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ALTERNATIVE SOURCES OF PROTEINS IN FARM ANIMAL FEEDING

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ABSTRACT

The global demand for protein is on the rise owing to the exponential increase in the world population and to meet the global protein requirements, it is imperative to seek alternative sources of proteins in farm animal feeding. Recognizing the importance of proteins and the fact that a major portion of human protein requirements is derived from livestock in the form of meat, milk, and eggs, the available protein-feeding stuff in the form of soybean meal cannot be regarded as sufficient for feeding to livestock. Oil seeds such as rapeseed meal and canola meal have a crude protein content of 30%-40% and are widely used and hence a potential alternative protein source to soybean meal. Going forward, Grain legumes such as peas, faba beans, and lupins, another alternative source of proteins have the potential to replace traditional protein feeds completely or partially such as bone and fish meals. Duckweed with a protein content of 20%-45% is another plant-based potential protein source that can be employed in livestock feeding particularly pigs owing to its huge potential as a growth promoter as evidenced by studies in pigs and piglets. Because of their nutritional qualities and possible environmental advantages, insects represent another class of alternative protein sources that have enormous potential to function as sustainable protein sources. Several insect species have been assessed for use as animal feeds; the most promising ones include the yellow mealworm (Tenebrio molitor, TM), the common house fly (MD), and the black soldier fly (Hermetia illucens, HI). Byproducts from aquaculture and fisheries are abundant in macro- and micronutrients, and their utilisation can provide fishmeal and fish oil, which can then be further adapted for use as a source of protein in animal nutrition. Employing microalgae as an alternative source of protein in animal feeding is somehow a new concept. Many nutritional and toxicological studies have demonstrated the potential of algae biomass as a valued feed supplement or substitute for conventional protein sources such as soybean meal. While these alternative protein sources in livestock feeding may serve as useful tools, parameters such as feed safety and acceptability should be monitored based on feed safety regulations.

Keywords: Protein, Farm Animal, Legumes, Insects, Single cell protein, Yeast, Duckweed

INTRODUCTION

Farm animals, their products, and byproducts have been essential in improving human health and life span for centuries, providing major contributions to the human diet, clothing, labour, medicine, and research **(Kues & Niemann, 2004)**. Milk, meat and eggs are the principal animal food products, and currently account for around 13% of the energy and 28% of the protein consumed globally; in industrialised countries, this climbs to 20 and 48% for energy and protein, respectively **(FAO, 2009)**. The primary goals of livestock breeding are to achieve long-term development in livestock production and so meet the population's food requirements. Improving animal and poultry productivity through the provision of balanced and complete feeds is an important strategy to increase the impact of livestock **(Nikolaev, Karapetyan, Shkalenko, Zabelina, & Struk, 2018)**. At present, insufficient fodder base and unbalanced diets in terms of lacking potential nutrients are the key contributors towards the low efficiency of agricultural animals and poultry **(Sankina, Chernysh, & Sankin, 2017)**. Since a major portion of the human protein requirements are being met from animal products such as meat, milk, and eggs, and as the population is rising globally, the demand for animal-origin proteins is also rising in parallel. Animal products serve as a vital source of protein, with 59% of the total consumed protein in the European Union (EU) being derived from animal products (de Visser, Schreuder, & Stoddard, 2014**)**. Like human beings, animals require an uninterrupted supply of feed rich in protein and energy to yield significant food products of human importance. The scarcity of available feed resources and the increasing costs resulting from economic reforms in the agricultural sector are the main barriers to increasing livestock and cattle breeding production (**Penkova & Mishina, 2012)**.

Proteins are essential nutrients for farm animals consisting of building blocks of amino acids that play an important role in growth, production maintenance, and reproduction. The traditional sources of proteins for farm animals are comprised of Soyabean, Canola meal, and Corn gluten meals. The protein shortage is a global concern, and substantial research into new sustainable protein sources is undertaken **(Gasco *et al.*, 2020)**. It is predicted that the world may soon face a shortage of Human-Edible Protein sources (HEP) for livestock production. HEP refers to plant-based feed sources that are both nutritious and valuable enough to be directly consumed by humans. Since both humans and livestock rely on these resources, creating competition. Livestock feed consists of mixture of HEP and Human Inedible Protein (HIP) elements, including by-products derived from the food industry. Proteins are essential for the development, maintenance, and proper functioning of cells, tissues, and organs. They also provide energy during times of severe malnutrition or extreme exercise conditions (**WAGENMAKERS, 1998)**. The sustainable development of the animal production sector needs alternative protein sources for feed formulation. Keeping in view the predicted protein shortage challenges, this review focuses on identifying the potential sources of alternative and new proteins for livestock feeding, their accessibility, safety, and acceptability.

ALTERNATIVE SOURCES OF PROTEINS IN FARM ANIMAL FEEDING

Oil seeds

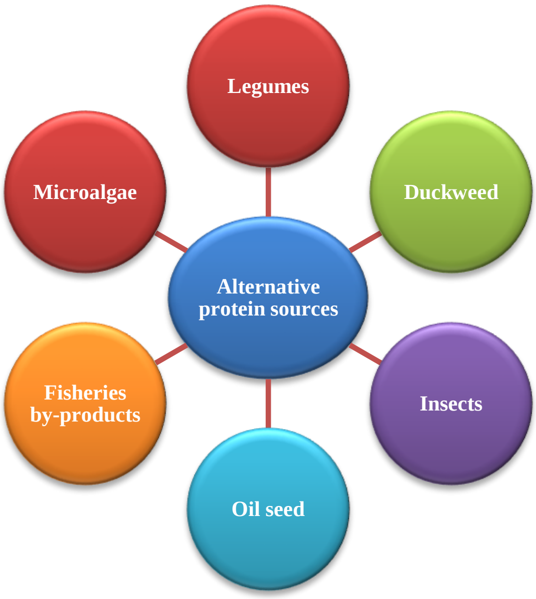

Figure 1 Alternative sources of proteins for farm animals feeding

Rapeseed meal or Canola meal is an alternative to soybean meal that can be used as a potential source of protein in animal nutrition. These oil seeds are widely used protein sources for various animal species such as poultry, pig, cattle, and fish around the world **(Enami, 2011).** The crude protein content of the meal ranges from 30% to 40%, depending on the extraction method used (**ELSAYED, 2019**). However, one of the limiting factors for incorporating rapeseed meal as a substitute protein source is the presence of its antinutritive compounds, particularly glucosinolates, which have detrimental effects in poultry and pigs. Plant breeding can help reduce the glucosinolate content in certain plant varieties. Some varieties with low glucosinolate content are available. For monogastric animals, the maximum concentration of glucosinolates in their feed should be less than 12,000 mg/kg of whole seed and less than 20,160 mg/kg of extracted meal (**Tripathi & Mishra, 2007**). Sunflower meal is another rich source of protein but due to its high phenolic content, particularly chlorogenic acid, the availability of proteins is impaired (**González-Pérez *et al.*, 2002**). Extracted cottonseed meal is also an alternative to soybean meal, but the associated drawback is that in certain countries there are only genetically modified varieties available, with protein concentrations largely depending upon the variety and the mode of extraction but typically varying from 30-50% (**ELSAYED, 2019**). Sunflower meal also serves as an alternative source of protein but its high content of phenol, particularly chlorogenic acid affects the protein availability (**González-Pérez et al., 2002**).

Legume seeds

Legumes like peas, faba beans, and lupins serve as valuable protein and energy sources for monogastric animals. They offer a viable alternative to conventional animal-derived protein sources such as meat and bone meal or fish meal. Moreover, they present an alternative protein-rich option compared to soybean meal (SBM) and other oilseed meals. Integrating grain legumes into animal feed formulations helps to ensure a nutritious and well balanced diet for livestock **(Jezierny, Mosenthin, & Bauer, 2010)**. The search for alternative protein sources has spurred a rising interest in the utilization of grain legumes, given their pivotal role as a valuable plant-based protein source. Additionally, grain legumes are also cultivated as a nitrogen-fixing crop in rotation systems **(López-Bellido, López-Bellido, & López-Bellido, 2005)**. In Europe, major grain legumes include peas, faba beans, and lupins whereas Soybeans production leads in Argentina, Brazil, China, India, and the United States **(Karr-Lilienthal, Grieshop, Merchen, Mahan, & Fahey, 2004)**. Cultivating peas in cool seasons is a good alternative for regions unsuitable for growing soybeans due to their sensitivity to low temperatures. Peas can withstand low temperatures for germination and growth because they are less susceptible to frost (**Miller *et al.*, 2002**). Although peas are mostly grown for human consumption, they are becoming more popular in the northern United States, Canada, and Australia as pig feed (**Blair, 2017**). Cultivated species of Lupins being used as feed ingredients in ruminant, pig, and poultry nutrition include *Lupinus angustipolius*, *Lupinus albus*, and *Lupinus luteus* with all of them originating from the Mediterranean region **(van Barneveld, 1999)**. Among the grain legumes, the crude protein content of lupins is the highest (324-381 g/Kg dry matter (DM)) as compared to faba beans ((301 g/kg DM) and peas (246 g/kg DM). The Crude protein content and level of amino acids in different grain legumes are given in *Tab 1*.

Table 1 Crude protein and amino acid content of grain legumes compared to soyabean meal (g/kg dry matter) (Jezierny et al., 2010) SBM - soybean meal; CP - crude protein; AA - amino acids.

	Vicia Faba	Pisum sativum	Lupinus albus	Lupinus angustifolius	Lupinus Luteus	Soyabean Meal
CP	301	246	381	324	361	541
Indispensable Amino Acids						
Valine	13.3	11.4	14.5	12.5	13.6	25.5
Lysine	18.4	17.3	18.2	15.0	16.3	33.1
Isoleucine	11.8	10.0	15.3	12.7	14.2	24.3
Leucine	21.4	17.4	27.5	21.5	24.1	40.9
Histidine	7.8	6.1	9.3	8.8	9.7	14.4
Methionine	2.2	2.2	2.5	2.0	2.0	7.3
Tryptophan	2.6	2.2	3.0	2.6	3.0	7.4
Threonine	10.5	9.1	13.3	10.9	11.9	21.3
Phenylalanine	12.6	11.7	14.9	12.5	13.6	27.2
Arginine	26.4	21.0	39.3	33.5	38.0	39.7
Dispensable Amino Acids						
Glycine	12.2	10.6	15.0	13.4	14.3	23.0
Glutamic acid	46.9	40.0	79.3	65.6	72.5	97.6
Cysteine	3.5	3.5	6.7	4.3	4.8	8.0
Aspartic Acid	31.6	28.2	38.5	31.5	35.1	62.0
Alanine	11.9	10.5	12.5	10.9	11.8	23.3
Proline	11.8	10.2	15.3	13.5	14.3	27.5
Serine	14.1	11.5	19.0	15.3	17.0	27.3

Duckweed (*Lemna minor)*

Duckweed is becoming more popular as people look for substitute protein sources for soybean meal in animal feeds. Since the 1960s and 1970s, this well-known plant has been used in Poland as a source of feed for pigs and ducks **(Sońta, Rekiel, & Batorska, 2019)**. One of the noteworthy characteristics of duckweed is its potential as a source of proteinaceous food, with several species having a suitable profile of essential amino acids (Table 2) **(Rusoff, Blakeney Jr, & Culley Jr, 1980)**. The dry matter composition of duckweed varies from 3% to 14%. The quality of the growth media affects not only the protein content but also the other elements. Protein content in dry matter can vary from 7% to 45%, with 20% to 45% being the most typical range. There is a range of 2% to 9% for fat content, 12% to 28% for fibre content, and 14% to 44% for carbohydrates **(Leng, 1999)**. Research has shown that when fed duckweed, piglets showed significant increases in body weight and feed consumption. Piglets in growth showed no reluctance to eat diets based on duckweed. It was discovered that the piglets fed 40 and 60% duckweed had daily body weight gains higher than those of the control group, which was fed soybean as the only source of protein. The animals receiving the longest-term highest dose of duckweed had the greatest body weight rise, indicating that the effects on body weights were significant **(Moss, 1999)**. Fresh duckweed supplementation (about 1.5 kg/day/animal) improved body weight gain and produced a better carcass output with more lean meat and less fat and bones **(Hang, Linh, Everts, & Beynen, 2009)**. Along with its chemical makeup, duckweed's potential use as bovine feed has also been investigated. It was discovered that the proximate composition of the three main varieties of duckweed—Spirodela, Lemna, and Wolffia—varies. Duckweed's dry matter and crude protein are highly degradable in the rumen, according to the evaluation of the rate and extent of digestion. For this reason, it's important to determine the level of duckweed supplementation in cattle feed **(Huque, Chowdhury, & Kibria, 1996)**.

Experimental trials have also been conducted regarding the supplementation of duckweed as a potential source of protein in small ruminants and revealed that nutritionally duckweed is comparable to soyabean meal with no adverse effects on ruminal pH, ammonium ions concentration, and the amount of volatile fatty acids **(Reid Jr, 2004)**. However, despite its great potential as an alternative protein source for farm animals and aquaculture, its use is limited owing to its difficult harvesting in some climatic zones and the costly production of processed feed **(Sońta *et al.*, 2019)**.

Table 2 Amino acid composition of important species of Duckweed (g/100 g)

Amino acid	*L. gibba*	*S. polyrhiza*	*S. punctata*	*W. columbiana*
Alanine	4.59	4.48	4.79	3.75
Histidine	1.89	2.15	1.90	1.18
Aspartic	7.12	7.55	7.38	5.63
Glutamic	7.60	8.00	7.69	5.76
Glycine	3.79	3.95	3.93	3.04
Arginine	4.29	5.25	4.86	3.78
Isoleucine	3.87	3.75	3.76	3.06
Leucine	7.15	6.85	6.88	5.83
Lysine	4.13	4.30	4.26	3.37
Valine	4.96	4.40	4.71	3.49
Phenylalanine	4.45	4.20	4.38	3.60
Threonine	3.20	3.45	3.31	2.55
Serine	2.61	2.80	2.83	2.28
Proline	2.93	3.38	2.95	2.41
Tyrosine	2.91	3.05	3.14	2.17
Methionine	0.83	0.83	1.07	0.87

(Rusoff et al., 1980)

Insects

Insects are now recognised in several countries as an essential and sustainable source of raw materials for animal feed. This is due to the fact that insects are a natural component of the diets of many animal species and may supply the essential nutrients and amino acid profile, making them a suitable dietary source **(Makkar, 2018)**. The nutritional qualities of insects and the possible environmental advantages of sustainable insect farming make the use of insects as a feed source for farm animals a very promising idea. Many insect species have been tested for use as animal feeds; the most promising ones include the yellow mealworm (Tenebrio molitor), black soldier fly (Hermetia illucens), and common house fly (Musca domestica). Insects' nutritional concentration is mostly determined by their life stage, however other elements including rearing circumstances and the make-up of the growth media used in insect production also have a role. Certain insect species, including caterpillars, have higher concentrations of amino acids, like lysine, with amounts reaching 100 mg/100 g of protein when compared to plant-derived proteins **(Sogari, Amato *et al.* 2019)**. Given their high nutritional value, little space requirements, and inherent inclusion in the diets of fish, fowl, and reptiles, insects offer great potential as a feed source. Because grasshoppers, often referred to as acridids, have a higher protein content than other protein sources like fish meal and soybean meal, they have been recognised as a possible addition to chicken feed. They are also a good source of iron, copper, zinc, magnesium, and calcium. In the Philippines, pasture-raised chickens are fed grasshoppers. In comparison to hens grown on commercial chicken feed, these pasture-fed chickens, who also consume grasshoppers, are prized for their excellent flavour and can fetch a higher price **(Rumpold & Schlüter, 2013)**. Insects can be fed to agricultural animals as a source of protein, according to several research studies. For example, bear pups fed a diet that contained 50% black soldier fly meal instead of fishmeal experienced growth rates and nutrient utilisation comparable to that of soybean meal. Researchers gathered wild black soldier fly larvae raised on the urine and excrement of beef cattle over forty years ago. These larvae were fed to a few developing pigs after being dried. The research findings indicate that black soldier fly larvae can still be a valuable addition to pig diets, even though their fat content may have an impact on their digestion and palatability **(Newton, Booram *et al.* 1977)**. A summary of studies conducted on incorporating insects in pigs' diets is given in *Table 3*.

Table 3 Summary of Growth Responses in Pigs Diet containing insects

Pig Age	Insect species	Feed inclusion level	Growth responses	References
5 weeks	BSF	33%	Increased feed intake; reduced apparent DM digestibility	(Newton, Booram, Barker, & Hale, 1977)
Early weened pigs	BSF	0%, 50% or 100% replacement of dried plasma	50% diet improved performance; 100% diet decreased performance	(Newton, Sheppard et al. 2005)
Weened pigs	Mealworm	0%, 1.5%, 3%, 4.5%, and 6% replacement of soyabean meal	Linear increase in BW, ADG, ADFI, DM and CP digestibility	(Jin, Heo, Hong, Kim, & Kim, 2016)
Weened female pigs	BSF	0%, 30% and 60% replacement of soyabean meal	Linear increase in ADFI, No effect on growth	(Biasato et al., 2019)
Barrows	BSF	50%, 75% and 100% replacement of soyabean meal	No effect on base meat quality measures, increased juiceness, higher backfat PUFA contents	(Altmann, Neumann, Rothstein, Liebert, & Mörlein, 2019)

BSF= Black soldier fly; ADG-Average daily gain; ADFI-Average daily feed intake; PUFA-Polyunsaturated fatty acid; Table adapted from (DiGiacomo & Leury, 2019).

Pig diets that use waste-reared larvae instead of soybean meal reduces land usage and global warming, but the resulting life cycle evaluation generates contradictory results **(van Zanten, Bikker, Meerburg, & de Boer, 2018)**. However, the legal implications of incorporating insects in animal diets vary from region to region as summarized by **(Lahteenmaki-Uutela *et al.*, 2017)**. In the European Union, processed animal protein (PAP) as a feed ingredient is prohibited by the transmissible spongiform encephalopathy (TSE) Regulation 999/2001. Later, though, the ban was amended to permit the use of processed animal protein for aquaculture diets that came from sources other than ruminants. In light of this, the International Platform for Insect and Feed (IPIFF) has expressed a wish to alter the EU feed legislation to permit the incorporation of insect products raised entirely on vegetable substrates as a source of protein for pigs, poultry, and aquaculture **(Lahteenmaki-Uutela *et al.*, 2017)**. When compared to conventional protein sources, the production of insects is probably going to result in lower greenhouse gas emissions, water use, and land use. However, optimal rearing conditions and methods are yet to be determined **(DiGiacomo & Leury)**.

Aquaculture and fisheries by-products

All the portions of farmed and captured fish, such as the head, fins, scales, skin, bones, and viscera, as well as shellfish crustaceans, such as the carapax, exoskeleton, shell, and debris, that are removed during processing for human consumption, are referred to as "fishery and aquaculture by-products." These byproducts can be utilised to make fishmeal and fish oil that are excellent for feeding animals. They are also a rich source of macro and micronutrients **(Li, Liu, Jiang, & Yan, 2019)**. Depending on the kind of fish and the portion of the fish under consideration, different fish by-products have different nutritional values. For instance, according to dry matter, the protein composition of the skin of yellowfin tuna is approximately 32%, the fat content is roughly 3%, and the ash level is approximately 63%. In the head area of Atlantic salmon, there is around 13% dry matter protein content, 22% dry matter lipid content, and 4% dry matter ash content. The same species' viscera have a dry matter protein content of around 8%, a dry matter lipid content of about 44%, and a dry matter ash content of about 1%. The tilapia skeleton contains approximately 50% dry matter protein, over 30% dry matter lipid component, and 15% dry matter ash. Finally, based on dry matter, the protein content of the by-products in anchovies is 46% and 34% for the head, 41% and 25% for the frame, and 31% and 62% for the viscera **(Gasco *et al.*, 2020)**. Significant quantities of by-products from seafood can be used to make feed ingredients and other items. The principal origin of these byproducts is marine finfish, which include parts such as heads, frames, fins, skin, and viscera, among others. In addition, there are by-products from the squid, prawn, crab, and other seafood sector divisions that are used to make unique feed ingredients. It becomes beneficial to carefully pick particular fish processing by-products (such as heads, liver, milt, and viscera) in order to produce premium feed ingredients that can be sold for a premium price, provided that the appropriate economic incentives are in place **(P. Bechtel, 2007)**.

Byproducts of fisheries can be used in a variety of ways, including fish oil, fish meal, fish silage, and protein hydrolysates. The primary purpose of fish meals and oils is as feed components for aquaculture, cattle, and poultry. In the animal feed industry, fish oil produces triglycerides and phospholipids, and protein hydrolysates are a great supply of nitrogen. Fertiliser and pet food are also made using these wastes. Furthermore, they can be treated to provide high-quality feed through methods including fermentation, biotechnology, and biopreservation **(Malaweera & Wijesundara, 2013)**.

Soybean meal and corn gluten meal are the primary players in the protein feed ingredient sector, with global soybean meal production surpassing 130 million metric tons (MMT). In contrast, animal proteins sourced from rendering facilities and capture fishing, such as fish meal and soluble, contribute a relatively minor share to the world's overall protein meal output. The combined worldwide production of fish meal and soluble hovers at around 6-7 MMT, contingent on the output from major industrial fisheries in Peru and Chile **(Barlow, 2002)**. To demonstrate the scale of fish meal derived from fish processing by-products, consider that Alaska's annual fish harvest for human consumption exceeds 2 million metric tons (MMT). Nonetheless, the fish meal produced in Alaska represents just a small fraction, ranging from 1 to 2%, of the total global fish meal production **(P. J. Bechtel, 2003)**.

Fish meal serves as an excellent component in aquaculture feeds due to its high-quality protein, which complements most plant-based proteins in feed formulations. Furthermore, fish meals typically boast significant quantities of long-chain omega-3 fatty acids and minerals, making them nutritionally valuable. They are also known for their appealing taste to aquatic species. The quality of fish meals has advanced thanks to various factors, such as a focus on using fresh raw materials and employing low-temperature drying techniques. Fish meals are frequently incorporated into the nutrition of young pigs, and feed components derived from hydrolysates have found applications in aquaculture, as well as in the diets of young pigs and calves. Young pigs weaned early necessitate specialized dietary elements until their digestive system matures completely. Some have proposed the use of more cost-effective, specialty fish meals as a substitute for the costly spray-dried animal plasma **(Van Dijk, Everts, Nabuurs, Margry, & Beynen, 2001)**. Studies have also revealed that the inclusion of marine fish oils in diets for pregnant sows can improve fetal survival rates. art from their role as feed components for farm animals, fish by-products have been incorporated into pet foods to provide protein and oil, and there is a growing enthusiasm for utilizing products derived from fish by-products to improve the well-being of pets **(P. Bechtel, 2007)**.

Single-cell proteins (SCP)

Single-cell protein (SCP), the first byproduct of fermentation, has shown to be a useful protein replacement. There is growing rivalry over food as the world's population rises and soon, SCP might be able to compensate for deficiency of protein. Numerous multinational corporations are placing a high priority on SCP manufacturing, and as knowledge and time permit, the range of applications for this technology is growing. Microorganisms, such as algae, yeast, fungi, and bacteria, can create vast amounts of SCP due to their rapid growth rate and high protein concentration in their chemical composition. In addition to proteins, SCP also includes lipids, minerals, vitamins, nucleic acids, and a variety of important amino acids **(Bratosin, Darjan, & Vodnar, 2021)**. The following types of single-cell proteins are discussed here in detail.

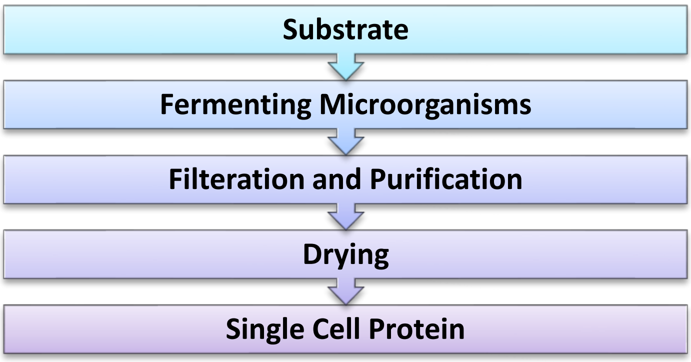

Figure 2 *Steps employed during the production of single-cell proteins at the industrial level.*

Microalgae

Owing to their fast growth rate, ability to be cultivated in saline water, and lack of need for arable land or artificial fertilisation, marine microalgae hold great promise as a sustainable substitute for traditional terrestrial animal feed **(Øverland, Mydland, & Skrede, 2019)**. The nutritional content and chemical composition of microalgae vary depending on geographic origin, harvesting season, and associated environmental conditions **(Jensen, 1993)**.

Brown (Phaeophyta), green (Chlorophyta), and red (Rhodophyta) algae are the three different types of marine macroalgae, which are multicellular protists that resemble plants. Fucoxanthin, a pigment, is responsible for the brown colour of Phaeophyta, phycobilins are responsible for the red colour of Rhodophyta, and a variety of pigments, including chlorophyll a and b, carotenes, and xanthophylls, are linked to the green colour of Chlorophyta **(Kadam, Tiwari, & O'Donnell, 2013)**. The protein content in microalgae may be challenging to interpret due to the different methodologies used in various studies. Nevertheless, microalgae produce nitrogen which is a critical component of amino acids, proteins, and chlorophyll. On the other hand, brown macroalgae generally have low protein content, usually below 150 g/kg of dry matter. Meanwhile, on a dry matter basis, green and red macroalgae have higher protein content **(Dawczynski, Schubert, & Jahreis, 2007; Lourenço, Barbarino, De-Paula, Pereira, & Marquez, 2002)**. The proximate composition of marine microalgae is given in Table *4*.

Table 4 Proximate composition of marine microalgae

Chemical constituent	*Brown microalgae*	*Green microalgae*	*Red microalgae*
Water, g kg^{-1} of wet biomass	610–940	780–920	720–910
Crude protein	24–168	32–352	64–376
Crude lipids	3–96	3–28	2–129
Polysaccharides	380–610	150–650	360–660

Proximate composition of marine microalgae. All the values are presented in the g/kg; Table adapted from (Øverland et al., 2019)

Numerous microalgal species possess an amino acid composition wherein the ratio of essential amino acids (EAA) to total amino acids (TAA) surpasses 450 g EAA kg-1 of TAA **(Angell, Angell, de Nys, & Paul, 2016)**. When compared to fishmeal, macroalgae generally have lower lysine concentration, but red algae may have higher lysine content than green and brown algae. Many macroalgae species have low histidine contents, although many also have quite high methionine contents. Glutamic acid is commonly present in macroalgae in high concentrations, both free and bound to proteins **(Mæhre, Malde, Eilertsen, & Elvevoll, 2014)**. Various studies have shown that supplementing the diet of monogastric farm animals, such as pigs, with macroalgae has a positive impact on their immune system and intestinal health **(Gardiner *et al.*, 2008)**.

The use of micro-algae as animal feed is a relatively new concept. Algal biomass has the potential to be a useful feed supplement or replacement for conventional protein sources like soybean meal, fish meal, and rice bran, according to several nutritional and toxicological studies. Since poultry presents the most promising opportunity for commercial usage in animal nutrition, poultry is the main domestic animal target for adding algae to their diets. Aquaculture is also using microalgae more and more. Approximately thirty percent of the world's algal production is currently sold for use in animal feed **(Becker, 2007)**. Over time, scientists have found that raising algae in tap water and ponds can aid in the growth of fish raised for aquaculture. Furthermore, adding 6–10% algae produced in sewage to a barley-based diet helps sustain the growth rate and feed conversion efficiency of pigs in the growing–finishing stage of their lives **(Hintz & Heitman, 1967)**. The apparent digestibility of the diets decreased when piglets were weaned early and their diet was substituted with S. maxima, which represented for as much as 12% of the total protein obtained from skim milk. Nonetheless, there was no discernible variation in the piglets' growth when compared to the control group **(Yap, 1982)**.

The effects of supplementing sows' diets with S. maxima were investigated. According to the data, the sows given algae gained less weight overall during their first reproductive cycle, but they produced more heavier piglets overall. The growth and litter characteristics of the algae-fed group and the control group did not significantly differ by the conclusion of the second reproductive cycle. Nonetheless, there was a greater rate of piglet culling in the sows fed algae. A further study was carried out to ascertain the effects of supplementing weanling pigs' diets with a combination of S. maxima, A. platensis, or Chlorella sp. in place of 33% soybean meal. The findings showed that the pigs fed the regular diet and those fed an algae-supplemented diet did not vary in terms of body weight gain, feed efficiency, or incidence of diarrhoea. The pigs fed the algae showed no symptoms of toxicity or digestive problems. De-fatted biomass from microalgal species can be a good alternative to maize and soybean meal in the diets of cattle, pigs and poultry, according to recent studies on the generation of biofuel **(Lum, Kim, & Lei, 2013)**.

Bacterial proteins

A variety of bacterial species have been investigated for protein production, therefore discussions on bacterial proteins are currently underway in addition to microalgae. Owing to a greater proportion of lysine and amino acids containing sulphur, bacteria produce a lot of high-quality protein. Hydrocarbons or their derivatives are used as substrates in the production of these proteins. To guarantee the calibre of the finished product, the production process must be closely regulated. Microbial protein products are currently offered on the feed market following several years of feeding trials in toxicology and nutrition conducted on a variety of domesticated animals.

Yeast and Fungi

Yeasts are a rich source of B complex vitamins and include modest levels of provitamin D and vitamin E. They are also a possible supply of protein due to their low sulphur content amino acids. Yeasts are more widely accepted as a source of protein by consumers, have a larger size, less potential for toxicity, and a lower nucleic acid content than bacteria. In a similar vein, mushrooms can be used as a source of protein. The idea of using fungal mycelium as a protein source for mass cultivation is relatively new. Studies have shown that fungi grow slower than yeasts and bacteria, and their protein content is lower. In addition, fungal protein often lacks sulfur-containing amino acids, making it difficult for monogastric animals to digest their cell walls. Therefore, it is essential to determine the toxicological status of any microbial protein before using it as an energy source **(Kuhad, Singh *et al.* 1997)**.

Although the discussed alternative sources of proteins have tremendous potential as a protein source, and by recognizing the fact that protein shortage will be a global challenge in the coming years, better strategies need to be formulated to better utilize these alternative protein sources and any obstacles in the implementation of these protein sources, particularly their safety and acceptability needs to be addressed by the animal and human health nutrition policymakers to achieve the desired goals towards overcoming protein shortage in the future.

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