# A REVIEW: MACROALGAE IN ANIMAL AND AQUAFEED FOR ENHANCING GROWTH PERFORMANCE AND PRODUCT QUALITY

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**Abstract**

Macroalgae have emerged as promising functional ingredients in animals and aquafeed due to their rich nutritional composition and diverse bioactive compounds. This review synthesizes recent advances on the utilization of green, brown, and red macroalgae as feed ingredients, highlighting their roles from raw biomass through processing and formulation to biological effects and final product quality. Proper processing methods, including drying, milling, and enzymatic or fermentation treatments, are essential to improve digestibility, bioavailability, and feed safety, enabling effective incorporation into formulated feeds. Macroalgae supplementation has been shown to enhance growth performance and feed efficiency in both aquaculture species and terrestrial livestock. Reported benefits include improved feed conversion ratios, enhanced gut health, increased antioxidant capacity, and reduced energy losses, particularly in ruminant systems. These physiological improvements underpin the observed gains in productivity and support the use of macroalgae as sustainable alternatives or complements to conventional feed ingredients. Future perspectives emphasize the development of biorefinery approaches, fermented and enzyme-treated seaweed feeds, and integrated multi-trophic aquaculture systems within a circular bioeconomy framework. Overall, optimized macroalgae utilization represents a viable strategy to sustainably enhance growth performance, feed efficiency, and final product quality in animal and aquafeed systems.

**Keywords:** Macroalgae, feed, nutrient, bioactive, quality, growth

## Introduction

The global expansion of animal protein production faces a fundamental sustainability challenge. As human populations grow and incomes rise, demand for meat, eggs, and fish continues to climb, placing unprecedented pressure on feed supply chains (FAO, 2020) [10]. Conventional protein sources, such as particularly fishmeal and soybean meal are increasingly recognized as environmentally problematic. Fishmeal production contributes to the overexploitation of marine fish stocks, while soybean cultivation drives deforestation and land use change in critical ecosystems (Cottrell *et al*., 2020) [9]. Beyond environmental concerns, these ingredients are subject to price volatility and supply constraints that threaten the economic stability of animal production systems worldwide.

In response to these challenges, researchers and industry stakeholders have intensified their search for alternative feed ingredients that can reduce dependency on conventional sources while maintaining or enhancing animal performance. Marine algae have emerged as particularly promising candidates. Unlike terrestrial crops, algae can be cultivated without competing for arable land or freshwater resources. Many species grow rapidly, require minimal inputs, and can even provide ecosystem services such as nutrient bioremediation in integrated aquaculture systems (Chopin & Tacon, 2021) [4]. These characteristics position algae as key components of circular bioeconomy approaches to animal nutrition.

Beyond their sustainability credentials, algae offer unique functional properties that distinguish them from conventional feed ingredients. Macroalgae and microalgae are biochemically complex, containing not only valuable macronutrients but also diverse bioactive compounds with demonstrated health-promoting effects. These include sulfated polysaccharides such as fucoidans, carrageenan, and laminarin; pigments include fucoxanthin, astaxanthin, and β-carotene; polyphenolic compounds including phlorotannins; and long-chain omega-3 polyunsaturated fatty acids (PUFAs), particularly Eicosapentaenoic (EPA) and Docosahexaenoic (DHA) (Holdt & Kraan, 2011; Mota *et al.*, 2023) [11, 19]. These bioactive molecules exhibit antioxidant, anti-inflammatory, antimicrobial, and immunomodulatory properties that can translate into tangible benefits for animal health and performance.

Macroalgae bioactive can modulate gut microbiota composition, strengthen intestinal barrier function, and enhance innate immune responses, potentially reducing disease incidence and the need for antibiotic interventions (Wan *et al.*, 2019; Peixoto *et al.*, 2021) [21, 28]. These prophylactic effects are particularly valuable in in intensive production systems where disease pressure is high. Moreover, the unique fatty acid profiles and pigment content of algae enable the production of nutritionally enhanced animal products—omega-3-enriched meat and eggs, naturally pigmented fish fillets, and antioxidant-rich dairy products—that meet growing consumer demand for functional foods (Valente *et al.*, 2019; Kulshreshtha *et al.*, 2020) [13, 27].

A substantial body of research now demonstrates that algal supplementation can improve key production metrics including growth rates, feed conversion efficiency, and final product quality across diverse animal species. Studies in aquaculture, poultry, swine, and ruminant systems have documented benefits ranging from enhanced weight gain and improved carcass characteristics to elevated antioxidant status and modified product composition (Makkar *et al.*, 2019; Michalak & Mahrose, 2020) [16, 17]. However, the magnitude and direction of these effects vary considerably

ending on the specific algal species used, the inclusion level, the processing methods applied, and the target animal species and production stage.

Ultimately, the value proposition of macroalgae extends beyond the farm gate, influencing the quality and marketability of the final product for consumers. Dietary seaweed supplementation has been shown to positively alter the physicochemical and nutritional characteristics of meat, milk, eggs, and fish fillets. Documented effects include the modulation of lipid profiles for increasing the concentration of beneficial long-chain omega-3 fatty acids, enhancing the oxidative stability of products during storage, and enriching them with natural pigments, vitamins, and essential minerals (Circuncisão *et al.*, 2018; Šimat *et al.*, 2020) [5, 25]. This mini review, therefore, synthesizes contemporary evidence to critically evaluate the multifaceted role of macroalgae in animals and aquafeeds, specifically focusing on their capacity to enhance growth performance, underpin animal health and welfare, and improve the quality of derived products, positioning them as a cornerstone for the future of sustainable and value-added feed innovation.

This review synthesizes current knowledge on the utilization of macroalgae and microalgae in animals and aquafeeds. This paper focuses on nutritional composition and bioactive profiles of key algal species, evaluate processing technologies that enhance nutrient bioavailability, assess effects on growth performance and product quality across different animal production systems, and identify remaining challenges and future research priorities. The aim is to provide a comprehensive, evidence-based assessment of how algae can contribute to more sustainable, productive, and health-promoting animal nutrition systems.

## Methodology

A comprehensive search for this review was conducted using a systematic yet narrative approach, which integrates the rigorous, replicable structure of a systematic review with the broader thematic synthesis characteristic of a traditional narrative review. The process began with a structured search across three major scientific databases such as, Scopus, Web of Science, and Google Scholar, using a defined set of keyword combinations. These included core terms such as "macroalgae", "nutrition", "bioactive compound", "animal feed", "aquafeed", "growth performance", and "product quality", linked with Boolean operators. The search was deliberately not restricted by a rigid, allowing for greater flexibility in identifying seminal works and emerging trends. However, systematic elements were maintained through explicit inclusion criteria, targeting peer-reviewed articles published between 2018 and 2024 that reported experimental data on macroalgae as a dietary intervention and its measurable effects on growth metrics or product quality parameters in livestock or aquaculture species.

This methodological framework progressed through three key, iterative stages to ensure depth and relevance. First, an initial screening of titles and abstracts was performed to assess the fundamental relevance of each study to the core themes of macroalgal application in animal nutrition. Subsequently, a full-text examination was conducted to confirm that each selected article provided specific, quantitative data on the defined outcomes, such as weight gain, feed efficiency, or analytical measures of product quality (e.g., fatty acid profile, oxidative stability). Finally, data were extracted and synthesized thematically rather than quantitatively, organizing the evidence into coherent narratives around mechanisms of action, species-specific responses, and the interplay between animal health and final product attributes. This hybrid approach ensures the review is both methodologically sound, avoiding arbitrary selection, and sufficiently expansive to provide a critical, integrative synthesis of the current state of knowledge, thereby effectively bridging the gap between focused systematic analysis and comprehensive scholarly discourse.

**Nutritional and Bioactive Composition of Macroalgae Relevant To Feed**

Macroalgae, commonly known as seaweed, represent a diverse and sustainable biomass with a distinct nutritional profile highly relevant to animals and aquafeed. Unlike terrestrial plants, macroalgae possess a unique cell wall composition rich in soluble and insoluble dietary fibers, including alginate, carrageenan, and ulvan, which can act as prebiotics to modulate gut microbiota in monogastric animals and ruminants (Cherry *et al*., 2019) [3]. Their protein content, while variable (5-47% dry weight), is notable in species like *Porphyra* and *Palmaria*, offering essential amino acids that can complement grain-based diets. Furthermore, macroalgae are a prolific source of essential minerals and trace elements—such as iodine, zinc, magnesium, and potassium—often at concentrations significantly higher than in terrestrial feedstuffs, addressing common micronutrient deficiencies in conventional feeds (Circuncisão *et al*., 2018) [5]. This broad-spectrum nutritional matrix makes them a valuable multifunctional ingredient for enhancing the foundational diet of livestock and aquaculture species.

The functional significance of macroalgae extends far beyond basic nutrition due to their rich repertoire of specialized bioactive compounds. Key among these are sulfated polysaccharides (SPs), such as fucoidans in brown algae and carrageenan in red algae, which exhibit potent immunomodulatory, antiviral, and prebiotic activities (Bahar *et al*., 2022) [1]. Phenolic compounds, particularly the phlorotannin unique to brown seaweeds (e.g., *Ascophyllum nodosum*), are powerful antioxidants and anti-inflammatory agents that can mitigate oxidative stress in animals and improve overall health status (O'Sullivan *et al*., 2021) [20]. Additionally, macroalgae contain pigments like fucoxanthin and unique peptides that contribute to antioxidant capacity and may influence metabolic processes. These bioactive collectively enhance animal resilience by supporting gut health, strengthening immune defenses, and improving stress responses, thereby offering a natural strategy to reduce reliance on antimicrobials and synthetic additives in animal production systems (Peixoto *et al*., 2021) [21].

The effective utilization of macroalgae in feed formulations necessitates a species-specific approach, as their biochemical composition—and thus their functional application—varies dramatically between the three main phylogenetic groups: Chlorophyta (green), Rhodophyta (red), and Phaeophyceae (brown) (Holdt & Kraan, 2011) [11]. The selection of a particular species or a blend is dictated by the target outcome, whether it is mineral supplementation, gut health modulation, immune stimulation, or product quality enhancement. Processing methods (e.g., drying, milling, extraction) further influence the bioavailability of nutrients and bioactive. Consequently, macroalgae nutritional and bioactive composition relevant for feeds as detailed in the following table 1.

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**Table 1:** Macroalgae nutritional and bioactive compound relevant to feed

| Microalgae Species | Nutrition Components | Bioactive Compounds | Feed Application | References |
|---|---|---|---|---|
| *Ascophyllum nodosum* | Diatery fiber, minerals (I,K), moderate protein | Phlorotannis, fucoidan, alginic acids | Antioxidant, anti-inflammatory, methane reduction in ruminants, immunostimulant in aquaculture | O Sullivan and Peixoto (2021) [21] |
| *Saccharina iatissima* | Mannitol, laminarin , iodine | Laminarin, fucoidan. fucoxanthin | Prebiotic (Gut health), immunomodulation, metabolic regulator | Bahar (2022) [1], Cherry (2019) [3] |

| | | | | |
|---|---|---|---|---|
| *Sargasum* spp. | Fiber, minerals (Ca, Mg), alginate | Fucoidan, polyphenols, sterols | Immune stimulayion, antioxidant, anti- pathogenic activity in shrimp and fish | Yu (2022) [30], Makkar (2019) [16] |
| *Palmaria palmata* | Protein, diatery fiber, vitamins B12 | Peptides, carrageenan, carotenoids | Protein supplement, muscle development, nutrient absorption enhancher | Circuncisao (2018), Wells (2020) [29] |
| *Porphyra* spp. | Protein, taurine, vitamins | Phycobiliproteins, peptides, porphyran | Nutritional fortification, antioxidant, pigmentation for egg and crustaceans shell | Bleakley and Hayes (2021) [2], Wan (2019) [28] |
| *Glacillaria* spp. | Agar, moderate protein, minerals | Agarose, floridean starch, phenolics | Gelling agent for pellets, prebiotics fiber, gut health, modulator | Maia (2023) [15], Holdt (2011) [11] |
| *Ulva Lactuca* | Proteins, carbohydrates, polysaccharides, iron | Ulvan, chlorophylls, lutein | Immunostimulant, growth promoter for fish and poultry | Peixoto (2021) [21], Kidgell (2019) [12] |
| *Codium* spp. | Dietary fiber, vitamins (C,A) | Sulfated galactans, flavonoids | Antioxidant, anti-inflammatory, disgetive health | Bahar (2022) [1], Makkar (2019) [16] |

**Macronutrient Profile**

The nutritional value of algae varies substantially across species, cultivation conditions, and processing methods, but certain general patterns are evident. Microalgae typically exhibit higher protein content than macroalgae, with many species containing 40-50% crude protein on a dry matter basis (Madacussengua *et al*., 2025) [14]. Species such as *Spirulina* (*Arthrospira*), *Chlorella*, and *Nannochloropsis* are particularly protein-rich, making them attractive partial replacements for fishmeal and soybean meal in monogastric and aquaculture diets (Siddik *et al*., 2023) [24]. The amino acid profiles of microalgae are generally well-balanced, though lysine and methionine levels may be limiting in some species, necessitating dietary supplementation or blending with complementary protein sources.

Lipid content in algae is highly variable, ranging from less than 5% to over 40% of dry matter depending on species and growth conditions. Microalgae such as *Schizochytrium* and *Nannochloropsis* are particularly valued for their high concentrations of long-chain omega-3 PUFAs, especially EPA and DHA (Demeda *et al*., 2020). These fatty acids are essential for fish and beneficial for human health, making algae-enriched animal products increasingly attractive to health-conscious consumers. In contrast, macroalgae generally contain lower lipid levels but may provide unique fatty acid profiles and bioactive lipid-soluble compounds. Carbohydrate composition in algae is dominated by structural polysaccharides that differ markedly from those in terrestrial plants. Brown macroalgae (*Phaeophyceae*) contain alginate, laminarin, and fucose-containing sulfated polysaccharides that form gel-like cell wall structures (Costa *et al*., 2022) [7]. These complex carbohydrates are largely indigestible by monogastric animals without enzymatic pre- treatment, though they may exert prebiotic effects by selectively promoting beneficial gut bacteria. Green (*Chlorophyta*) and red (*Rhodophyta*) macroalgae contain different polysaccharide profiles, including ulvan and carrageenans respectively, each with distinct structural properties and potential biological activities.

**Micronutrient and Minerals**

Algae are exceptionally rich sources of minerals and trace elements, often accumulating these nutrients to concentrations far exceeding those in terrestrial plants. Macroalgae in particular concentrate iodine, iron, zinc, manganese, and selenium from seawater, making them valuable mineral supplements for animal diets (Circuncisão *et al*., 2018) [5]. However, this capacity for mineral accumulation can be a double-edged sword. While moderate algal inclusion can help meet animal mineral requirements, excessive inclusion or the use of algae from contaminated waters can lead to toxic accumulations of heavy metals or excessive iodine levels in animal tissues (Costa *et al*., 2022) [7]. Careful sourcing, species selection, and monitoring of mineral content are therefore essential to ensure both nutritional adequacy and food safety.

Algae also provide fat-soluble vitamins and pigments that contribute to their functional properties. Carotenoids such as β-carotene, astaxanthin, lutein, and fucoxanthin serve as provitamin A sources and powerful antioxidants (Thapa, 2020) [26]. When animals consume algae, these pigments accumulate in tissues, enhancing the color of egg yolks, fish flesh, and poultry skin while also providing antioxidant protection against oxidative stress. Tocopherols (vitamin E) and other lipid-soluble antioxidants further contribute to the nutritional and functional value of algal biomass.

**Bioactive Compounds and Their Biological Activities** The bioactive compounds in algae represent perhaps their most distinctive and valuable feature for animal nutrition. These molecules exert effects that extend far beyond basic nutrient supply, influencing immune function, gut health, oxidative status, and product quality.

***Polysaccharides*****:** Sulfated polysaccharides from macroalgae, including fucoidans, carrageenans, and ulvans, have demonstrated immunomodulatory, antiviral, and prebiotic properties in numerous studies (Ringø *et al*., 2025) [22]. These compounds can stimulate macrophage activity, enhance antibody production, and modulate cytokine expression, thereby strengthening both innate and adaptive immune responses. Laminarin, a β-1,3-glucan from brown algae, has shown particular promise as an immunostimulant in aquaculture, improving disease resistance in fish and shrimp (Peixoto *et al*., 2021) [21]. The prebiotic effects of algal polysaccharides may also promote beneficial gut bacteria, improving nutrient utilization and intestinal health.

***Carotenoids*****:** These pigmented compounds serve dual roles as colorants and antioxidants. Astaxanthin, abundant in Haematococcus microalgae, is a particularly potent antioxidant that accumulates in fish muscle, producing the characteristic pink-red coloration valued in salmonids (Valente *et al*., 2019) [27]. Beyond aesthetics, carotenoids

ect cell membranes from oxidative damage, support immune function, and may improve reproductive performance. Fucoxanthin, a carotenoid unique to brown macroalgae and some diatoms, has attracted attention for its potential anti-obesity and anti-inflammatory effects, though research in livestock applications remains limited.

***Polyphenols and Phlorotannins:*** Brown macroalgae are rich in phlorotannins, a class of polyphenolic compounds with strong antioxidants and antimicrobial activities (Mlambo *et al*., 2022) [18]. While these properties can be beneficial, high phenolic content may also reduce feed palatability and nutrient digestibility through protein binding. The net effect of phlorotannins therefore depends on concentration, with moderate levels potentially beneficial but excessive levels detrimental to animal performance.

***Omega-3 Fatty Acids*****:** Perhaps the most commercially significant bioactive components of certain microalgae are the long-chain omega-3 PUFAs, EPA and DHA. These fatty acids are essential for fish and highly beneficial for human cardiovascular health, making them key drivers of consumer demand for functional animal products. Microalgae such as Schizochytrium, Nannochloropsis, and Isochrysis are natural sources of these compounds and can effectively enrich the omega-3 content of meat, eggs, and milk when included in animal diets (Coelho *et al*., 2020; Martins *et al*., 2021) [6].

**Effect on Growth Performance and Production Metrics** The incorporation of macroalgae into animals and aquafeeds consistently demonstrates significant positive impacts on growth performance and feed utilization metrics across diverse species. In aquaculture, the inclusion of brown seaweeds like *Ascophyllum nodosum* at low dietary levels (1-5%) has been shown to enhance specific growth rates (SGR) and improve feed conversion ratios (FCR) in species such as Nile tilapia (*Oreochromis niloticus*) and European seabass (*Dicentrarchus labrax*). This enhanced efficiency is often attributed to the bioactive compounds, particularly sulfated polysaccharides and phlorotannins, which improve nutrient digestibility and modulate gut microbiota, creating a more favorable environment for nutrient absorption (Peixoto *et al*., 2021; Wan *et al*., 2019) [21, 28]. Similarly, red macroalgae such as *Palmaria palmata*, with its high protein content, can serve as a valuable partial fishmeal replacement in shrimp diets, supporting comparable or superior growth rates while enhancing the nutritional profile of the final product (Cottrell *et al*., 2020) [9].

**Aquaculture Species**

Aquaculture represents one of the most promising applications for algal feed, given that many fish and crustaceans naturally consume algae or algae-consuming prey in the wild. Numerous studies have demonstrated that algal inclusion can enhance growth, health, and product quality in aquaculture species, though outcomes depend critically on species, algal type, inclusion level, and dietary formulation. A particularly compelling example comes from research on European seabass (*Dicentrarchus labrax*) juveniles fed a commercial blend of macroalgae (*Ulva* sp., *Gracilaria gracilis*) and microalgae (*Chlorella vulgaris*, *Nannochloropsis oceanica*) at 2-6% of diet dry matter (Mota *et al*., 2023) [19]. This study found that the 6% inclusion level increased apparent digestibility of nutrients and energy, enhanced lipid retention, and remarkably increased final body weight by approximately 70% compared to controls over a 12-week period. The blend also enriched muscle EPA and DHA content, improving the nutritional value of the final product. These results suggest that carefully formulated algal blends can deliver synergistic benefits, combining the unique bioactive profiles of different species.

In grass carp (*Ctenopharyngodon idella*), dietary supplementation with 5% of individual macroalgae specie, such as *Sargassum hemiphyllum*, *Asparagopsis taxiformis*, and *Gracilaria lemaneiformis* influenced growth performance and antioxidant activity, with *Sargassum* providing the most consistent benefits in body weight gain and hepatic superoxide dismutase (SOD) activity (Mota *et al*., 2023) [19]. Interestingly, macroalgae supplementation also altered gut microbial composition, enriching *Shewanella* species that correlated with enhanced amino acid metabolism and growth-related metabolites. This finding highlights the potential for algae to exert prebiotic effects that indirectly support growth through microbiome modulation.

Studies in salmonids, tilapia, shrimp, and other commercially important aquaculture species have generally reported similar patterns: moderate algal inclusion (typically 2-10% of diet) supports or enhances growth, improves immune markers, increases flesh pigmentation, and enriches omega-3 content, while very high inclusion levels may impair palatability or growth (Wan *et al*., 2019; Peixoto *et al*., 2021; Ringø *et al*., 2025) [21, 22, 28]. The species-specific nature of these responses emphasizes the need for tailored formulations optimized for each target species.

**Poultry**

The application of algae in poultry nutrition has yielded mixed but increasingly promising results. Microalgae such as *Chlorella* and *Spirulina* have been more extensively studied than macroalgae in poultry, largely due to their higher protein content and more favorable amino acid profiles. Several studies have demonstrated that moderate microalgae inclusion (typically 2-5% of diet) can improve meat lipid composition, increase carotenoid deposition in tissues, and enhance antioxidant status without impairing growth performance (Madacussengua *et al*., 2025; Thapa, 2020) [14, 26].

However, macroalgae inclusion in poultry diets presents greater challenges. A detailed study with broilers fed 15% *Laminaria digitata* (brown macroalgae) found that while the algae increased meat antioxidant pigments and omega-3 fatty acids, it also impaired final body weight and worsened feed conversion ratio (Costa *et al*., 2022) [7]. The negative effects were attributed to increased intestinal viscosity caused by alginate and other non-starch polysaccharides, which reduce nutrient absorption. Supplementation with alginate lyase enzyme partially mitigated the viscosity problem but did not fully restore growth performance, suggesting that enzymatic solutions alone may be insufficient at high inclusion levels.

The key to successful algal inclusion in poultry appears to be moderation and processing. Lower inclusion levels (2- 5%), appropriate enzyme supplementation, and selection of algal species with lower fiber and phenolic content can deliver functional benefits, such as enhanced egg yolk pigmentation, improved meat omega-3 profiles, and stronger immune responses without compromising growth or feed efficiency (Kulshreshtha *et al*., 2020; Michalak & Mahrose, 2020) [13, 17]. Layer hens may benefit from algal supplementation through improved egg quality, enhanced yolk color, and potential prebiotic effects on gut health.

**Ruminant**

Ruminant nutrition presents unique opportunities and challenges for algal supplementation. The large fermentation capacity of the rumen can potentially degrade algal cell walls and utilize fibrous components that monogastric animals cannot digest. However, ruminal biohydrogenation of unsaturated fatty acids limits the effectiveness of algal omega-3 enrichment unless protected formulations are used.

Studies with sheep have yielded encouraging results. Barki rams fed *Nannochloropsis oculata* at 1.5% and 3% of diet dry matter showed improved body weight gain, enhanced antioxidant status (increased total antioxidant capacity and SOD, decreased malondialdehyde), and elevated immune markers including lymphocyte counts and cytokines (IL-6, IL-12, TNF-α, γ-interferon) (Costa *et al*., 2022) [7]. The authors recommended the 3% inclusion level for optimal performance under their trial conditions, demonstrating that substantial benefits can be achieved at moderate inclusion rates.

In dairy cattle, the use of rumen-protected algal products has proven particularly effective. A study with lactating cows under heat stress found that rumen-protected *Schizochytrium* supplementation improved milk yield, feed efficiency, and nutrient digestibility compared to unprotected algae or control diets (Costa *et al*., 2025) [8]. The protected formulation also increased milk omega-3 content, enhanced antioxidant enzyme activities (glutathione peroxidase and SOD), and modulated heat shock protein expression, suggesting improved resilience to thermal stress. These findings highlight the importance of targeted delivery systems that protect bioactive compounds from ruminal degradation.

Beef cattle fed *Schizochytrium* at 1.7% of diet dry matter showed enriched muscle omega-3 content, though one trial reported reduced dry matter intake and average daily gain (approximately 16.5% and 19.1% declines, respectively) (Demeda *et al*., 2020). This negative effect on intake and growth underscores the need for careful formulation and potentially lower inclusion levels in finishing diets where maximizing growth rate is the primary objective.

A particularly exciting application of macroalgae in ruminant nutrition is methane mitigation. Red seaweed *Asparagopsis taxiformis* contains bromoform, a compound that inhibits methanogenic archaea in the rumen, dramatically reducing enteric methane emissions (Roque *et al*., 2021) [23]. Studies have demonstrated methane reductions exceeding 80% in beef cattle supplemented with *Asparagopsis*, with minimal effects on feed intake or growth performance when used at appropriate doses. These application positions algae not only as a nutritional ingredient but also as a critical tool for reducing the greenhouse gas footprint of ruminant production, addressing one of the most pressing environmental challenges facing the livestock sector.

**Enhancement of Final Product Quality**

A principal advantage of incorporating macroalgae into animal diets is the demonstrable improvement in the quality attributes of the final animal-derived products, adding significant market value. In aquaculture, this is most prominently observed through enhanced pigmentation. The carotenoids present in macroalgae, such as astaxanthin precursors in certain species, are effectively transferred and deposited in the flesh of salmonids and the shells of crustaceans like shrimp, resulting in the desirable reddish- pink hue that consumers strongly associate with premium quality and health (Peixoto *et al*., 2021; Wan *et al*., 2019) [28] [21]. Beyond color, macroalgae supplementation plays a crucial role in improving the oxidative stability and shelf- life of seafood. The potent antioxidant compounds, including phlorotannins and fucoxanthin, inhibit lipid peroxidation in muscle tissues during storage, reducing rancidity and preserving freshness without the need for synthetic additives (Makkar *et al*., 2019) [16].

The impact of dietary macroalgae extends to the nutritional profile of meat, milk, and eggs, aligning with growing consumer demand for functionally enhanced foods. In ruminants and poultry, supplementation has been shown to favorably modify the fatty acid composition of products. For instance, certain red and brown seaweeds can increase the concentration of beneficial long-chain omega-3 fatty acids, such as eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), in milk and egg yolks, while concurrently decreasing the ratio of saturated to unsaturated fats (Cottrell *et al*., 2020) [9]. This biofortification creates a "designer" product with inherent health claims. Additionally, the rich mineral content of seaweeds, particularly iodine, selenium, and zinc, can be transferred to animal products, offering a natural means to address human dietary deficiencies and enhance the nutritional density of everyday staples like eggs and milk (Circuncisão *et al*., 2018) [5].

In the poultry industry, macroalgae have proven particularly effective for enhancing egg quality. Laying hens fed diets supplemented with species like *Ulva* or *Gracilaria* produce eggs with intensified yolk color, a key visual quality parameter for consumers in many markets. Furthermore, improvements in eggshell strength and thickness have been reported, attributed to the bioavailable minerals like calcium and magnesium in seaweeds, which can reduce breakage losses during handling and transportation (Kulshreshtha *et al*., 2020) [13]. Beyond physical attributes, studies indicate that such supplementation can also lower cholesterol levels in egg yolks, further enhancing the functional food appeal of the final product (Michalak & Mahrose, 2020) [17].

The mechanisms driving these quality enhancements are multifaceted. The direct deposition of algal pigments and bioavailable minerals into tissues is a primary pathway. Simultaneously, the systemic antioxidant and anti- inflammatory effects of seaweed bioactives improve the overall metabolic health of the animal, leading to a reduction in oxidative stress markers in muscle and other tissues, which directly correlates with improved post- mortem meat quality, including water-holding capacity and tenderness (Valente *et al*., 2019) [27]. As the evidence solidifies, macroalgae are transitioning from a novel feed additive to a strategic tool for precision animal nutrition, enabling producers to tailor specific quality traits in their products—from improved visual appeal and extended shelf- life to enhanced nutritional content, thereby meeting sophisticated market demands and securing premium pricing in a competitive agricultural landscape.

**Challenges and Future Persepctives**

Despite the compelling evidence supporting the use of macroalgae in animal and aquafeed, significant challenges impede its widespread commercial adoption. The most prominent barrier is the high degree of variability in the biochemical composition of algal biomass. Nutrient and bioactive compound profiles fluctuate dramatically based on species, geographic origin, season, harvesting time, and environmental conditions such as water temperature and nutrient availability (Cherry *et al*., 2019) [3]. This inconsistency complicates the formulation of standardized, predictable feed rations, making it difficult for feed manufacturers and farmers to guarantee consistent animal performance and product quality. Furthermore, the presence of antinutritional factors and contaminants poses a serious concern. Some macroalgae species can accumulate high levels of iodine, heavy metals (e.g., arsenic, cadmium), and salinity, which may lead to toxicity in animals or result in unsafe levels of these elements in meat, milk, or eggs for human consumption (Circuncisão *et al*., 2018) [5]. Robust, cost-effective processing methods and stringent quality control protocols are therefore essential to ensure biosafety and regulatory compliance.

The economic and logistical viability of large-scale macroalgae supply chains presents another major hurdle. Currently, the production cost of cultivated seaweed is often higher than that of conventional feed ingredients like soybean meals or fishmeal, undermining its economic competitiveness (Cottrell *et al*., 2020) [9]. Wild harvest is limited by sustainability concerns and seasonal availability. Establishing a reliable, year-round supply of consistent- quality biomass requires significant investment in offshore or onshore aquaculture systems, which face their own challenges related to site licensing, operational costs, and potential environmental interactions. Additionally, optimal inclusion levels and formulation strategies are not yet fully defined for all animal species and production stages. High fiber content in some seaweeds can reduce palatability and nutrient digestibility in monogastrics, while the optimal dose for eliciting positive health effects without negatively impacting growth remains a delicate balance that requires further species-specific research (Makkar *et al*., 2019) [16].

To overcome these challenges and unlock the full potential of macroalgae, a multi-faceted research and development agenda is required for the future. First, advancements in cultivation and processing are paramount. Developing selective breeding programs and controlled cultivation techniques (e.g., integrated multi-trophic aquaculture – IMTA can standardize biomass quality and enhance the yield of target bioactive compounds (Peixoto *et al*., 2021) [21]. Innovative, low-cost processing methods, such as mild cell disruption and targeted extraction, are needed to concentrate functional fractions (e.g., fucoidan, phlorotannin extracts) while removing excess minerals and antinutrients, thereby improving efficacy and safety. Second, comprehensive animal trials are essential. Long-term, large- scale *in vivo* studies across diverse livestock and aquaculture species are needed to establish clear dose- response relationships, elucidate long-term health impacts, and conduct thorough food safety assessments, including the fate of potential contaminants.
The integration of macroalgae into feed systems aligns perfectly with the global push toward a circular blue bioeconomy. Future perspectives should focus on leveraging

macroalgae not just as a feed ingredient but as a central component of sustainable food systems. This includes exploring the valorization of algal co-products from other industries (e.g., biofuel, bioplastic) for feed use and developing precision nutrition strategies where specific algal supplements are deployed to target precise outcomes, such as methane mitigation in ruminants or stress resilience in fish during transport (Roque *et al*., 2021; Wan *et al*., 2019) [23, 28]. Ultimately, realizing this vision will depend on strong collaboration between phycologists, animal nutritionists, economists, and policymakers to create supportive regulatory frameworks, incentivize sustainable production, and build market confidence. By addressing the current challenges through targeted innovation, macroalgae can transition from a promising niche ingredient to a cornerstone of next-generation, sustainable animal production.

## Conclusion

Macroalgae represent a multifaceted opportunity to enhance the sustainability, functionality, and productivity of animal nutrition systems. The evidence accumulated over recent years demonstrates that algae are not merely alternative protein sources but rather functional ingredients with unique bioactive profiles that can improve animal health, performance, and product quality. From omega-3 enrichment in aquaculture and livestock products to immune enhancement, antioxidant protection, and methane mitigation in ruminants, the applications of algae span the full spectrum of animal production. However, realizing the full potential of algae requires overcoming significant challenges related to digestibility, palatability, economic viability, and regulatory acceptance. Looking forward, algae are likely to play an increasingly important role in animal nutrition, not as wholesale replacements for conventional ingredients but as strategic supplements that deliver specific functional benefits. As production costs decline, processing technologies improve, and regulatory frameworks mature, the commercial adoption of algae in animal feeds will continue to expand. In doing so, algae will contribute to more sustainable, resilient, and health-promoting food systems capable of meeting the nutritional needs of a growing global population while reducing environmental impacts.

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