



AGRI MAGAZINE

(International E-Magazine for Agricultural Articles)

Volume: 03, Issue: 04 (April, 2026)

Available online at <http://www.agrimagazine.in>

© Agri Magazine, ISSN: 3048-8656

From Ocean to Feed Bowl: How Seaweed Can Transform Aquaculture

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Aquaculture is expanding rapidly to meet global seafood demand, but its sustainability is challenged by the high cost and environmental impact of fishmeal-based feeds. Seaweeds (marine macroalgae) have emerged as promising alternative ingredients due to their abundance, eco-friendly production, and rich composition of proteins, polysaccharides, minerals, vitamins, and bioactive compounds. This study highlights the nutritional and functional roles of green, red, and brown seaweeds in aquafeeds. At optimal inclusion levels, seaweeds improve growth performance, feed conversion ratio, palatability, immune response, antioxidant activity, and gut microbiota in cultured species. However, higher inclusion levels may reduce nutrient digestibility due to complex polysaccharides and anti-nutritional factors. Processing methods such as enzymatic treatment and fermentation can enhance nutrient availability and feed efficiency. In addition to nutritional benefits, seaweeds contribute to environmental sustainability through bioremediation and reduced reliance on antibiotics and synthetic additives. Overall, seaweeds have strong potential as functional feed ingredients for developing sustainable and health-oriented aquaculture systems.

Keywords: Seaweeds, Aquaculture nutrition, Fishmeal replacement, Functional feed, Growth performance, FCR, Immunity, Antioxidants, Gut microbiota, Sustainable aquaculture

Introduction

As capture fisheries reach their limits due to overfishing and environmental stress, aquaculture is becoming essential to meet the growing demand for seafood. However, feed accounts for nearly half of production costs, largely driven by fishmeal derived from wild fish, which adds pressure on marine resources (FAO, 2022; Lovell, 2003; Tacon & Metian, 2008). At the same time, intensive farming has increased reliance on antibiotics and chemicals, raising concerns about residues, environmental impact, and resistance. In this context, seaweeds emerge as a promising, sustainable alternative due to their abundance and rich nutritional and bioactive properties.

Seaweed

Seaweeds are marine macroalgae that grow in oceans, coastal waters, and even brackish environments. Unlike terrestrial crops, they do not require freshwater, fertilizers, or arable land, making them inherently sustainable.

They are broadly classified into three groups:

- **Green seaweeds** such as Ulva
- **Red seaweeds** such as Gracilaria and Porphyra
- **Brown seaweeds** such as Laminaria

Each group differs in nutritional composition and functional properties, which makes them suitable for different roles in aquafeeds.

Why Seaweed? The Sustainable Advantage

Seaweeds are marine plants that grow abundantly in oceans without requiring freshwater, fertilizers, or land. This makes them one of the most sustainable biological resources available.

- **Renewable and eco-friendly production**
- **No competition with human food crops**
- **Ability to absorb excess nutrients (bioremediation)**
- **Reduction in environmental pollution**

Additionally, seaweeds help in improving water quality by absorbing nitrogen and phosphorus from aquaculture systems.

Nutritional Properties of Seaweeds

Polysaccharides

Seaweeds are rich in carbohydrates, mainly present as **storage polysaccharides** (like laminaran, floridean starch, and starch) and **cell wall polysaccharides (NSP)** such as carrageenan, agar, alginates, and ulvans. These carbohydrates can make up **20–76% of dry weight**, with NSP forming the major fraction (Holdt & Kraan, 2011). Although largely indigestible in fish due to lack of enzymes, they function as **dietary fibre** and provide health benefits like antioxidant and immune support. However, high inclusion levels may reduce nutrient digestibility, which can be improved through feed processing methods like enzyme or heat treatment.

Pigments in Seaweeds

Seaweeds contain natural pigments such as **fucoxanthin in brown algae, chlorophyll and carotenoids in green algae, and phycoerythrin and phycocyanin in red algae**, which give them their characteristic colors. These pigments are not only important for photosynthesis but also play a key role in aquaculture by **enhancing fish skin and flesh coloration**, influencing consumer preference (Gomes et al., 2002). Hence, seaweeds serve as a **natural alternative to synthetic colorants** in fish feeds, supporting more sustainable and organic aquaculture practices.

Lipids

Seaweeds contain low total lipids (about **1–5% dry weight**), mainly in the form of **glycolipids and phospholipids**, though some brown species like *Sargassum* may reach higher levels (Terasaki et al., 2009; Nomura et al., 2013). Despite the low quantity, they are rich in **polyunsaturated fatty acids (PUFAs)**, especially **omega-3 fatty acids like EPA**, which are higher than in terrestrial plants. Lipid composition varies with species, season, and environmental factors. In aquaculture, lipids provide essential energy, and although seaweeds contribute beneficial fatty acids, they may require supplementation of certain essential fatty acids for optimal fish growth.

Protein in Seaweeds

Protein content in seaweeds varies widely (**5–47% dry weight**) depending on species, season, and environmental conditions (Černá, 2011; Lourenço et al., 2002). **Red seaweeds generally have higher protein levels** than brown and green types due to the presence of functional pigments like phycobiliproteins. Seaweeds contain **all essential amino acids required for fish growth**, making them nutritionally valuable. However, protein levels tend to be higher in colder seasons and lower in summer. In aquaculture, while seaweeds can contribute to dietary protein, they are usually used as a **supplement rather than a primary protein source**.

Vitamins and Minerals

Seaweeds are rich in **minerals such as iodine, calcium, iron, zinc, potassium, and phosphorus**, often making up to **36% of dry matter**, with higher levels in brown seaweeds (Holdt & Kraan, 2011). They also contain both **water-soluble (vitamin C, B-complex)** and **fat-soluble vitamins (A and E)**, with some species like *Porphyra* being notable sources of **vitamin B12**. In aquaculture, seaweeds can supply essential micronutrients for fish; however,

bioavailability may be limited due to binding with polysaccharides, often requiring supplementation in feeds.

Growth performance in fish

The effectiveness of seaweed as a feed additive varies greatly depending on the nutritional profile and the species-specific feeding nature of fish. In general, low dietary inclusion of seaweed, up to 10%, has been shown to impart significant improvements in growth, feed utilization, and the assimilation of essential nutrients. The dietary supplementation of *Laminaria* sp. with levels of 3 and 10% has been shown to significantly enhance the daily feed intake and weight gain in Atlantic salmon (**Kamunde et al., 2019**). Likewise, Sony et al., 2019 found that dietary supplementation of fucoidan, a polysaccharide derived from brown algae (*Cladosiphon okamuranus*), at a level of 0.4%, significantly improved the growth performance of juvenile red sea bream (*Pagrus major*). Feeding high levels of seaweed can hinder digestion by interfering with proteolytic enzymes, leading to poor protein utilization, reduced nutrient absorption, and lower growth. However, proper processing methods can break down these complex compounds and improve nutrient availability, allowing better feed efficiency and performance.

Feed conversion ratio

Improvements to FCR could be partly due to the presence of various bioactive compounds (carotenoids, polysaccharides, amino acids, and fatty acids) that significantly improve the palatability and, consequently, intake of feed, hence improving feed utilization. Several studies reported that dietary seaweed inclusion resulted in a lower FCR in Nile tilapia, *Salmo salar*, *Pagrus major*, *Acanthopagrus schlegelii*, and *Labeo rohita*. Bioactive substances have been shown to stimulate the secretion of several enzymes (amylase, lipase, and protease) that are known to enhance the digestion of essential nutrients as well as their assimilation into fish tissues.

Feed Palatability

The palatability of aquafeed is one of the most crucial factors influencing the consumption of feeds by farmed species. However, the palatability of an aquafeed is largely influenced by the nutrient composition of its ingredients as well as feed processing techniques, nutrient digestibility, water stability, and species-specific nutritional requirements and physiology of fish. (**Kamunde et al., 2019**). reported that Atlantic salmon consumed more feed when brown seaweed (*Laminaria* sp.) was included in the diet in comparison to a seaweed-free control feed. Similarly, greater consumption of an *Ulva* sp.-based diet was reported in seabream (*S. aurata*) and sea urchin (*Tripneustes gratilla*).

Feed digestibility

Feed efficiency in aquaculture largely depends on how well fish can digest the ingredients used in their diets. Seaweeds can be included without major issues at moderate levels—for example, certain species like *Ulva* can be used up to around 20% in tilapia diets without affecting nutrient digestibility, although higher inclusion or substitution levels may reduce protein utilization. Digestibility varies depending on the type of seaweed, the fish species, and the overall feed composition. Herbivorous and omnivorous fish generally handle seaweed better because they possess enzymes that can break down complex carbohydrates, while carnivorous species have a limited ability to do so. As a result, the success of incorporating seaweed into aquafeeds is strongly influenced by the feeding habits and digestive physiology of the cultured species.

Immunity and Disease Resistance

A feeding trial on Nile tilapia evaluated the effects of incorporating *Ulva lactuca* into the diet as a functional feed additive. Fish were fed a diet supplemented with moderate levels of *Ulva* over several weeks. The results showed a clear improvement in innate immune responses, including increased lysozyme activity, higher white blood cell counts, and enhanced phagocytic activity. In addition, antioxidant status was significantly improved, indicating better stress resistance. These physiological changes translated into increased survival rates when the fish were exposed to pathogenic bacteria, demonstrating improved disease resistance. The study highlights that dietary seaweed supplementation can serve as an

effective, eco-friendly alternative to antibiotics by strengthening the natural defense system of fish.

Antioxidant response

Seaweeds serve as effective natural antioxidants in aquaculture, enhancing fish health by boosting key enzymes such as SOD, GPx, and catalase, which help reduce oxidative stress and cellular damage. Studies have shown that seaweed extracts can improve antioxidant and immune responses in grouper, while inclusion of *Gracilaria* enhances GPx activity in European seabass due to its selenium content. Similarly, *Laminaria* supplementation increases overall antioxidant capacity in Atlantic salmon, and improved stress resistance has been observed in rainbow trout fed *Gracilaria pygmaea*. In addition, *Ascophyllum nodosum* helps reduce lipid peroxidation and supports antioxidant status. Overall, the benefits of seaweed depend on the type used, inclusion level, and fish species.

Gut microbiota composition

Seaweeds can improve gut health in fish, but only at the right inclusion level. Moderate amounts generally promote beneficial microbes and suppress harmful ones, while higher levels may reduce microbial diversity and affect digestion. For example, around 4% *Gracilaria gracilis* improved gut bacteria in European seabass, whereas 8% reduced diversity. Similarly, about 30 g/kg fucoidan from *Undaria pinnatifida* enhanced gut function in gibel carp, and 3 g/kg *Sargassum dentifolium* reduced harmful bacteria in Pacific white shrimp. Low levels (<3%) of *Ulva ohnoi* also improved microbial balance, showing that controlled inclusion is key for better gut health.

Conclusion

Seaweeds are increasingly recognized as valuable functional ingredients for sustainable aquaculture, but their inclusion in feeds must be carefully optimized according to the digestive capacity of each species, as excessive levels can negatively affect nutrient absorption and metabolism. Their effective use depends on advanced processing techniques such as enzymatic hydrolysis and fermentation, which help reduce anti-nutritional factors and contaminants while improving nutrient bioavailability. Establishing harmonized global regulations for contaminant limits is also essential to ensure safety and support trade. Beyond basic nutrition, seaweeds offer additional benefits by acting as prebiotics and immunostimulants, enhancing fish health and reducing the need for antibiotics. Future advancements should focus on precision nutrition using omics technologies to develop species-specific feed formulations, allowing seaweeds to transition from a supplementary ingredient to a key component of next-generation, health-oriented aquafeeds.

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