REVIEW PAPER

MICROALGAE AS A SUSTAINABLE FEED SOURCE AND A BIOREMEDIATION STRATEGY FOR AGRO-INDUSTRIAL EFFLUENTS

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Abstract

Recently, microalgae have emerged as nutrient-dense feed sources with substantial benefits for animal health and productivity. They contain high-quality protein, essential fatty acids, vitamins, minerals, and bioactive compounds that help to improve the quality and quantity of animal-derived products, including milk, meat, and eggs, thereby presenting a sustainable alternative to conventional feed sources. Additionally, their immunomodulatory properties enhance gastrointestinal health, disease resistance, growth performance, and reproductive outcomes in livestock. Beyond animal nutrition, microalgae bio-actives hold value in cosmetics, pharmaceuticals, and nutraceuticals, showcasing their industrial versatility. Microalgae can grow in diverse environments, including wastewater and effluents. Wastewater has the potential to substitute synthetic media used in cultivation, providing nutrient-rich biomass that can serve as an alternative feed source. Cultivating microalgae in effluents/wastewater has emerged as a sustainable and eco-friendly approach for wastewater treatment and biomass production. However, high production costs and scalability constraints limit its widespread application. This review highlights the cultivation of microalgae using different wastewater sources as an alternative substrate and their nutritional value, as well as the health and environmental benefits of using it in animal feed. It also discusses the current challenges and examines the potential of microalgae to transform animal agriculture while contributing to a circular bioeconomy.

Keywords: effluent-grown microalgae, algal bioremediation, protein-rich algal biomass, omega-3 feed supplements, microalgae biorefinery, bioactive algal compounds, industrial effluent treatment, aquafeed innovation, regulatory-compliant algal feeds

Introduction

The world's population is rising drastically, and in order to meet its food and feed production demands, researchers are looking into alternative sources of supplements that can provide the required nutrients (Torres-Tiji *et al*., 2020). According to United Nations figures, the global population is expected to grow by almost 50% since 2000, to 9.5 billion in 2050 (Camacho *et al*., 2019). The dependence on conventional feed sources has raised significant concerns regarding sustainability, environmental impact, and production constraints closely linked to availability and cost. The elevated expense of these traditional feeds can impose a substantial financial burden on small and medium-scale farmers, thereby diminishing their profit margins. Furthermore, this reliance often results in overexploitation of the resources, leading to deforestation. These challenges underscore the critical need for alternative feed options that could be locally accessible, sustainable, and economically viable. Some of the potential alternatives to conventional animal feed are insect feed (Vrabec *et al*., 2015), Algae-based feed (Kusmayadi *et al*., 2021) and Genetically Modified Feed (Flachowsky *et al*., 2012). Such alternatives could reduce reliance on costly commercial feeds and enhance the economic resilience of the livestock sector. Moreover, these alternative feed sources must be capable of meeting the increasing demand for animal protein. One of the most promising and abundant alternative sources found in the environment is algae (Kovač *et al*., 2013). The benefits of using algae include their rapid growth, their capacity to thrive in saline water, and their capacity to be produced in controlled systems with a lower land footprint. (Øverland *et al*., 2019).

The global protein per capita has increased to 68 grams per person per day (Ranganathan, 2016). Algal biomass can be used as a natural source to replace synthetic substances to meet the growing demand for protein requirements (Miklos *et al*., 2011). The algae can be categorised as microalgae and macroalgae based on physical characteristics (Hughes *et al*., 2021). Macroalgae are multicellular plants, whereas microalgae are unicellular or simple multicellular photosynthetic organisms (Biris-Dorhoi *et al*., 2020; Thoré *et al*., 2023). Comparatively, microalgae are more nutritious than macroalgae (Madeira *et al*., 2017). Since ancient times, algae have been considered as food and feed (Borowitzka, 1998) and are as follows: *Porphyra* sp. (Nori- seaweed wrap- an ingredient in sushi - a Japanese dish), *Asparagopsis taxiformis* (used as feed supplement) (Cochrane *et al*., 2024), *Gracilaria* sp. (used as traditional medicine and human diet) (Torres *et al*., 2019), *Chondrus crispus* (commonly known as Irish moss, used as a dietary supplement and thickener) (Collén *et al*., 2014), *Spirulina* sp. (used as a food and feed supplement) (Holman and Malau-Aduli, 2013) *Chlorella* sp. (used as a food and feed supplement) (Masojídek and Torzillo, 2008), *Dunaliella salina* (used as an ingredient in food and feed supplements) (Alghamdi *et al*., 2024), *Aphanizomenon flosapuae* (used as a feed supplement) (Lyon-Colbert *et al*., 2018). Currently, 22000-25000 tonnes of microalgal biomass are produced for human and animal nutrition, with around 30% being used for feed production (Costa *et al*., 2016). The cultivation condition of microalgae plays a major role in their nutritional composition, and because of recent

water scarcity issues, people are looking for alternative media to cultivate microalgae. One assured source is microalgae that grow in effluents, utilising nutrient-rich wastewater from urban, industrial, and agricultural sources. *Chlorella vulgaris* and *Scenedesmus obliquus* thrive in treated municipal effluents. (Pittman *et al*., 2011). Industrial effluents contain valuable nutrient sources. However, they must complete pre-treatment to remove harmful chemicals effectively. Agricultural effluents strong in nitrogen and phosphate are appropriate, even if herbicides are present. Species like *Nannochloropsis* sp., *Chlorella* sp. and *Scenedesmus* sp. thrive in these conditions, absorbing nutrients efficiently (Calisto *et al*., 2011). However, problems include contaminants, salinity, and massive effluent volumes. This environmentally friendly technique improves wastewater management while simultaneously encouraging biomass production. The Food and Drug Administration (FDA) has categorised some of the algae as Generally recognised as safe foods and these are: *Chlamydomonas reinhardtii*, *Auxenochlorella prototothecoides*, *Dunaliella bardawil*, and *Euglena gracilis* (Torres-Tiji *et al*., 2020), *Schizochytrium* sp. (2021), *Chlorella* sp. (2020), *Dunaliella* sp. (2008), and *Spirulina* sp. (2002) (Torres-Tiji *et al*., 2020), (Parry Limited, 2012),(GRAS-Notice-GRN-1008-Use-of-Algal-Oil-from-Schizochytrium-Limacimum-TKD-1-with-Amendments_0). Algae are not only used as food and feed alternatives, but they are also used for biofuel production (Benemann, 2013), bio-energy production (Baicha *et al*., 2016), wastewater treatment (Nagarajan *et al*., 2020), increased crop Vigor (Thoré *et al*., 2023), cosmetic industry (Spolaore *et al*., 2006) and in the production of high-value molecules like fatty acids (Certik and Shimizu, 1999) and pigments (Becker, 2013). This paper discusses the nutritional benefits of microalgae, their use as animal feed, and addresses the challenges, future trends, and market developments associated with microalgae.

Habitat

Microalgae are photosynthetic organisms that require sunlight and carbon dioxide to thrive, but they can also be cultivated under controlled conditions that don't rely solely on photosynthesis. These adaptable organisms are ubiquitous and can be found in a wide range of environments including rivers, seas, lakes, and mountains (Dineshbabu *et al*., 2019) (Table 1). Their survival is limited by reduced light penetration in extremely foggy or deep ocean environments (Arsad *et al*., 2022). The optimal temperature for microalgal growth ranges between 25°C and 35°C (Chisti, 2007), and they require a neutral pH level (7-8) for better development (Yu *et al*., 2022). Microalgae can be cultivated commercially in lagoons, ponds, and less fertile lands. Incorporating plastic tubes into ponds has increased production efficiency several times compared to traditional pond cultivation. Some species, such as Spirulina sp. and Chlorella sp., are mostly found in freshwater (Sorrenti *et al*., 2021), while Dunaliella salina predominantly inhabits marine water (Oren, 2005). Nannochloropsis sp. and certain Chlorella sp. strains can survive in both freshwater and marine environments (Fithriani and Ambarwaty, 2019).

Table 1. Nutritional compositions of microalgae

Species	Nutritional composition			Vitamins	Minerals	Reference
	Fat (%)	Protein (%)	Carbohydrate (%)			
Acutodesmus dimorphus	18.8	28.1	38.6	A, B1, B2, B6, B12, C, E	-	(Tibbetts *et al.*, 2015)
Botryococcus braunii	34.4	39.9	18.5	-	Mg, Ca, P, K, Na, S	(Tibbetts *et al.*, 2015)
Chlorella vulgaris	14-22	51-59	12-17	A, C, E, K	Ca, Mg, K, Na, Zn	(Kusmayadi *et al.*, 2021; Lorenzo *et al.*, 2023)
Dunaliella sp.	3.49	36.2	59.4	-	-	(Bombo *et al.*, 2023; Rizwan *et al.*, 2022)
Haematococcus pluvialis	20-25	29-45	15-17	B1, B2, B6, B12, C, E	-	(Oslan *et al.*, 2021)
Isochrysis galbana	12-14	50-56	10-17	A, B1, B2, B3, B5, B6, B12, E	Ca, P	(Kumar *et al.*, 2023)
Nannochloropsis sp.	39	30	10	All, especially D3	Ca, K, Na, Mg, Zn, Fe, Mn, Cu, Ni, Co	(Torky *et al.*, 2023)
Scenedesmus quadricauda	12-14	8-56	10-18	B2, B3, B7, B12	Se, Ca	(Yukesh Kannah *et al.*, 2021)
Spirulina sp.	6-9	55-70	15-20	A, C, E	Zn, Fe, Mg	(Miklos *et al.*, 2011)
Tertraselmis sp.	7.04	31.2	18.1	A, C, E, B complexes	K, Ca, Mg, Na, P	(Pereira *et al.*, 2019)

Microalgae are observable on the water surface, even within the hundred micrometres of the water surface, and can also be found in the subsurface water column at depths of 200 to 300 metres (Singh and Saxena, 2015). Some microalgae confer advantages to their hosts; for instance, *Zooxanthellae* sp. live inside the tissues of corals, assisting in photosynthesis to provide nourishment and protection (Cheirsilp *et al.*, 2020). Various microalgae species are adaptable to diverse land environments, from challenging locations like city building walls (Rindi *et al.*, 2007), crusts in hot deserts (Flechtner, 2007), to Antarctic snow (Snow algae) (Soto-Sierra *et al.*, 2020; Broady, 1996), and even the atmosphere, where airborne microalgae—ranging from a few micrometres to 500 µm in size—are found (Sharma *et al.*, 2007). Some extremophile species demonstrate remarkable tolerance to high salinity (*Dunaliella salina*), pH extremes (*Dunaliella acidophila*), extreme cold (*Chloromonas nivalis* and *Raphidonema nivale*), and extreme heat (*Chlorella* sp.) (Borowitzka, 2018; Øverland *et al.*, 2019).

Wastewater as a substrate for the cultivation of microalgae

The world is currently facing pressing environmental concerns, including the need for sustainable waste utilisation and management, as well as the necessity to develop new energy sources which arise from environmental concerns such as climate change, pollution, resource scarcity and the challenges faced by inefficient waste management systems (Chiu *et al*., 2015). The scientific community has made significant strides in understanding the intricacies of microalgae cultivation in wastewater environments (Ummalyma *et al*., 2023). The three-step water treatment process (solid-liquid separation, horizontal anaerobic fermentation, and an activated sludge process in anaerobic treatment) can decrease the biochemical oxygen demand (BOD) and suspended solids (SS) (Rayen *et al*., 2019). Microalgae production systems are primarily categorized into open and closed cultivation systems, depending on the environmental control (Rayen *et al*., 2019). Open systems include natural or artificial ponds and raceway ponds exposed to sunlight, offering low capital and operating costs but limited control over growth parameters and vulnerability to contamination. Closed systems such as photobioreactors (flat-panel, tubular horizontal/ vertical, plastic bags) enclose the culture and allow for precise regulation of temperature, pH, light, and nutrients, leading to higher productivity and sterile environment at higher operational costs (Jerney and Spilling, 2020).

While photosynthesis remains the primary mode of growth for many microalgae, it is important to recognize alternative cultivation modes:

Heterotrophic cultivation: In this mode of cultivation, microalgae grow in absence of light by utilizing organic carbon sources such as glucose and acetate. This allows for biomass production in dark fermenters, overcoming limitations posed by light penetration and day- night cycles. Heterotrophic cultivation can achieve high cell densities and spatial requirements.

Mixotrophic cultivation: This combines heterotrophic metabolism and autotrophic photosynthesis, enabling microalgae to simultaneously utilize light and organic carbon sources. Mixotrophic growth often results in higher growth rates, greater biomass yields, and increased production of valuable compounds such as lipids.

Cultivating microalgae in wastewater helps by reducing COD and BOD, thereby improving the quality of the wastewater before being released into the environment (Costa *et al*., 2021). Open cultivation systems have advantages such as low capital, operating expenses, and maintenance costs (Jerney and Spilling, 2020). However, they also have downsides, such as poor cell density, being prone to contamination, less control over growth factors, and a low production ratio. In open raceway ponds, they typically range from 0.02 to 0.05 g L^1 day^1, corresponding to aerial yields of about 10–25 g m^2 day^1. In contrast, closed photobioreactors can sustain volumetric productivities of 0.10–0.30 g L^1 day^1, with areal outputs climbing to 30–60 g m^2 day^1. As an alternative, closed farming techniques provide better control and higher productivity (Kumar *et al*., 2019). Due to the high cost and complexity of closed culture methods, open raceway ponds are frequently used for commercial microalgal production (Daneshvar *et al*., 2019). Open ponds are cost-effective and suitable for large-scale cultivation, but are more susceptible to contamination and environmental

variations. (Rawat *et al*., 2011). Conversely, photobioreactors will provide controlled conditions, enhance productivity and allow for the cultivation of monocultures, but they require higher operational costs (Borowitzka, 1999). Cultivation of microalgae on a large scale requires a large amount of nutrients and water (Costa *et al*., 2021). A recent study showed that water is a valuable resource which can't be wasted (Chew *et al*., 2018). A sustainable solution to this issue would be replacing the synthetic medium with nutrient-rich effluents/solid waste (Kumar *et al*., 2019). Cultivating microalgae on waste materials is known for bioremediation of toxins, thus helping to reduce environmental concerns regarding water and soil contamination (Ghosh and Kiran, 2017). The types of wastewater can be split into domestic, leachate, agricultural, refinery, and industrial (Gonçalves *et al*., 2017).

Cultivation of microalgae through food and agriculture-based industrial effluents

Industrial effluents originate from various sectors like agro-industrial industries, especially food and beverage (Markou and Georgakakis, 2011). Species like *Chlamydomonas reinhardtii*, *Scenedesmus obliquus, Chlorella vulgaris, Dunaliella salina*, and *Nannochloropsis oculata* can withstand varying levels of salinity, organic loads, and heavy metal stress while maintaining productivity (Christenson and Sims, 2011). These strains have been shown to utilise nutrients effectively (Mallick, 2002) and mitigate toxic substances like ammonia and sulphates through biosorption and bioaccumulation mechanisms (Singh and Gu, 2010). The cultivation of microalgae in industrial effluents relies on optimising growth parameters such as photoperiod, light intensity, aeration, and temperature, all of which affect photosynthetic efficiency and nutrient uptake rates (Griffiths and Harrison, 2009). By deliberately imposing nitrogen limitation in a two-stage process—first growing cells under nitrogen-replete conditions to build biomass, then reducing nitrogen supply—many strains reroute excess fixed carbon into storage lipids. This can raise triacylglycerol content from 20–30 % up to 50–80 % of dry weight without drastically cutting overall lipid productivity once high cell densities are reached. Effluents from the food processing industry contain high concentrations of phosphorus, carbon, and nitrogen (Kumar et al., 2020). The wastewaters outlined exhibit similar organic content, although variations exist in their inorganic components. Notably, approximately 75% of the organic carbon in effluent is made of carbohydrates, fats, proteins, amino acids, and volatile fatty acids (Makowska and Sowinska, 2020). The inorganic constituents include significant concentrations of sodium, calcium, potassium, magnesium, chlorine, sulphur, phosphate, bicarbonate, ammonium salts, and heavy metals. Dairy effluent is a commonly used industrial waste for microalgal cultivation, providing organic and inorganic nutrients essential for growth (Figure 1). Other than this, the effluent released from the palm oil manufacturing unit is also packed with nitrogen, which makes it a good medium for cultivation (Cheah *et al*., 2016).
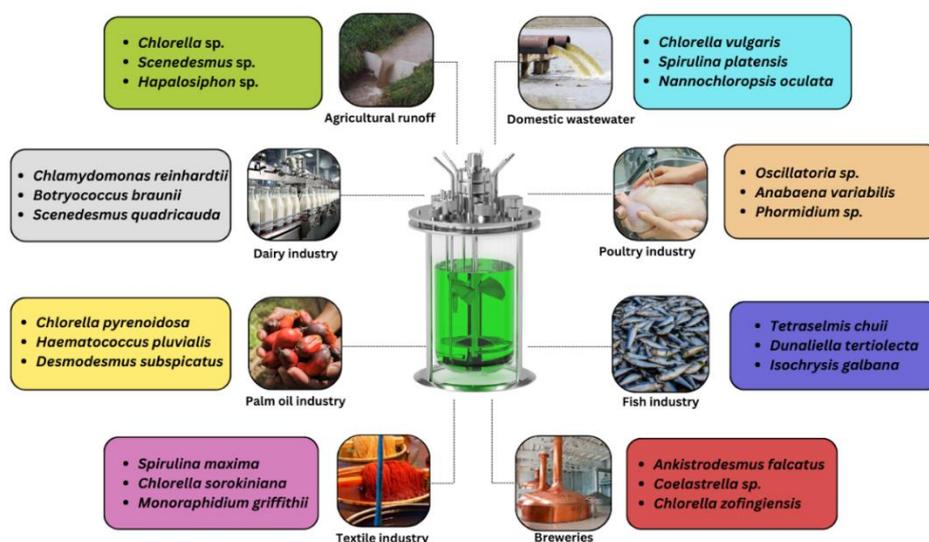
Figure 1. Cultivation of microalgae using different industrial effluents

Chlorella emersonii and *Ankistrodesmus falcatus* are some freshwater microalgae, where wastewater can be used as an alternative medium for cultivation (Chew *et al*., 2018). One of the most commonly cultivated strains in wastewater is *Scenedesmus obliquus*, known for its high CO_2 tolerance (Posadas *et al*., 2017). The harvested biphotoperiod biomass of algae contains a high concentration of proteins, carbohydrates, and lipids, and serves as a versatile feedstock in various aspects (Chisti, 2007). Microalgae contain rich polyunsaturated fatty acids, chlorophylls, carotenoids, and phycobilin substances. Hence, biomass can be used in multiple fields such as food supplements, animal feed, and to produce energy (Chiu *et al*., 2015). Lipid extracted from microalgal biomass can be utilised as a sustainable alternative to fossil fuels, and the lipid-extracted residual biomass can be used as a high-protein animal feed and even as a fertiliser (Becker, 2007). Despite these advantages, challenges remain in scaling up due to factors such as high-water evaporation rates in open ponds, contamination by other microbes and the energy-intensive processes (Singh and Gu, 2010). Furthermore, the co-cultivation of microalgae with other microorganisms, such as bacteria in symbiotic systems, has shown potential for high pollutant removal rates and promotes bioflocculation, thereby simplifying the biomass harvesting (Christenson and Sims, 2011).

Algal remediation process

Microalgae have been shown to effectively remove nutrients, such as inorganic nitrogen and phosphorus, from different sources of wastewater, like municipal, industrial and agricultural effluents. (Tan *et al*., 2014). Though sewerage has the potential to be an alternative natural medium for cultivation, it is not suitable for every strain of algae. (Grau and Klein, 1957). These effluents are often nutrient-rich, but they may have a notable number of toxic substances such as heavy metals, organic pollutants, and high salinity, posing challenges for cultivation and having

deleterious effects on aquatic ecosystems when discharged untreated. (Wang *et al*., 2021). Raw sewage contains multiple pathogens and dissolved toxins which impede algal development and generate biosafety issues. To change these effluents into a dependable cultivation medium, a complete pre-treatment is required. The multi-barrier system begins with physical screening and sedimentation before microfiltration and then biological treatment processes, including anaerobic/anoxic/oxic or A_2O systems, achieve 1.5–2.0 log_{10} pathogen removal. Research shows that membrane bioreactors (MBRs) help reduce bacterial and viral loads by 3.0–5.0 log_{10} when used together with other treatment methods. *(*Wang *et al*., 2021). Sometimes, wastewater contains pathogens and inhibitory substances, which will result in counter-productivity; hence, the proper selection of strain and medium is necessary to get the desired result. (Moed *et al*., 2015). The cultivation of microalgae also removes heavy metals and xenobiotic substances. (Ding *et al*., 2015). The cultivation of microalgae in nitrogen wastewater can effectively reduce the concentration of pollutants, increase O_2 concentration, produce certain compounds based on the biochemical composition of biomass and uptake CO_2 (Daneshvar *et al*., 2019). The ability of microalgae to absorb nutrients in wastewater and the simultaneous generation of value-added products make the effluent a potential medium for biomass production at a reduced cost. This nutrient removal process not only enhances the quality of the discharged effluent but also provides a valuable feedstock for the production of biofuels, biofertilizers, and other high-value bioproducts. (Abinandan *et al*., 2018).

Specific pre-treatment of these effluents is advised to enhance productivity and variability (Razzak *et al*., 2013). For instance, removing suspended solids and other floating matter through filtration and sedimentation prevents shading effects and promotes growth (Markou and Georgakakis, 2011). The inorganic CO_2 is either directly dissolved or supplied externally to aid their photosynthetic activity, contributing to carbon sequestration and mitigating greenhouse gas emissions (Singh and Gu, 2010). The ability of microalgae to grow in high concentrations of CO_2 makes them particularly advantageous for coupling with flue gas from industrial sources, making a synergistic system for carbon capture and utilisation (Brennan and Owende, 2010). Studies have shown that the nitrogen and phosphorus removal efficiencies exceed 90% under optimal conditions, attributed to their rapid uptake and incorporation into cellular biomass (Woertz *et al*., 2009; Posadas *et al*., 2017).

Nutritional composition and bioactive compounds

Microalgae are typically composed of carbohydrates (range- 12 to 30%), protein (range – 50 to 70% of dry weight) and lipid (range – 30 to 70% of dry weight) (Adarme-Vega *et al*., 2012; Mosibo *et al*., 2024). According to the species, the nutrient composition may also vary. (Becker, 2007; Timira *et al*., 2022; Mosibo *et al*., 2024) Higher essential amino acid indices (0.9–1.2) indicated that high concentrations of arginine, tryptophan, leucine, and lysine are found in the microalgae. (Becker, 2007; Tibbetts *et al*., 2015; Mosibo *et al*., 2024). Becker et al. (2013) found that microalgae consist of abundant vitamins such as A, B1, B2, B6,

B12, C, and E, as well as minerals like potassium, iron, magnesium, calcium, and iodine. The high concentration of vitamins and minerals (iron, magnesium, calcium, and other minerals) supported several metabolic processes. (Tibbetts *et al*., 2015; Koyande *et al*., 2019; Mosibo *et al*., 2024) (Table 2).

Table 2. Bioactive components of microalgae

Species	Habitat	Bioactives	Reference
Aphanizomenon flosapuae	Freshwater algae	Phenylethylamine Pigments (Carotene, Beta-carotene and Chlorophylls)	(Nuzzo *et al*., 2019)
Botryococcus braunii	Freshwater algae	Hydrocarbons Biolipids antioxidants	(Cheng *et al*., 2019)
Chlorella sp.	Freshwater algae	PUFAs Polysaccharides Pigments (Chlorophylls, Carotenoids, Lutein) Phenolic compounds	(Lorenzo *et al*., 2023)
Dunaliella salina	Marine algae	Carotenoids Antioxidants Apigenin	(Hyrslova *et al*., 2022)
Haematococcus pluvialis	Freshwater algae	Astaxanthin Carotenoids Fatty acids	(Oslan *et al*., 2021)
Isochrysis galbana	Marine algae	Peptides Carotenoid fucoxanthin Bioactive lipids	(Bonfanti *et al*., 2018)
Nannochloropsis sp.	Freshwater algae / Marine algae	Tocotrienols Pigments (Chlorophyll-a, Zeaxanthin, Canthaxanthin, Astaxanthin and Violaxanthin)	(Fithriani and Ambarwaty, 2019)
Navicula sp.	Freshwater algae / Marine algae	Polysaccharides Antioxidants	(Fimbres-Olivarria *et al*., 2018)
Scenedesmus sp.	Freshwater algae	Polyunsaturated fats (PUFAs) Polysaccharides Pigments (Carotenoids, Chlorophyll, phycobiliproteins)	(Ishaq *et al*., 2016)
Spirulina sp.	Freshwater algae / Marine algae	Carotenoids Bioactive Peptides Bioactive lipids Phenolic compounds	(Bortolini, 2022)

According to Torres-Tiji *et al*. (2020), microalgae in the feed industry can be categorised into two groups. The dried biomass of microalgae (like *Spirulina* sp. and *Chlorella* sp.) was the first group. The second category comprises specialty products that are extracted or isolated from microalgae and can be incorporated into feed to enhance their nutritional content (Torres-Tiji *et al*., 2020). The growth and development of microalgae depend on essential elements such as phosphorus and nitrogen (Singh and Gu, 2010). Among these, nitrogen plays a critical role not only in growth but also in determining the biochemical composition of the cells. When

nitrogen is abundant, microalgae prioritize protein synthesis and cell division. However, under nitrogen limitation, a well-documented metabolic shift occurs, wherein microalgal cells divert their resources from growth-associated processes toward the synthesis and accumulation of storage lipids, mainly triacylglycerols (TAGs). This nitrogen limitation or starvation triggers an adaptive response that results in increased lipid content, often doubling or tripling the percentage of lipids relative to dry cell weight, depending on the strain (*e.g*., *Chlorella vulgaris*, *Nannochloropsis* sp., *Scenedesmus* spp.). The accumulation of neutral lipids serves as an energy reserve during unfavorable conditions. This characteristic has been harnessed as a controlled cultivation strategy, where an initial biomass growth phase under nitrogen-replete conditions is followed by a nitrogen-deprivation phase to maximize lipid accumulation. While nitrogen starvation reduces overall biomass productivity due to restricted cell division, this trade-off is optimized in industrial applications by manipulating the timing and extent of nitrogen limitation to maximize the total lipid yield per cultivation cycle. Morphologically, cells under nitrogen stress display increased size and numerous lipid droplets, and biochemically, pigments and proteins decrease as the carbon flux is redirected. Moreover, the levels of nutrients present in the living environment of microalgae—whether aquatic, terrestrial, on walls, or in other areas — will also influence their growth. High concentrations of the neurotrophic and anti-allergic ω-3 fatty acids, Docosahexaenoic acid and Eicosapentaenoic acid, are found in some microalgae, especially in diatoms and Prymnesiophytes, which are associated with enhanced heart function, digestive system, and immune health (Tibbetts *et al*., 2015; Nicoletti, 2016).

The bioactive compounds of microalgae have demonstrated positive effects when consumed by animals as part of their feed. (Balasubramaniam *et al*., 2021). *Spirulina* sp., a widely utilised microalga in the feed industry, contains rich carotenoids, bioactive peptides, bioactive lipids, and phenolic compounds, and also has high nutritional value. (Bortolini, 2022) Bioactive lipids in the microalgae used in the bovine diets improve the flavour of milk and increase its fat content. (Becker, 2013). *Isochrysis galbana* contains carotenoid fucoxanthin, peptides, and bioactive lipids such as DHA and EPA, which are known for their anti-inflammatory properties. (Bonfanti *et al*., 2018). Tannins found in *Nannochloropsis oculata* exhibited anti-hypercholesterolemic properties, effectively contributing to the reduction of cholesterol levels in the intestine. (Fithriani and Ambarwaty, 2019). *Haematococcus pluvialis* is considered to be a rich source of astaxanthin and lutein. (Mularczyk *et al*., 2020) which is utilised in the feed industry due to its antioxidant properties (Oslan *et al*., 2021). Polysaccharides with diverse structural characteristics derived from *Chlorella* sp. and other microalgae exhibited a wide range of biological activities, including immunomodulatory, antioxidant, hypolipidemic, antitumor, and anti-asthmatic properties. (Lorenzo *et al*., 2023). *Aphanizomenon flosapuae* contains natural bioactive compounds, *i.e.* Klamin®, which act as neuroprotective and neuro-regenerative agents. (Nuzzo *et al*., 2018). Among the compounds, the microalgae pigments such as astaxanthin, β-carotene, lutein, violaxanthin, and fucoxanthin have been commercialised and used as nutraceuticals, cosmetics supplements, and dietary supplements. (Loy and Chu, 2012; Becker, 2013; Balasubramaniam *et al*., 2021).

Microalgae as animal feed

Microalgal biomass is used to supplement livestock diets, providing numerous benefits. (Holman and Malau-Aduli, 2013). The demand for dairy and meat products from animals is expected to increase by 48-60% within a year. (Alexandratos and Bruinsma, 2012). By 2050, fish production will nearly triple and poultry and cattle meat production will double. (Parisi *et al*., 2020). The amount of feed available will surpass 1.3 billion tonnes due to increased cattle production. Microalgal species like *Pavlova* sp., *Isochrysis* sp., *Spirulina* sp., *Chlorella* sp., *Tetraselmis* sp., *Navicula* sp., *Nannochloropsis* sp., *Nitzschia* sp., *Scenedesmus* sp., *Chaetoceros* sp., *and Crypthecodinium* sp. (Hemaiswarya *et al*., 2011) (Table 3) can be safely substituted for conventional proteins in poultry rations (Spolaore *et al*., 2006).

Table 3. Details of the microalgae used as a feed

Animals	Details of the microalgae used as feed	Health benefits	References
Cattles	*Chlorella* sp. *Spirulina* sp.	Favourably impact overall animal physiology, growth, health, and both the number and quality of the products produced.	(Doreau and Chilliard, 1997)
Fish	*Nannochloropsis* sp. *Tetraselmi* sp. *Isochrysis* sp. *Haematococcus* sp.	Stimulate the production of functional growth hormone.	(Kiron, 2012)
Pigs	*Spirulina* sp. *Chlorella* sp.	Increase the growth rate up to 9% in crossbreeds.	(Gatlin *et al*., 2007)
Poultry	*Spirulina* sp. *Chlorella* sp. *Dunaliella* sp.	Increase fertility in birds, simulate breeding, produce brighter plumage, raise resistance to disease, and increase intestinal tract flora.	(Becker, 2013)
Shrimp	*Tetraselmis* sp. *Isochrysis* sp. *Nannochloropsis* sp. *Phaeodactylum* sp.	High nutritional supplement.	(Shah *et al*., 2018)

Algal biomass is an effective supplement or replacement for conventional protein sources. (Becker, 2013), with approximately 30% of the algae produced today being used as fodder for animals (Garcia-Moscoso *et al*., 2015).

Cattle feed

Microalgae such as *Chlorella* sp., *Scenedesmus* sp., and *Arthrospira* sp. can boost immunity and improve the quality of meat and milk when incorporated into conventional feed. Microalgae help cattle to gain weight and produce fewer methane emissions, which are both good for sustainability. (Torres-Tiji et al., 2020; Nagarajan *et al*., 2021). The composition of ω-3 fatty acids in the milk from Holstein cows was observed to increase without negatively impacting the milk fat content. (Udayan *et al*., 2021). Dineshbabu *et al*. (2019) reported that feed supplementation with rumen-protected microalgae resulted in higher levels of linolenic acid and DHA.

Dehydrogenation of microalgae within the rumen of animals can be prevented by encapsulating them with lipids. (Dineshbabu *et al*., 2019). Consumption of microalgae-enriched rapeseed feed by lactating cows increased milk lactose, protein, and caloric content, as well as overall milk production.(Lamminen *et al*., 2017). Tropical grasses supplemented with *Spirulina platensis* and *Chlorella pyrenoidosa* increased the amount of branched fatty acids and microbial protein in the rumen of Zebu cattle (*Bos indicus*) (Costa *et al*., 2016). *Dunaliella tertiolecta-based* sheep's feed exhibited anti-inflammatory properties. (Rizwan *et al*., 2022). Regular feed consumption in cattle and other bovines can be significantly reduced by the incorporation of microalgae. (Lum *et al*., 2013). Cows fed with *Spirulina* sp. produce 7.6% more milk than cows fed with a control diet and increase the milk fat content (17.6-25%), milk protein (9.7%), and lactose (11.7%) (Becker, 2013).

Adding small quantities of microalgal biomass to feed improves gut function, disease tolerance, and antiviral/antibacterial action (Hayes *et al*., 2017). This leads to improved animal development, feed conversion ratio, weight, and reproductive performance (Siddiki *et al*., 2022). The antioxidant properties of microalgae, particularly those high in carotenoids, help the body combat free radicals.

Poultry feed

Algal supplementation improved weight in chickens and reduced feed intake. (Dineshbabu *et al*., 2019). Studies reported that *Chlorella* sp., *Spirulina* sp., *Dunaliella* sp., *Porphyridium* sp., *Scenedesmus* sp., *Desmodesmus* sp., *Nannochloropsis* sp., *Staurosira* sp., and *Oocystis* sp. based feeds improved the egg and meat quality. (Hayes *et al*., 2017; Saadaoui *et al*., 2021; Alghamdi *et al*., 2024). Adding microalgae to chicken feed is an effective way to improve nutrition than using other protein sources. (Abd El-Hack *et al*., 2023). In washout periods, the DHA and EPA content of the eggs increased as the chicken was fed *Nannochloropsis gaditana* at 5% and 10% concentrations. (Bruneel *et al*., 2013; Wu *et al*., 2019). There was a slight increase in protein synthesis in the muscles and liver of broiler chickens while fed with the green microalgae *Nannochloropsis oceanica* (Abd El-Hack *et al*., 2023).

These microalgae incorporated in the animal feed help to improve the colour of flesh, skin, feathers, or egg yolks, thereby enhancing the visual appeal of animal products. (Østerlie *et al*., 2000). The essential fatty acid, micronutrient profiles and other potential molecules of microalgae may benefit the animals' reproductive health (Table 4). This may result in enhancements in hatchability, fertility, and overall reproductive success (Swati *et al*., 2022).

The gut microbiota may be enhanced by the addition of microalgae to animal feed, which will protect the animal from dysbiosis. This could lead to a healthier digestive system and a favourable shift in the composition of the gut microbiota. (Ringø and Gatesoupe, 1998).

Poultry feed with microalgae has several advantages over traditional poultry feed, including increased disease resistance, decreased cholesterol levels, and improved yolk colour. (Hayes *et al*., 2017). Chicks fed with *Spirulina platensis* exhibited

bigger spleen and thymus with lesser microbial infection in their compartments, indicating its favourable influence on the immune system. (Becker, 2013)

Table 4. Health benefits of microalgae

Species	Used as	Benefits	Reference
Aphanizomenon flosapuae	Supplement	Helps in preventing neurodegenerative disease. Has anti-ageing and anti-obesity factors	(Nuzzo *et al*., 2018)
Botryococcus braunii	Supplement	Makes a lot of polysaccharides, since these can aid in fortifying the cell wall.	(Blifernez-Klassen *et al*., 2018)
C.zofingiensis	Supplement	Rich in astaxanthin - good for animal health.	(Liu *et al*., 2014)
Chlorella vulgaris	Feed and Supplement	Contains lutein, astaxanthin, canthaxanthin, β-carotene Supplementation (1%) may decrease diarrhoea incidence and encourage intestinal development, Treats mild digestive disorders in weaning pigs.	(Abreu *et al*., 2023)
Dunaliella salina	Feed and Supplement	β-carotene and extracellular polysaccharides Immunostimulant, antiviral, and antitumor properties.	(Alghamdi *et al*., 2024)
Haematococcus pluvialis	Feed and Supplement	Anti-diabetic Anti-inflammatory Antioxidants	(Oslan *et al*., 2021)
Nannochloropsis sp.	Feed	Reduces the cholesterol level. Anti-melanogenic Anti-wrinkling	(Kim *et al*., 2021)
Navicula sp.	Feed and Supplement	Provides high-quality protein, carbohydrates, and lipids.	(da Silva *et al*., 2021)
Scenedesmus sp.	Supplement	Enhances the fillet's nutritional quality by raising its levels of n-3 PUFA, particularly DHA.	(Skalli *et al*., 2020)
Spirulina sp.	Feed and Supplement	Acts as a prebiotic	(Holman and Malau-Aduli, 2013; Nagarajan *et al*., 2021

Aquaculture feed

The increasing popularity of aquaculture has led to a depletion of wild fisheries resources in recent times. (Han *et al*., 2019). The identification of suitable feed sources for the growing number of aquatic animals that will be farmed in the future is a significant concern. Live prey remains the primary food source for aquatic

animals, but the scarcity of intensive breeding technology to produce live prey from natural growth in ponds and wild capture makes the supply unreliable, often leading to larval breeding failure. The incorporation of microalgae into the diets of aquaculture has the potential to bolster their antioxidant defences, thereby mitigating oxidative stress and promoting general health. (Fabregas and Herrero, 1990). The β-carotene and violaxanthin produced by *Haematococcus pluvialis* and *Dunaliella salina* have high antioxidant potential and anti-inflammatory properties, respectively.(Alghamdi *et al*., 2024; Hyrslova *et al*., 2022). Astaxanthin has powerful biological antioxidant, anti-diabetic, anti-cancer, and anti-inflammatory properties. (Dufossé *et al*., 2005; Mularczyk *et al*., 2020).

Microalgae include biologically active compounds such as ω-3 long-chain PUFAs, pigments, polysaccharides, and vitamins, making them sustainable aquafeed additives. (Ma and Hu, 2024). Microalgae feed in aquaculture provide fish with nourishment and colour, and enhance their biological activities. (Dineshbabu et al., 2019). The most utilised species in the aquaculture include *Chlorella* sp., *Tetraselmis* sp., *Isochrysis* sp., *Pavlova* sp., *Phaeodactylum* sp., *Chaetoceros* sp., *Nannochloropsis* sp., *Skeletonema* sp., and *Thalassiosira* sp. (Dineshbabu *et al*., 2019; Hemaiswarya *et al*., 2011; Madeira *et al*., 2017). The combination of microalgal strains resulted in a more balanced nutritional profile and enhanced animal growth as compared to the single-species diet. (Spolaore *et al*., 2006).

Market trends

Food and feed products from microalgae are still less popular and have a lower market and production volume than those made from other sources, such as commodity crops or cereals (Vigani *et al*., 2015). The global microalgae market was valued at USD 12.8 billion in 2024 and is projected to reach nearly USD 27.5 billion by 2034, reflecting a compound annual growth rate (CAGR) of approximately 7.95%. Another industry source (Eilam *et al*., 2023) estimates that market revenues could rise from USD 11.8 billion in 2023 up to USD 25.4 billion by 2033 with a similar growth rate. If the scaling of biomass output mirrors growth in market revenue, production could increase from the current 35,000 tonnes per year to over 60,000 tonnes annually by 2033. These figures highlight robust expansion and future potential for microalgae in food and feed applications. Microalgae harbour significant potential as a sustainable supply of food for both humans and animals. On the other hand, global demand and acceptance for food and feed products derived from microalgae are increasing, according to market trends (Eilam *et al*., 2023). However, obstacles like production processes, cultivation costs, and adaptation need to be addressed shortly (Enzing *et al*., 2014). UN-Comtrade data, from 2010 to 2012, indicated that China, Indonesia, and South Korea were the top three algae exporters worldwide, exporting over 125 million dollars of algae-based products. All these countries have a long tradition in the production and incorporation of microalgae into food and feed (Vigani *et al*., 2015). Incorporating microalgae into animal feed enhances the nutritional profile of the product, elevating the overall quality of animal feed (Tibbetts *et al*., 2015). The aquaculture industry is particularly interested in

incorporating microalgae into fish and prawn feeds to improve the nutritional profiles and colour of the final products (Brown and Jeffrey, 1992). With the increased demand for fatty acids from animal products, researchers are looking into microalgae-derived oils as a sustainable alternative to traditional fish oil in aquafeed. Safi *et al*. (2013) stated that many industries focused on optimising microalgae strains for specific animal species, as well as improving cultivation and processing methods for commercial-scale production (Safi *et al*., 2013). Especially in the animal feed industry, microalgae are gaining favour due to their elevated nutritional content and their potential to replace conventional protein sources like fishmeal (Sarker *et al*., 2016). Ishika *et al*. (2017) stated that concentrating on refining methods and broadening product applications is the way forward to increasing the market (Ishika *et al*., 2017).

Challenges and future perspectives

Careful consideration is needed in microalgae cultivation issues like energy consumption, potential ecological disruptions, and the use of water and land. For a more concrete perspective, estimates from multiple studies indicate that producing one kilogram of dry microalgal biomass usually requires between 400 and 3,000 liters of water. Energy input can range from around 15 to 50 megajoules (MJ) per kilogram—this is higher for closed photobioreactors but lower in open pond systems. Regarding land, typical open pond operations need about 15–25 square meters for one-kilogram annual yield, whereas advanced photobioreactor setups can produce this amount using less than 10 square meters. These figures make it clear that, while microalgae can sometimes be more resource-efficient than terrestrial crops—especially if non-arable land or wastewater is used—it remains crucial to optimize management practices and improve system efficiencies to minimize the overall environmental footprint. In microalgae-based feed formulations, the safety of biomass, economic feasibility, and harvesting techniques-related issues have to be resolved (Wang *et al*., 2013). Only limited microalgal strains are used in animal feed formulations, and large-scale harvesting also has some real-world drawbacks. Furthermore, cost-effectiveness is a significant challenge in the production of microalgae-based animal feed. The overall processing cost made it impractical to be used as a successful commercial animal feed. In the animal feed industry, ensuring scalability is essential to make microalgae economically viable (Milledge and Harvey, 2016). The differences in dietary composition could make it difficult to satisfy the unique dietary needs of various animal species (Becker, 2013)**.** The acceptance of microalgae-based feed by animals is largely dependent on its palatability. Certain microalgae species possess strong or atypical organoleptic characteristics—such as distinct flavors and odors—that can negatively impact the palatability of feed, potentially reducing feed consumption or acceptance in some animals (Siddiki *et al*., 2022). Optimising the microalgal feed formulations for specific animals is very challenging, and the market range is limited.

PUFA-rich feed can affect the flavour of the milk and the meat. (Shingfield *et al*., 2008) And the digestion is heavily affected by the high fibre and polysaccharide content present in *Tetraselmis* sp. (Saadaoui *et al.,* 2021). While microalgae

cultivation is frequently seen as eco-friendly because of its carbon dioxide capture capability, it is important to conduct a comprehensive assessment of the environmental effects of large-scale cultivation to further enhance its sustainability. Technological challenges arise in the effective extraction of valuable components, like proteins, lipids, vitamins, and bioactives from microalgae. The development of sustainable and affordable extraction techniques that maintain the nutritional integrity of microalgae is essential for the successful integration of these algae into animal feed. (Chen *et al*., 2011). Furthermore, microalgal cultures cultivated in open systems may be contaminated during the culturing process through invading pathogens, which can affect aquatic life. (Shah *et al*., 2016).

Conclusions

Microalgae offer a highly promising alternative for sustainable animal feed, thanks to their rich nutritional makeup, including essential amino acids, omega-3 fatty acids, vitamins, and minerals. Using wastewater and industrial effluents as cultivation substrates not only reduces environmental strain but also repurposes nutrient loads that would otherwise harm ecosystems. However, the high costs associated with energy-intensive cultivation and harvesting technologies remain a major barrier to widespread adoption. Making microalgal feed economically viable will require improvements in strain selection, streamlined growing methods, and integrated biorefinery processes. Regulatory clarity and thorough safety evaluations are also essential to ensure compliance with stringent animal nutrition standards. Moreover, it is vital to critically assess the full environmental footprint using life cycle analysis to confirm long-term benefits over conventional feed systems. In essence, while microalgae show immense potential, meaningful progress hinges on coordinated innovation, investment, and policy support.

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