less space for a comparable amount of protein than soybean farming (Leger et al. 2021).

7.2.1 Microbial protein or single-cell protein production globally and in Australia

The global demand for single-cell protein is expanding due to its benefits as an alternative feedstuff and increased animal feed output, which positively influence human health and the environment (Helkar et al. 2016). The global single cell protein market is expected to grow to an estimated USD $18.5 billion by 2030, therefore operating costs are likely to reduce due to economy of scale. In terms of volume, the single-cell protein market share sourced from *haematococcus pulvialis* is expected to reach more than 15 kilotons by 2030. In terms of volume, the single-cell protein industry share from bacteria segment (sourced from bacterial production) is poised to surpass 240 kilotons by 2030 (Selbyville 2022). No data are available on production volume of single-cell protein/microbial protein in Australia.

7.2.2 General characteristics

Because of its high protein concentration, the development and use of microbial biomass as a food protein source has raised attention as a viable alternative to agricultural produced proteins. Single-cell protein contains additional nutrients besides proteins, like fats and vitamins. As a result, biomass has received increasing interest in recent years as a dietary supplement with greater economic success

than as a mere protein source (Sharif et al. 2021). Its crude protein level ranges from 45 to 73% with fats and minerals at 2–20% and 5–10%.

The changes in nitrogen content are caused by various factors, including the microbial strain, the nutritional medium, optimal growth circumstances and the method used to prepare the biomass after fermentation. For example, in the case of the Lavera yeast, extraction of the crude fat results in a relatively high concentration of the remaining micronutrients. The crude protein level of these types of feeds should be at least 50% of the dry matter (Upadhyaya et al. 2016).

In the case of the total-fat fraction, there are also significant variations. A high 'unsaponifiable' fraction may be present in addition to triglycerides and fatty acids. In a nutshell, fatty acids of C4–C8 are prominent. Unsaturated fatty acids predominate in yeasts, with polyacids accounting for a significant amount. Unsaturated fatty acids make up a significant component of the fat of the bacteria studied.

Some fatty acids can be found in all products (Mei et al. 2020). Most regions have rules to guarantee that food and feed are safe to eat. These usually discriminate not just between human-based food and livestock feedstuff, but also between food (for nutrition and maybe flavour and aroma) and food additives (preservatives, colourants and texture modifiers), or feed additives (Bagchi 2006).

7.2.3 Nutritive value for animal feed

Single-cell protein is a viable alternative for commercial feed formulation because it serves as a cost-effective protein supplement, replacing expensive protein sources, and can be produced in large quantities within a short period. (Chee et al. 2019). It is believed to be a viable solution for addressing the problem of high protein feed prices (Reihani et al. 2018). Single-cell protein can be created on industrial wastewater to produce protein feed while also treating wastewater for environmental sustainability, according to Alloul et al. (2018).

Carotenoids are in high demand for poultry, farmed fish and crabs. Because these animals cannot generate carotenoids, they must be included in their diets. Carotenoids are feed ingredients that boost the immune system and scavenge toxic reactive oxygen species. Egg yolks, fish meat and shrimp meat all have different colours depending on the carotenoid combinations in their diets. Supplementing food with natural carotenoids helps animal producers achieve the colour preferences of meat and eggs for consumers (Das & Biswas 2016).

Photosynthetic bacteria have been used as a source of single-cell proteins for decades. They have a high protein content and all-important amino acids, carotenoids, vitamins and other high-value nutrients (Wang, Yang et al. 2017). The possible photosynthetic bacterium used as single-cell protein, has been identified as *Rhodopseudomonas faecalis* PA2. This bacterium's dried biomass is a rich source of protein and carotenoids, lipid and polyunsaturated fatty acids like omega-3 and omega-6. This bacterium has previously been used as an ingredient in the freshwater fairy shrimp's production. It improved fairy shrimp's survival and growth, but it also lowered ammonia, nitrite and nitrate levels in the water compared to those fed with the alga *Chlorella vulgaris* and the yeast *Saccharomyces cerevisiae*. These findings indicate that this strain might make a good single-cell protein biomass for livestock feed (Patthawaro et al. 2020; Saejung et al. 2018).

Most of the recent attention in single-cell protein has centred on the use of microbes to boost the protein content of side streams, which can then be used in animal feed.

In creating single-cell proteins, mixed populations are increasingly used rather than pure strains. Furthermore, methane is becoming increasingly commercialised as a source of carbon for single-cell

proteins, and more protein-rich products generated from algae are being developed for food and feed (Saejung & Ampornpat 2019). Single-cell proteins have previously been utilised in a wide range of applications, including food (aroma carriers, vitamin carriers, emulsifying acids, and so on) and feed (pigs, poultry, cattle and fish), and the paper and lead industries. (Bratosin et al. 2021).

7.2.4 Antinutritional factors – nutritional limitations

Despite the numerous benefits, there are a few limitations in single-cell protein use as a feed ingredient and due to these issues, single-cell protein has not been widely recognised for human ingestion (Hadi & Brightwell 2021):

a) Biomass with a high quantity of nucleic acid is challenging to consume since it can cause digestive difficulties.
b) If the digestive tract identifies the biomass as a foreign substance, it may cause an allergic response.
c) The existence of significant nucleic acids causes uric acid levels to rise.
d) If ingested in a large quality, it might cause kidney stones and gout in some people.
e) The occurrence of secondary toxic metabolites that cause hypersensitivity and other skin responses are possible.
f) Because complex equipment is required, the capital production cost is expensive (Øverland & Skrede 2017).

Toxins created by bacteria, allergic symptoms and hazardous compounds derived from the feedstock, such as heavy metals, are significant issues. Methods for reducing the RNA content to reasonable standards have been developed and used in industry (Ritala et al. 2017).

Toxins are avoided by carefully choosing the producing organism, process conditions and product composition. Toxins produced by bacteria can limit their utilisation as a feed ingredient/supplement. Toxins can be external (exotoxins) or intracellular (endotoxins), however, heat can destroy these.

7.2.5 Microbial protein (single-cell protein) in the laying hen diet

Lee and Chen (1983) found that egg production and the final body weight of 400 White Leghorn hens, 72 weeks of age were significantly greater with *ad libitum* feeding of SCP. When single-cell protein was fed to layers, no depression in egg production was observed and the nucleic acid content in tissues and eggs were not affected (Al-Ani 1985). Layers' performance was optimised when single-cell protein was fed at 2.5% of dry matter or 10% of dietary protein.

Widjajanti et al. (1990) reported no differences between 0 and 5% dietary yeast plus dried brewer grain in Haugh units, body weight or eggshell weight of laying hens (69-week-old) raised under a warm environmental temperature (between 24 and 27°C). Najib (1996) studied the effect of incorporating Yeast Culture '*Saccharomyces cerevisiae*' in White Leghorn and local (Baladi) layers' diet. He found that the best performance in terms of egg production, egg weight, feed conversion and feed intake was achieved when 0.3% yeast was fed to the local birds, and 0.2% to the White Leghorn.

Hassanein and Soliman (2010) observed that supplementation of *Saccharomyces cerevisiae* in the basal diet of laying hens at 0.4%, 0.8%, 1.2% and 1.6% inclusion rates, showed no significant effect on ileal pH.

Najib et al. (2014) supplemented the diets of laying hens with 0, 5, 10, and 15% of SCP yeast. The single-cell protein yeast contained 48% CP (1.2% lysine), 3380 kcal true ME/kg, 6.41% EE (43.2% oleic acid). The performance of the hens in terms of hen-day egg production, egg mass, egg weight and feed conversion was improved when 5% yeast was included in the ration. However, there was a clear indication that the addition of 15% SCP may be harmful to the birds. It was concluded that adding 5% single-cell protein produced from date waste to the poultry diet resulted in no adverse effect on the performance of the birds and may be included in their diet. Layer performance was optimised when they were fed at 2.5% of DM or 10% of dietary protein. It seems that inclusion of up to 10% of the dietary protein or 2–5% single-cell protein produced favourable results and can be advised to the industry.

7.2.6 Microbial protein (single-cell protein) in the pig diet

Different studies have shown that single-cell protein can replace up to 550 g soybean meal (SBM)/kg without impairing growth performance in weanling (Slagle & Zimmerman 1979; Øverland et al. 2001; Hellwing et al. 2007a; Hellwing et al. 2007b; Hellwing et al. 2007c) and growing-finishing pigs (Barber et al. 1971; Øverland et al. 2004).

Slagle and Zimmerman (1979) reported that the inclusion of 150 g single-cell protein/kg improved apparent dry matter and nitrogen digestibility in weanling pigs. In pigs, single-cell protein replacing 50% of fishmeal in their diet had similar growth performance, nutrient digestibility and intestinal morphology to the control group (Zhang et al. 2013). However, due to a large variation in the composition and characteristics of individual single-cell proteins, suitable inclusion levels should always be determined per source of biomass (Becker 2002). Previous studies showed that in pigs up to 50% of dietary N could be replaced by single-cell protein without affecting nitrogen retention, heat production and energy retention (Hellwing et al. 2005; 2007a).

The incorporation of 15% of single-cell protein in pigs diet exhibited a comparable result with the pigs fed diet containing soybean meal (McDonald et al. 2010).

Pinzón-Fajardo and Hurtado-Nery (2021) have aimed at evaluating the anaerobic fermentation of liquid rice bran with *Saccharomyces cerevisiae* as a single-cell protein (SCP) source for raising pigs. Single-cell protein inclusion in food rose from 8.23% to 13.97%. There were significant differences regarding average daily gain and FCR among the treatment favouring single-cell protein inclusion. The researchers concluded that anaerobic fermentation of rice bran enhanced feed protein content through *S. cerevisiae* growth, making it a viable addition to diets for growing pigs. It demonstrated good palatability, and at inclusion levels of up to 10%, it resulted in good yield while offering a more cost-effective diet.

In summary, it seems that up to 10% single-cell protein inclusion level can generate good performance and pork quality. Further research is required to revisit this topic and refresh the existing data for more accurate evaluation and feeding trials.

7.2.7 Carbon footprint and sustainability of microbial protein production

Microbial protein is continuously getting traction and may substitute 10–19% of conventional crop-based livestock feed protein demand by 2050. As a result, a 6–9% reduction in agricultural greenhouse gas emissions can be expected (Yang et al. 2021).

Although microbial protein production is exceptionally efficient in land and nutrient utilisation, there is scope to improve the carbon footprint. It is expected that recycling CO_2 will facilitate a carbon-negative protein production process by 2030 (Van Peteghem et al. 2022). However, currently, the

overall carbon footprint (captured CO_2 included) for microbial protein production comes from the use of acetate (5.8–13 kg CO_2-eq/kg product), then ethanol (6.8–14 kg CO_2-eq/kg product) and lastly methanol (9.4–32 kgCO_2/kg product), whereas microbial protein from formic acid produces the highest CO_2 emissions (15–58 kgCO_2/kg product) (Figure 28; Van Peteghem et al. 2022). Another study reported that a bacterial protein produced from methanogenesis has a carbon footprint of 2.229 kgCO_2 per kg protein but may attain an even lower carbon footprint if biogas is used instead of natural gas in the process (Sillman et al. 2020).

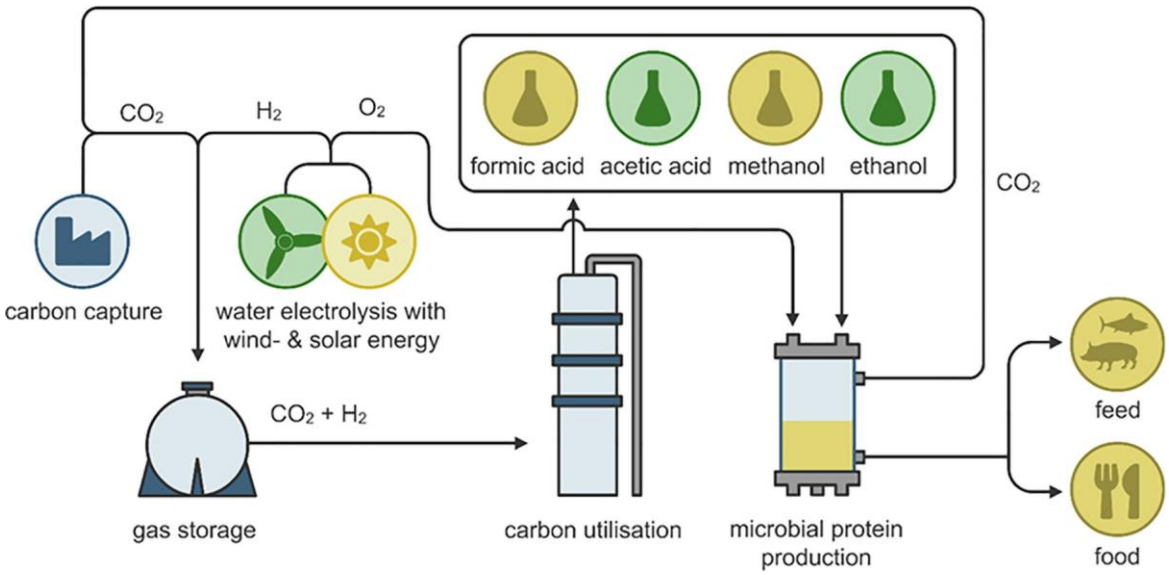


Figure 28 Microbial protein food and feed production pathways

(Source: Van Peteghem et al. 2022)

A study by Järviö et al. (2020) assessed the environmental impacts of microbial protein (MP) using life cycle assessment (LCA) with a cradle-to-gate approach. It found that electricity consumption has the maximum contribution to environmental impacts. Using hydropower as an energy source in microbial protein production may lower the GWP by 94% compared to other sources. Microbial protein has 53–100% lower environmental impacts compared to animal-based protein sources for food production. Likewise, in comparison with protein sources for feed production, microbial protein production caused a lower environmental impact for GWP.

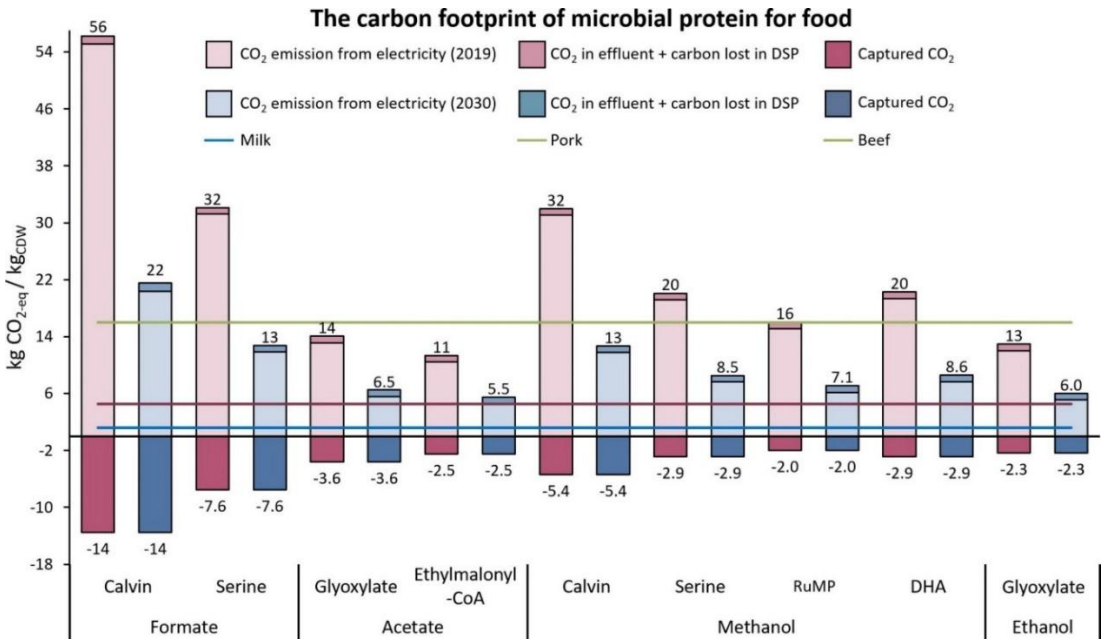


Figure 29 Average CO_2 emissions per ton of product for food-grade microbial protein

(Source: Van Peteghem et al. 2022)

8 Summary and further research directions

Soybean meal has long been a staple protein source in poultry and pig feed due to its high protein content, amino acid profile, and digestibility. However, there is growing interest in finding alternative protein sources to replace or reduce reliance on soybean meal. This shift is driven by several factors, including price volatility, environmental concerns related to soybean cultivation, and the need for more sustainable and locally available feed ingredients. Soybean meal is favoured in poultry diets because of its high protein content (typically around 44–48%), well-balanced amino acid profile, and high digestibility. Replacing soybean meal in poultry and pig feed requires careful consideration of alternative ingredients that can provide similar nutritional value while maintaining optimal animal health, growth rates, and feed efficiency.

One major challenge in replacing soybean meal is ensuring an adequate supply of essential amino acids, particularly lysine, methionine, and threonine, which are crucial for poultry and pigs growth performance, including chicken meat and egg and pork production. Many alternative protein sources may require supplementation with synthetic amino acids or blending with other ingredients to achieve a balanced nutritional profile. Globally some ingredients have been considered as alternatives to replace soybean meal in livestock feed including canola meal, sunflower meal, cottonseed meal, pulses, algae and insect meal. Our literature review concluded that canola meal, lupins (or lupin kernel meal), cottonseed meal, sunflower meal, and insect meal such as black soldier fly larvae are among the most viable alternative ingredients that can potentially replace the imported soybean meal in the diet where the diet is balanced for digestible amino acids following ideal protein profile for laying hens and pigs (specific to the growth stage). Supplementation of crystalline amino acids such as lysine, methionine, valine, threonine, leucine, isoleucine and tryptophane will assure the amino acid profile of the feed matching the requirements. Proper digestibility of protein results in improved feed efficiency and, as a result, this will have a positive impact on the sustainability of egg production.

In addition, our literature review concluded that insect meal such as black soldier fly larvae are emerging novel alternative ingredients that can replace 25–50% of the soybean meal in a balanced diet for laying hens. For pigs, back soldier fly larvae meal can be included in pig diets at rates of up to 19% for post-weaning pigs, and up to 10% for weaning pigs. The advantage of insect meal lies in its role in the circular economy, as it is produced by feeding insects on waste streams. This not only reduces the carbon footprint of egg production but also significantly enhances the overall sustainability of the system. However, the technology of BSFL farming needs to be optimised and the production costs should be reduced to be successfully included in least-cost feed formulations. However, further research is required to develop a framework where industry transitions to practical diets without imported soybean meal inclusion.

Some important aspects that require further research include:

Nutritional profile

- When replacing soybean meal, feed formulation must be adjusted to ensure that alternative ingredients provide not only adequate protein but also a well-balanced amino acid profile, good digestibility, and minimal anti-nutritional factors. Updated nutritive value and amino acid digestibility coefficients of alternative ingredients such as canola meal, sunflower meal, cottonseed meal, and lupin and lupin kernel meal.

Palatability, digestibility, optimum inclusion

- *In vivo* trials (with pigs and laying hens at different stages of production) to identify optimum inclusion rates in reduced crude protein diets, using crystalline amino acids to balance the amino acid profile.

Processing techniques

Various feed processing techniques, such as fermentation, extrusion, heat treatment, enzyme treatment, and micronisation, can enhance their nutritive value, improving protein digestibility, amino acid availability, and overall feed efficiency.

- **Fermentation**: Fermentation is one of the most effective methods for improving the nutritional profile of alternative feed ingredients. It involves using beneficial microorganisms (bacteria, fungi, or yeast) to break down complex compounds, reduce anti-nutritional factors, and enhance digestibility.
- **Reduction of anti-nutritional factors**: Many plant-based feed ingredients contain compounds like tannins, phytic acid, and protease inhibitors that limit nutrient absorption. Fermentation can break down these compounds, increasing nutrient bioavailability.
- **Improved protein quality**: Microbial fermentation can enhance the amino acid profile of alternative protein sources by synthesizing essential amino acids or improving their digestibility.
- **Enhanced gut health**: Fermentation produces beneficial metabolites such as organic acids and probiotics, which support gut health and improve feed conversion efficiency in poultry and pigs.
- **Extrusion and heat treatment**: Extrusion and heat treatment involve the application of high temperature and pressure to modify the physical and chemical properties of feed ingredients. These processes help:
- **Denature anti-nutritional factors** such as trypsin inhibitors in legumes and gossypol in cottonseed meal.
- **Improve starch gelatinization**, making carbohydrates more digestible and energy-dense.
- **Enhance protein digestibility** by breaking down complex protein structures into more accessible forms.

Heat treatment is particularly beneficial for cottonseed meal and legume-based feeds, which contain anti-nutritional compounds that can interfere with digestion and nutrient absorption.

- **Enzyme treatment**: Adding feed enzymes, such as proteases, phytases, and carbohydrases, can further improve the nutritional quality of alternative protein sources.
- **Phytase** helps break down phytic acid in plant-based ingredients, increasing phosphorus availability.
- **Proteases** improve protein digestibility by breaking down protein molecules into smaller, more absorbable peptides.
- **Carbohydrases** aid in fibre degradation, making energy from fibrous ingredients more accessible to animals.
- **Micronisation and particle size reduction**

Reducing the particle size of feed ingredients through micronisation or grinding increases surface area, improving digestibility and nutrient absorption. This technique is particularly useful for insect meal, where finely ground insect protein has been found to enhance amino acid digestibility and absorption rates in poultry and pigs.

Cost and availability

- Cost-effectiveness, local availability, volume of production, and consistent supply throughout the year are other critical factors. The cost and availability of alternative ingredients can vary depending on factors such as geographical location, seasonal fluctuations and market demand. Some alternatives, such as black soldier fly larvae, are still relatively expensive compared to soybean meal, though ongoing research and scaling production may reduce costs over time. Further research is needed to assess the economic feasibility of replacing soybean meal with alternative ingredients in poultry feed formulations.

Environmental impact

A comprehensive assessment of carbon footprint, water usage, and land use requirements is essential when selecting alternative feed ingredients for poultry and pig production. Sustainable feed choices should balance environmental impact, and economic feasibility in addition to nutritional quality, to create a more resilient and eco-friendly poultry industry. With the right strategies, producers can significantly reduce environmental degradation while ensuring efficient and responsible poultry production for the future.

- As the poultry and pig industries seek to reduce its environmental footprint while maintaining productivity and profitability, assessing the impact of alternative feed ingredients is crucial. This includes evaluating their **carbon footprint, water usage, and land use requirements** to ensure a sustainable transition away from traditional feed sources such as soybean meal.
- By assessing the life cycle emissions of various feed alternatives, poultry producers can prioritize lower-carbon ingredients and reduce the overall environmental impact of egg and meat production.
- Water usage.
- Water is a critical resource in agriculture, and different feed ingredients vary widely in their water footprint. Soybean cultivation, for instance, requires significant amounts of irrigation, contributing to water scarcity in some regions. In contrast, alternative feed sources like insect meal, algae, and food industry byproducts often require far less water to produce.
- Land use requirements.
- One of the biggest environmental concerns with soybean meal is its link to deforestation and habitat destruction, particularly in South America. Finding alternative feed ingredients with lower land use requirements is essential to reducing biodiversity loss and promoting land conservation. By shifting toward alternative feed sources with **low land-use demands**, poultry production can **minimize its impact on forests, grasslands, and other natural ecosystems**.

In conclusion. while there are several alternative ingredients available to replace soybean meal in poultry and pig feed, further research is needed to evaluate their nutritional value, palatability, digestibility, and economic and environmental sustainability. By addressing these research gaps, poultry and pig producers and feed industry can make informed decisions about incorporating alternative ingredients into their feed formulations to optimise performance, reduce costs and promote sustainability in the poultry industry.

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10 Plain English Summary

Project Title:	Alternative protein-rich ingredients for Australian pigs and laying hens
Australian Eggs Limited Project No.	XXXXXX
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Objectives	To conduct a systematic literature review to Identify alternative protein rich feed ingredients and study: • Global and Australian production quantities. • General characteristics. • Nutrient composition and digestibility. • Antinutritional factors and processing requirements (extraction methods, quality). • Production performance of pigs and laying hens when fed with the alternative ingredients. • Sustainability of production, carbon footprint and life cycle assessments.
Background	Soybean meal is the main protein ingredient to feed pigs and poultry, to produce animal protein for human consumption. Soybean production has expanded (and will continue to expand) more than any other crop due to the increase in population and the demand for animal protein. Currently, there is an increasing awareness and move towards responsible soybean meal use in animal feed to reduce its impacts on the loss of forests, grasslands and savannahs. Due to the severe domestic production shortfall, Australia is a net importer of soybean meal. In 2020-21, 1.2 M tonnes of soybean meal were brought into Australia for the livestock sector. For any livestock farmer, reducing costs whilst maintaining a desirable level of output is an objective. The breeding and development of new protein crops, or the enhancement of the nutritional value of indigenous crops, offer the potential to increase competitive advantage. Apart from being less dependent on soybean meal imported from outside Australia, there are acute environmental hazards to be considered while using soybean meal in the animal diet. The livestock sector increasingly competes for scarce resources, such as land, water and energy, and has a severe impact on air, water and soil quality because of its emissions. Various aspects of soy production generate greenhouse gases that contribute to climate change. Carbon footprint is the amount of carbon dioxide released into the atmosphere as a result of the activities of a

	particular individual, organisation, or community. The carbon footprint is also an important component of the ecological footprint, as it is linked to the amount of land and natural resources needed to absorb carbon emissions. The resulting CO_2 from human activities must be absorbed by forests, oceans, and other ecosystems, however, the same biologically productive spaces are also needed for agriculture and urban development. As there is a limitation in such space, the carbon footprint creates competition for the biological spaces. Reliability on international markets, as well as constant price change, introduce a high degree of uncertainty and potential risk factors for livestock producers in Australia where their feed formula is highly dependent on imported soybean meal inclusion. To improve sustainability and resilience, and reduce the costs of livestock production in Australia, it is critical to identify locally produced alternative protein ingredients to replace soybean meal – fully or partially – without having detrimental effects on livestock production performance.
Research	*Systematic literature review – consultation with industry stakeholders and commodity traders* A systematic literature review has been performed to collect the information regarding the potential alternative ingredients to replace soybean meal, fully or partially. The literature review included: • Domestic and global production of alternative ingredients • General characteristics • Nutrient composition and digestibility • Antinutritional factors and processing requirements • Sustainability of production, carbon footprint and LCA • Maximum inclusion rate of alternative ingredients for optimum production performance of pigs and poultry *Potential alternatives* • The review divided alternative ingredients into six categories including: • Oilseed and fruit by-products (cottonseed meal, linseed meal, sesame meal, sunflower meal, coconut meal, groundnut meal, palm kernel meal). • Plant protein sources: grain by-products (brewers' grain (BG) and distiller's dried grains with solubles (DDGS), gluten feed, and meal from corn and sorghum. • Grain legumes or pulses (beans, chickpea, lupine, pea, guar meal, copra meal). • Aquaculture protein sources: seaweed, microalgae and duckweed. • Animal/insect protein sources (silkworm pupae meal, slaughterhouse and hatchery by-products, insect meals). • Other sources including food waste and single-cell protein.
Outcomes	Our literature review concluded that canola meal, lupins (or lupin kernel meal) and sunflower meal are among the most viable alternative ingredients that can potentially replace imported soybean meal in the diet, where the diet is balanced for digestible amino acids following ideal

	protein profile for laying hens. This requires crystalline amino acids (such as lysine, methionine, valine, threonine, leucine, isoleucine and tryptophane) supplementation. In addition, our literature review concluded that insect meals, such as black soldier fly larvae (BSFL) are emerging as novel alternative ingredients that can replace 25–50% of soybean meal in a balanced diet for laying hens. The beauty of insect meal is the circular economy resulting from its growth on waste streams. This can reduce the carbon footprint of egg production and largely improve the sustainability of the production system. However, the technology of BSFL farming needs to be optimised, and production costs should be reduced to successfully include it in least-cost feed formulations. Food waste also shows promise to be used as a nutrient-rich ingredient in layer nutrition. However, further research is required to develop a framework where industry transitions to practical diets without imported soybean meal inclusion.
Implications	Feed cost accounts for 70% of the production costs in farming, and any strategy to reduce it will have a significant impact on total production costs and farm profitability. The value of this project lies in identifying the viable alternative ingredients to replace soybean meal, which will result in reducing the cost of imported soybean meal and increasing domestic production of protein-rich ingredients. In terms of animal production, it will create resilience, predictability and sustainability. However, the metric value of the project is one of the objectives of this systematic study to be explored and estimated after the literature review, consultation with industry and commodity stakeholders is complete. Through this project, potential cost-savings in feed as well as capacity to reduce carbon footprint will be investigated for the alternative protein ingredients and a ranking score will be allocated.
Key Words	Alternative ingredients, carbon footprint, laying hen, pig, soybean meal, sustainability
Publications	No publication at this stage

11 Appendix

11.1 Generation of carbon in agriculture

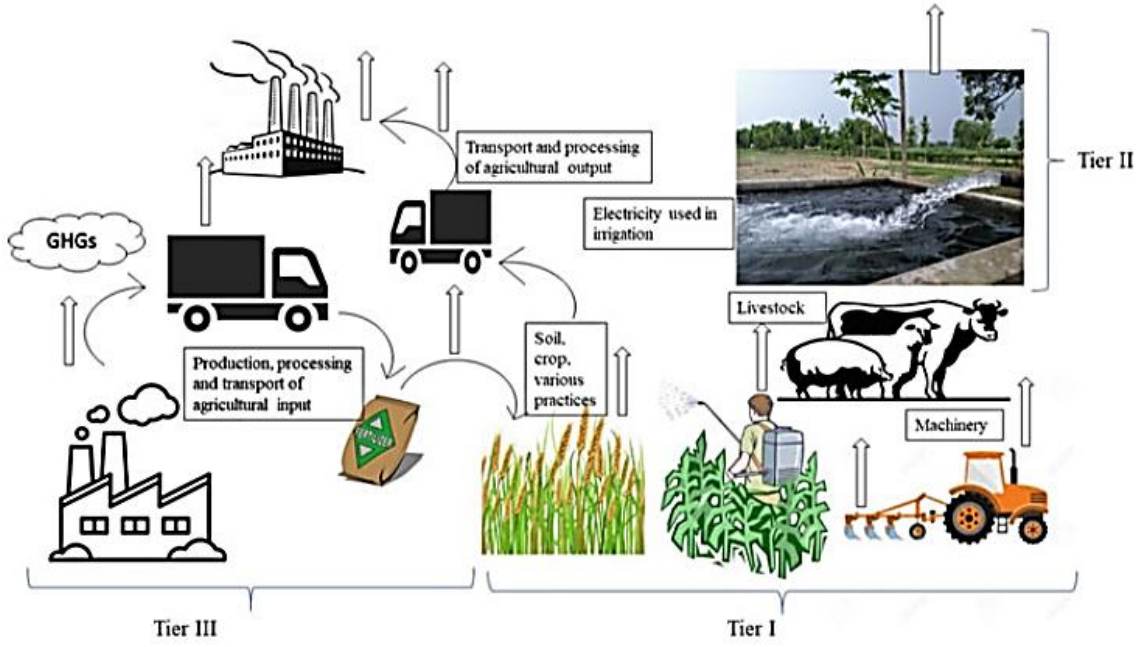


Figure 30 Emission sources from agriculture sector under different tiers

(Source: Jaiswal & Agrawal 2020)

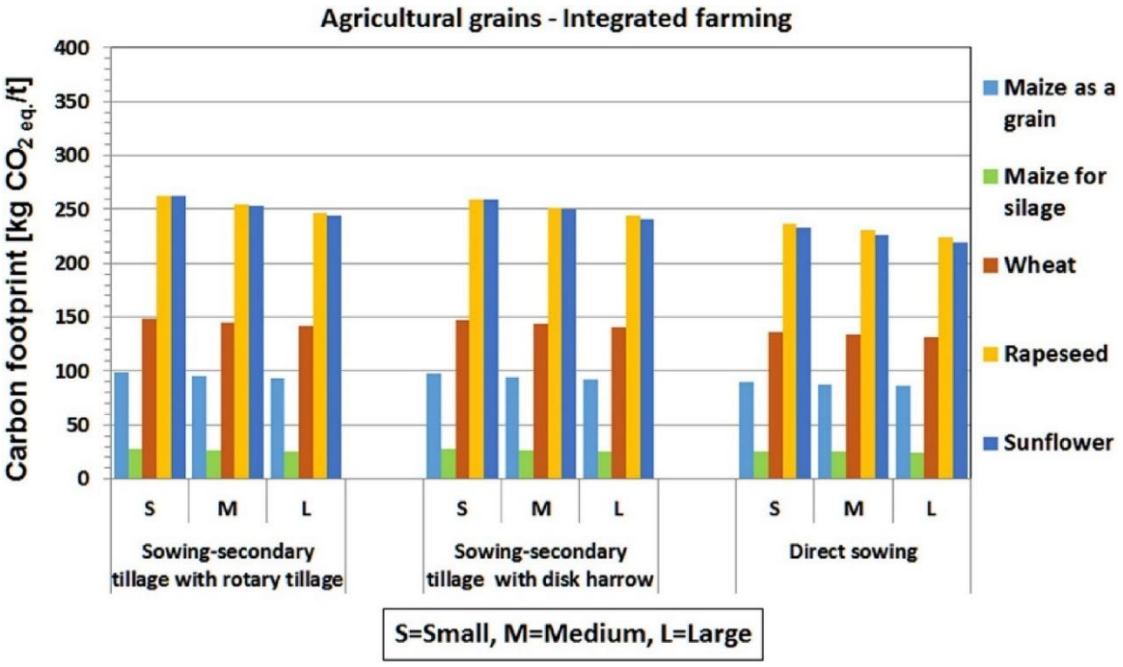


Figure 31 Carbon footprint of agricultural grains in integrated farming systems

(Source: Al-Mansour & Jejcic 2017)

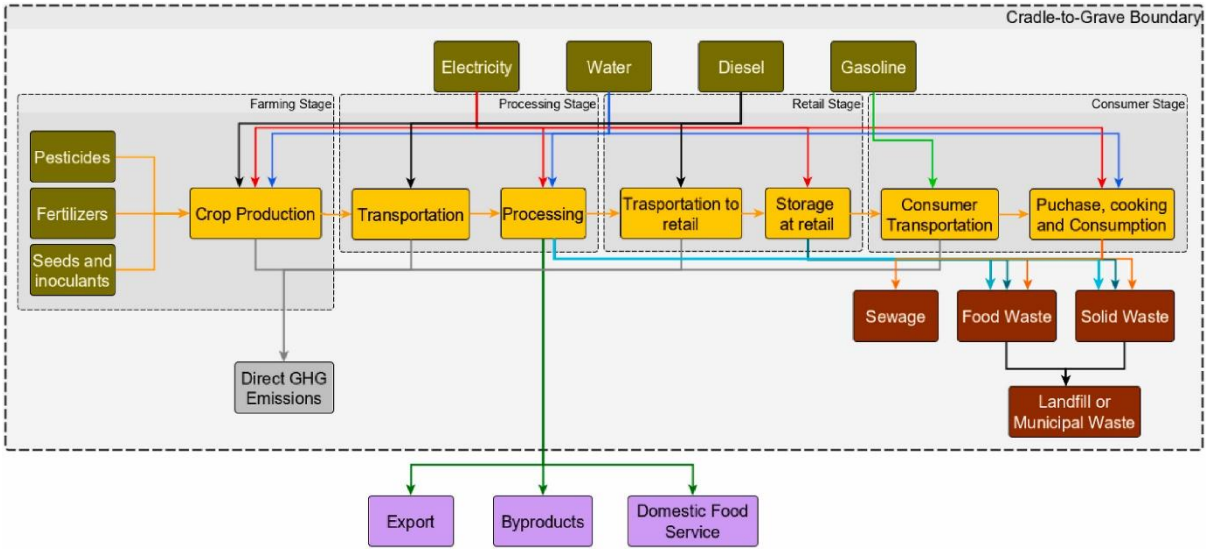


Figure 32 Conceptual model with system boundaries and processes in production and consumption of pulses in the United States

(Source: Bandekar et al. 2022)

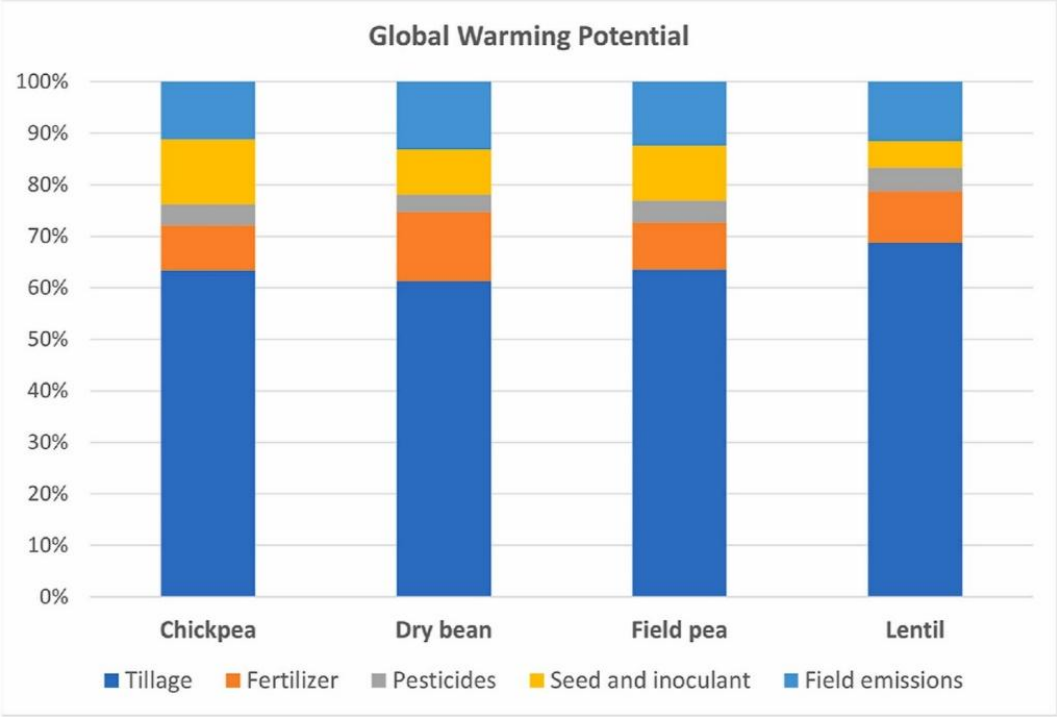


Figure 33 Contribution from various farm activities to the GWP of 1 kg of pulses harvested at the farmgate

(Source: Bandekar et al. 2022)

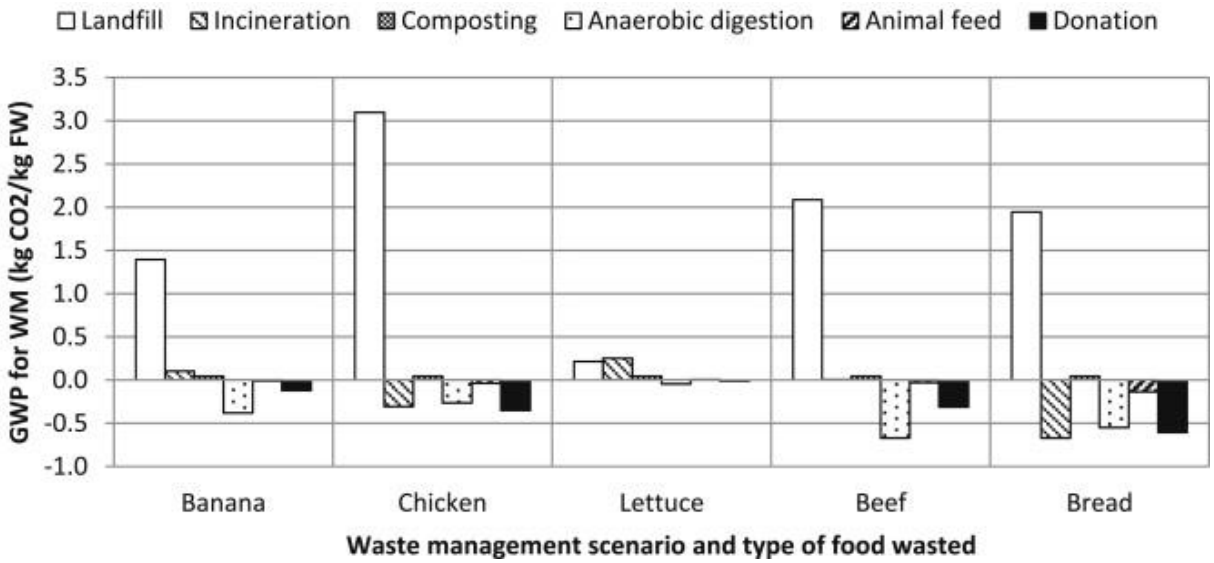


Figure 34 Global warming potential of each waste management scenario and food product

(Source: Eriksson, Strid & Hansson, 2015)