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Seaweed in Animal Nutrition: Opportunities, Challenges, and Future Prospects for Sustainable Livestock Production

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Abstract

Seaweeds (marine macroalgae) represent a promising and sustainable alternative feed resource for livestock, offering unique nutritional profiles rich in minerals, bioactive compounds, polyunsaturated fatty acids, and complex polysaccharides. This review synthesizes current knowledge on the taxonomy, nutritional composition, and applications of brown (Phaeophyceae), red (Rhodophyceae), and green (Chlorophyceae) seaweeds in animal nutrition, including ruminants, poultry, swine, aquaculture species, and rabbits. While seaweeds can enhance gut health, immunity, and product quality (e.g., enriched omega-3 eggs), significant challenges remain, including variable composition, anti-nutritional factors, potential mineral overload (iodine, heavy metals like arsenic), and digestibility limitations. Optimal inclusion levels vary by species, processing method, and animal type, with prebiotic effects often observed at low inclusion (<5%). Future research must focus on standardized cultivation, safety monitoring, processing technologies to improve nutrient bioavailability, and large-scale in vivo trials to fully harness seaweed's potential in reducing reliance on conventional feedstuffs and antibiotics while supporting sustainable animal production systems.

Keywords: *Seaweed, Macroalgae, Animal Feed, Sustainable Livestock, Bioactive Compounds, Prebiotics, Heavy Metals, Ruminants, Poultry, Aquaculture, Nutritional Value*

1. Introduction

The global demand for animal products is projected to surge by 60–70% by 2050, placing unprecedented pressure on conventional feed resources such as soybean meal and corn. This intensification contributes to land degradation, food-fuel-feed competition, and resource depletion, necessitating the exploration of novel, sustainable feed ingredients (Makkar et al., 2016). In this context, seaweeds, or marine macroalgae, have emerged as a compelling alternative. With a long history of use in coastal regions—from ancient Greece to Icelandic sagas—seaweeds are gaining renewed scientific and commercial interest for their potential to enhance animal nutrition, improve product quality, and reduce the environmental footprint of livestock production (Evans and Critchley, 2014; Morais et al., 2020).

Seaweeds are a heterogeneous group of photosynthetic organisms broadly classified into brown (*Phaeophyceae*), red (*Rhodophyceae*), and green (*Chlorophyceae*) algae. They do not require arable land or freshwater for cultivation and exhibit rapid growth rates, making them a highly productive biomass. Their ability to sequester carbon and absorb excess nutrients from marine environments also positions them as a key component in integrated aquaculture systems (Troell et al., 2009). This review provides a comprehensive analysis of the nutritional attributes of different seaweed groups, evaluates their applications across various livestock sectors, addresses critical safety and regulatory challenges, and outlines future research directions needed to unlock their full potential in sustainable animal agriculture.

2. Seaweed Taxonomy and Nutritional Profiles

The nutritional value of seaweeds is highly variable and dependent on species, geographic location, harvest season, and environmental conditions such as water temperature and nutrient availability. The three main taxonomic groups exhibit distinct compositional profiles that dictate their specific applications in animal feed.

2.1 Brown Algae (*Phaeophyceae*)

Brown algae, such as *Ascophyllum nodosum*, *Laminaria spp*., *Macrocystis pyrifera*, and *Sargassum spp.,* are the largest seaweeds and have been most extensively studied for animal feed due to their size and ease of harvesting. They are characterized by lower protein content (typically 5–14% dry matter [DM]) but exceptionally high mineral content (14–35% DM), particularly iodine, which can accumulate to levels over 30,000 times the concentration in seawater (Makkar et al., 2016). Their cell walls contain unique polysaccharides like alginates, fucoidans, and laminarin, which possess prebiotic and immunomodulatory properties. While their lipid content is low (1–5% DM), it is rich in polyunsaturated fatty acids (PUFAs) like eicosapentaenoic acid (EPA). Brown algae also contain significant amounts of phenolic compounds, such as phlorotannins, which act as potent antioxidants (Morais et al., 2020).

2.2 Red Algae (*Rhodophyceae*)

Red algae, including *Palmaria palmata* (Dulse), *Porphyra/Neopyropia spp.* (Nori), and *Gracilaria spp.,* generally possess the highest protein content among seaweeds, ranging from 18% to as high as 50% DM for some Porphyra species (Makkar et al., 2016). Their amino acid profile is relatively balanced, with essential amino acids comprising nearly half of the total. Red algae are a primary source of industrially important hydrocolloids like carrageenans and agars, which function as soluble fibres. Their mineral content is moderate, and iodine levels are lower than in brown algae. Lipids are also low but are a valuable source of EPA and, in some species, Docosahexaenoic acid (DHA) (Morais et al., 2020).

2.3 Green Algae (*Chlorophyceae*)

Green algae, predominantly represented by *Ulva spp*. (Sea lettuce) and *Codium spp.,* offer a moderate to high protein content (15–30% DM) and a more balanced mineral profile compared to brown algae. *Ulva* species, in particular, are noted for their relatively high levels of sulphur-containing amino acids like methionine and cystine, which are often deficient in conventional feedstuffs (Makkar et al., 2016). Their signature polysaccharides are sulphated ulvans, which have demonstrated prebiotic, antiviral, and antioxidant activities. Green algae are fast-growing and can form "green tides," making them an abundant but underutilized resource (Morais et al., 2020).

Table 1: Comparative Nutritional Composition of Major Seaweed Groups (% Dry Matter)

Nutrient	Brown Algae	Red Algae	Green Algae	Primary Sources
Crude Protein	5–14	18–50	15–30	(Makkar et al., 2016)
Ash (Minerals)	14–35	12–37	17–39	(Makkar et al., 2016)
Crude Lipids	0.5–3.9	0.7–3.8	0.3–4.2	(Morais et al., 2020)
Crude Fiber	5.5–10.1	1.5–24.7	29–65.7	(Makkar et al., 2016)
Key Polysaccharides	Alginates, Fucoidans, Laminarin	Carrageenans, Agars	Ulvans	(Morais et al., 2020)
Notable Minerals	Iodine (very high), K, Na	Ca, Fe, Mg	Ca, Mg	(Makkar et al., 2016)

3. Applications in Animal Nutrition

The unique composition of seaweeds allows for diverse applications across livestock sectors, primarily as a source of minerals, functional bioactives, and, to a lesser extent, protein and energy.

3.1 Ruminant Nutrition

In ruminants, seaweeds are primarily used as functional additives rather than primary energy or protein sources due to their high mineral content and low energy density. The complex polysaccharides in brown algae, such as alginates and laminarin, are partially fermentable by rumen microbes. A step-wise increase in dietary seaweed levels allows for microbial adaptation, enhancing the availability of energy from these carbohydrates (Makkar et al., 2016). *Ascophyllum nodosum* meal and its extracts are widely used in dairy and beef cattle at low inclusion rates (<5%) to improve immunity, antioxidant status, and reduce fecal shedding of pathogens like E. coli (Allen et al., 2001; Evans and Critchley, 2014). The Orkney sheep of North Ronaldsay Island, which subsist almost entirely on a diet of brown seaweeds like *Laminaria digitata*, demonstrate the remarkable adaptability of ruminants to such forage, though this is an extreme case (Hansen et al., 2003).

3.2 Poultry Nutrition

In poultry production, seaweeds are incorporated into both broiler and layer diets to improve growth performance, gut health, and product quality. For broilers, green seaweeds like Ulva lactuca included at 1–3% of the diet have been shown to improve body weight gain and dressing percentage, likely due to their higher protein and methionine content (El-Deek and Al-Harthi, 2009; Ventura and Castanon, 1998). Red seaweeds, such as *Chondrus crispus*, do not significantly impact growth but exhibit strong prebiotic effects, increasing beneficial gut bacteria (e.g., *Lactobacillus*) and short-chain fatty acid concentrations while reducing pathogens like Salmonella (Kulshreshtha et al., 2014). For laying hens, dietary seaweed can enhance egg quality. Inclusion of Ulva spp. (1–3%) increases egg weight, shell thickness, and yolk color, while brown seaweeds like Sargassum spp. (3–6%) can reduce yolk cholesterol and triglyceride levels and enrich eggs with carotenoids like lutein and zeaxanthin (Ribeiro et al., 2020).

3.3 Aquaculture Nutrition

Aquaculture is a major area of opportunity for seaweed application. In fish farming, seaweed meal can partially replace fishmeal or plant proteins. For example, up to 10% inclusion of *Laminaria sp.* meal in Atlantic salmon diets was found to improve growth performance, plasma antioxidant capacity, and resilience to temperature stress without adverse effects (Kamunde et al., 2019). In rainbow trout, kelp (*Saccharina latissima*) supplementation at <4% increased protective activity against oxidative stress (Morais et al., 2020). Furthermore, seaweeds are integral to Integrated Multi-Trophic Aquaculture (IMTA) systems, where they absorb excess nutrients (e.g., nitrogen and phosphorus) from fish farm effluent, mitigating environmental pollution while producing a valuable biomass for feed or other uses (Troell et al., 2009). In oyster hatcheries, seaweeds like Ulva sp. are investigated as a cost-effective alternative to live microalgae for broodstock conditioning and larval rearing, though careful monitoring of heavy metal bioaccumulation is essential (Cardoso et al., 2020).

3.4 Swine and Rabbit Nutrition

In swine, seaweeds are primarily valued as a source of iodine and functional bioactives. Brown seaweeds can prevent iodine deficiencies, while their polysaccharides act as prebiotics to improve gut health and nutrient absorption (Dierick et al., 2009). However, their high fiber content can limit digestibility, suggesting that enzyme supplementation may be beneficial. For rabbits, studies with *A. nodosum* and *L. digitata* at inclusion levels up to 5% have shown no negative effects on growth performance, while green seaweeds like *Ulva* and *Ruppia maritima* offer a good source of protein (Makkar et al., 2016).

4. Challenges and Safety Concerns

Despite their significant potential, several critical challenges must be addressed for the widespread and safe adoption of seaweeds in animal feed.

4.1 Heavy Metal and Mineral Accumulation

Seaweeds are powerful bioaccumulators of minerals from seawater, which can be both a benefit and a risk. While this makes them excellent sources of essential trace elements, it also leads to the accumulation of toxic heavy metals such as arsenic (As), cadmium (Cd), and lead (Pb). Brown algae, in particular, tend to accumulate high levels of arsenic, often in organic forms that can be toxic (Makkar et al., 2016). Excessive iodine intake, especially from brown algae like Laminaria, can lead to hyperthyroidism or hypothyroidism in animals (Morais et al., 2020). Regular monitoring of mineral and heavy metal concentrations in seaweed batches destined for feed is therefore non-negotiable to prevent toxicity and ensure product safety for both animals and human consumers.

4.2 Variability and Anti-Nutritional Factors

The nutritional composition of seaweeds is highly inconsistent, influenced by species, season, geography, and processing methods. This variability poses a significant challenge for formulating consistent and balanced animal diets. Furthermore, some seaweeds contain anti-nutritional factors. For instance, the high polysaccharide content can reduce nutrient digestibility in monogastric animals, and the presence of phlorotannins in brown algae may bind proteins and reduce their availability (Makkar et al., 2016). Processing techniques like drying, milling, and enzymatic hydrolysis can help mitigate these issues but add to production costs.

4.3 Regulatory Gaps and Palatability

The regulatory framework for seaweeds in animal feed is not yet globally harmonized. In the European Union, their use as feed additives is governed by regulations (EC) No 1831/2003 and No 429/2008, but many countries lack specific maximum limits for contaminants like heavy metals in seaweed feed ingredients (Morais et al., 2020). Additionally, palatability can be an issue, especially at higher inclusion levels. Some studies have reported reduced feed intake in calves and poultry fed high levels of certain brown seaweeds, possibly due to their high salt content or unpalatable compounds (Erickson et al., 2012).

5. Future Prospects and Conclusion

The integration of seaweeds into animal feed systems represents a viable pathway toward more sustainable and resilient livestock production. To fully realize this potential, a concerted effort is needed in several key areas. First, advancing sustainable cultivation practices, such as IMTA and controlled on-land systems, will ensure a consistent, safe, and traceable supply of seaweed biomass, minimizing the risks associated with wild harvesting. Second, investment in processing technologies, including enzymatic hydrolysis and fermentation, is crucial to enhance the digestibility and bioavailability of nutrients and bioactive compounds. Third, establishing standardized safety protocols and international regulatory guidelines for heavy metals and iodine will build consumer and industry confidence.

Seaweeds are not a panacea for the challenges facing animal nutrition, but they are a multifaceted and valuable resource. Their ability to provide essential minerals, functional prebiotics, and health-promoting bioactives makes them a powerful tool for enhancing animal welfare, reducing reliance on antibiotics, and improving the nutritional quality of animal products. While challenges related to safety, variability, and digestibility are significant, they are not insurmountable. Through focused research, technological innovation, and robust regulatory oversight, seaweeds can transition from a traditional coastal supplement to a mainstream, science-driven component of global feed strategies, contributing to a more sustainable and secure food future.

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