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Seaweed as a functional feed supplement in animal diet–A review

P BAGAVAN REDDY[1✉], A DAS[1] and A K VERMA[1]

ICAR-Indian Veterinary Research Institute, Izatnagar, Bareilly, Uttar Pradesh 243 122 India

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ABSTRACT

Seaweeds or marine macro-algae are multicellular organisms that grow abundantly along the coastal line. The use of seaweeds as animal feed is a very common practice in coastal areas since ancient times. Generally, seaweeds are categorized into green, brown, and red seaweeds, based on their colouring pigments. Commercially, seaweeds are used as a source of phycocolloids, fertilizer, livestock feed, and for direct human consumption. The use of seaweeds as livestock feed gained much importance in recent years, as they have good nutritive value and also contain a variety of bioactive compounds that are responsible for many health related benefits. The bioactive compounds of seaweeds exhibit prebiotic, antimicrobial, antioxidant, anti-inflammatory, anticancer and immunomodulatory effects. Over the years, the beneficial effects of using seaweed in animal diets have been studied and reported by many researchers to promote the health and productive performance of livestock. In particular, the brown seaweeds were explored extensively as livestock feed because of their large size. The nutrient value and bioactive compounds concentration in seaweed varies with the species, growing conditions, habitat, environmental changes, season, harvesting procedure, and time. While including seaweed in animal diets all these factors should be taken into consideration. In this review, all the studies related to seaweed supplementation in animal diets will be discussed with a special focus on the potential health benefits.

Keywords: Antimicrobial, Antioxidant, Anticancer, Functional feed, Livestock, Seaweed

Seaweeds or marine macroalgae, grow in large quantities along the coastal line, are the main resources for variety of phycocolloids such as agar, alginates, and carrageenan that have wide range of applications in food, pharmaceutical, animal feed industries. Seaweeds are also rich in functional bioactive compounds like indigestible sulfated-polysaccharides, proteins, polyunsaturated fatty acids (PUFA), pigments like carotenoids, phycobiliproteins (Paul *et al.* 2024), polyphenolic compounds such as phenolic acid, phlorotannins, and flavonoids and minerals like Ca, K, Mg, Zn, Mn, I, Se (Angell *et al.* 2016, Makkar *et al.* 2016) and also a good source of dietary fiber, and protein with well-balanced amino acid profiles (Machado *et al.* 2020). Seaweed bioactive compounds are shown to have nutritional value as well as health benefits when used in animal diets.

Seaweed and their extracts gained good importance in recent years because of their potential as a strong antimicrobial, antioxidant, anti-inflammatory, and immunomodulatory agents (Morais *et al*. 2020, Lomartire *et al*. 2021). Supplementation of seaweeds in animal diets has shown to have positive effects on milk yield, antioxidant status, and immune profile (Singh *et al.* 2017, Maheswari *et al.* 2021, Anderson *et al.* 2023). Considering the potential benefits that seaweeds offer to the different livestock species, it is more obvious to use them as functional feed supplements for livestock (Makkar *et al.* 2016). The information about the possible health advantages of different seaweed species and their role as a functional animal feed is included in this overview.

Seaweed types: There are around 10,000 different species of seaweeds that exist in the world in different forms and sizes, and only 5% of them are utilized as food for humans and animals (Makkar *et al.* 2016). In general, marine seaweeds are classified into red (Rhodophyceae), brown (Phaeophyceae), and green (Chlorophyceae) algae based on the colouring pigments. Brown seaweeds are more explored as animal feed than red and green seaweeds because of their larger size and ease of harvesting. As compared to red and green algae, brown algae are having less nutritional value as they are poor in protein content and have higher ash content (Makkar *et al.* 2016).

Seaweed cultivation and availability in India: India with 7,516 km of long rich bio-diverse coastline has a huge scope for seaweed production and its contribution to global seaweed market. Seaweed cultivation is growing worldwide due to increased demand for seaweed as a source of phycocolloids, fertilizer, livestock feed, and human food. India has produced 34,000 tonnes of seaweed in 2021, which is 2.5% of the production potential of our

Present address: [1]ICAR-Indian Veterinary Research Institute, Izatnagar, Bareilly, Uttar Pradesh. ✉Corresponding author email: bhagavanreddyperudi3@gmail.com

country (Reddy *et al.* 2023). As per the CMFRI report, India has a potential to produce 9.7 MT in 342 identified potential coastal sites (Mohamed 2015). In order to boost the seaweed cultivation in India, the government has taken several initiatives like establishment of seaweed parks in the coastal states under PM Matsya Sampada Yojana (PMMSY) with an aim to raise the level of production to 11.5 million MT by 2025 (Mantri *et al.* 2022).

In India, seaweeds grow abundantly along the coastal states of Tamil Nadu and Gujarat and also around Lakshadweep and Andaman and Nicobar Islands. Out of approximately 700 species of marine algae found in both inter-tidal and deep-water regions of the Indian coast, nearly 60 species are commercially important (Mohamed 2015). Agar yielding red seaweeds such as *Gelidiella acerosa* and *Gracilaria spp.* are collected throughout the year while algin yielding brown algae such as *Sargassum spp.* and *Turbinaria conoides* are collected seasonally from August to January in Southern coastal states.

Seaweed nutritive value: The chemical composition of the seaweed changes with the species, growing season, location, climate, and post-harvest processing. Fresh seaweeds contain about 70-90% water, macro, and micronutrients as well as bioactive compounds. Different bioactive compounds present in the seaweeds is depicted in Supplementary Table 1. Among the three types of algal forms, red and green seaweeds are a rich source of carbohydrates whereas; brown seaweeds are the source of soluble fiber and iodine (Gupta and Abu-Ghannam 2011a). Seaweeds are a good source of a variety of nutrients such as dietary fiber, protein, lipids, vitamins (A, B, C, D, and E) minerals (Ca, P, Na, K, I) (Ahmed *et al*. 2022), PUFA, carotenoids, polyphenols, and pigments (Maheswari *et al*. 2021). Seaweeds are rich sources of structural (cellulose, hemicellulose, and xylose) and storage polysaccharides such as carrageenan, laminarin, fucoidan, alginic acid, alginate, and agar (Cherry *et al*. 2019), which are having economic importance. Seaweeds contain crude protein (CP) ranges from 5-35%, which is considered of high quality compared to soybean meal and fishmeal due to higher essential amino acids, in particular red seaweeds typically have a higher quality of protein (more methionine and lysine concentrations) than brown and green seaweeds (Angell *et al*. 2016). The seaweed proteins are having high nutritional value because they are rich in aspartic acid, glutamic acid, leucine, and isoleucine, while tryptophan, threonine, sulphur-containing amino acids, and histidine are limited, but still, their concentration is found to be higher than the terrestrial plants (Ganesan *et al*. 2020). The lipid content of the seaweed ranges from 1-5% with a good amount of PUFA especially n-3 and n-6 fatty acids, which play importantrole in health performance. The chemical composition of some commonly used seaweed, red seaweed (Anderson *et al*. 2023), brown seaweed (Singh *et al*. 2017, Samarasinghe *et al*. 2021), green seaweed (El-Banna *et al*. 2005) in animal diet is presented in Table 1. In addition to their nutritive value seaweeds also exhibit some additional therapeutic and pharmacological properties such as antimicrobial, antioxidant, anti-inflammatory, anti-cancer, and immunomodulatory functions (Bach *et al*. 2008). Antimicrobial activity of seaweeds is presented in Supplementary Table 2.

Prebiotic action: The recent research studies in the area of diet-host-microbe interactions provided a scope to exploit the host gut microbiome through the functional dietary ingredients such as prebiotic compounds to maintain the healthy gut and to prevent the occurrence of several diseases by strengthening the immune system. Prebiotic is a substrate that is selectively utilized by some beneficial microorganisms that offers health benefits to the host. Seaweeds are a rich source of non-complex polysaccharides such as alginate, fucoidan and laminarin of brown seaweeds, galactans (agar, carrageenan, porphyran) from red seaweeds, and xylan and ulvan from green seaweeds, which can act as prebiotics and exert positive effects on gut health by acting as substrate for the growth of health-positive bacteria (Cherry *et al*. 2019).

In particular, brown seaweeds are having a higher content of indigestible polysaccharides, such as laminarin, and fucoidan, as compared to green and red seaweeds and they are proven to have positive effect on gut health as prebiotics when offered in animal diets (Gupta and Abu-Ghannam 2011a). The prebiotic potential of brown seaweed derived alginate oligosaccharides (AOS) was confirmed on supplementation of 2.5% to Wistar rats. AOS supplementation improved the caecal and faecal *Bifidobacteria* and *Lactobacilli* as compared to the control (Wang *et al*. 2006). Laminarin and fucoidan are effective against both gram-positive and gram-negative pathogenic bacteria (Kamenarska *et al*. 2009). Laminarin mainly

Table 1. Chemical composition of some common seaweeds used in livestock diets

Attribute	Red seaweed			Brown seaweed		Green seaweed
	Kappaphycus alvarezii	*Gracilaria salicornia*	*Euchema spinosum*	*Ascophyllum nodosum*	*Sargassum wightii*	*Ulva lactuca*
Organic matter (%)	67.58	48.88	66.86	70.50	68.00	77.80
Crude protein (%)	6.14	6.94	5.60	11.40	10.10	24.82
Ether extract (%)	1.57	1.59	1.52	3.00	1.10	2.45
Crude fibre (%)	19.14	18.87	16.49	5.50	11.30	12.31
Nitrogen free extract (%)	53.45	26.40	43.25	50.60	45.50	38.22
Total ash (%)	32.42	51.12	27.80	29.50	32.00	22.20

consists of β-glucans which are indigestible components and are well utilized by health-beneficial organisms like *Bifidobacteria* and *Lactobacilli spp.* in the hindgut that reveal its prebiotic function (Jaskari *et al*. 1998). Laminarin can indirectly modulate gut health through microbial production of short-chain fatty acids (SCFA), especially butyrate, which is the main energy source for colonocytes, and stimulates cell growth (Lynch *et al*. 2010). In recent studies, it was found that laminarin was able to reduce the pathogenic *Escherichia coli* population and improved the health-promoting *Lactobacilli*, *Enterobacteria*, and *Bifidobacteria* in weaned piglets (O'Doherty *et al*. 2010). The carrageenan rich red seaweed (*Chondrus crispus*) supplementation improved faecal bifidobacteria and SCFA, with the concurrent reduction in health negative bacteria, i.e. *Clostridium septicum* and *Streptococcus pneumonia* in rats (Liu *et al*. 2015).

Antioxidant activity: Seaweeds in their natural habitat are exposed to variety of stress factors such as salinity, extreme environmental temperatures, UV radiation and pollutants. Seaweeds can withstand adverse effects of biotic and abiotic stress factors due to their ability to synthesize certain protective secondary metabolites. An important group of such seaweed secondary metabolites that exert antioxidant activity are phenolic compounds such as phenolic acids and polyphenols (flavonoids and non-flavonoids), carotenoids fucoxanthin, and sterols (Balboa *et al*. 2013). These secondary metabolites actively scavenge the free radicals and prevent oxidative damage of the cells (Begum *et al*. 2021).

The major group of antioxidant compounds present in seaweeds are phenolics, polysaccharides, and pigments (Michalak *et al*. 2022). The phenolics that are found in seaweeds include simple phenolic acids (hydroxy cinnamic acid and hydroxy benzoic acid), and polyphenols such as flavonoids (flavones, flavanol, flavanones, anthocyanins, iso-flavones), nonflavonoids (phlorotannins, lignans and stilbenes). Phlorotannins are found to be the major phenolic compounds that present in brown seaweeds (Corona *et al*. 2016, Aminina *et al*. 2020), whereas; flavonoids, other carotenoid pigments are stable antioxidants in red seaweeds. Brown seaweeds are reported to have higher antioxidant activities as compared to green and red seaweeds (Cox *et al*. 2010, Kindleysides *et al*. 2012). The seaweed polysaccharides such as fucoidan, alginate and laminarin of brown seaweeds, agar and carrageenan of red seaweeds and ulvan from green seaweeds were also found to have an antioxidant activity (Liu and Sun 2020). Especially, sulfated polysaccharides (fucoidan, carrageenan, ulvan) of marine algae are found to have excellent antioxidant activity (Salehi *et al*. 2019). In addition to this, natural pigments such as chlorophyll, carotenoids (carotene, lutein, fucoxanthin, zeaxanthin), phycobiliproteins, and some other micronutrients that present in seaweeds are responsible for the antioxidant potential of seaweeds (Kumar *et al*. 2021). However, the composition of seaweeds varies with species, habitat, climate, environment, and location. Hence, selection of seaweed compounds as an antioxidant substance in animal diets should be dependent on the prior analysis of compounds (Michalak *et al*. 2022). *In vitro*, antioxidant assay confirmed that the brown algae extracts were found to have similar or superior antioxidant activity than the synthetic antioxidants (Balboa *et al*. 2013). Microminerals such as Se, Zn, Mn, and Cu are found in marine algae, and they are structural elements of some antioxidant enzymes, which may help in improving the antioxidant activity when consumed (Baghel *et al*. 2023). Weaning induced oxidative stress in pigs was found to be reversed by the supplementation of brown seaweed derived alginate oligosaccharides (Wan *et al*. 2016, 2017, 2018).

Anti-inflammatory action: The nutritional management of chronic inflammatory conditions in livestock is very important in maintaining the normal health and well-being. Seaweeds and their extracts are shown to have anti-inflammatory effects and for this reason they are widely used in pharmaceutical industry (Lomartire and Gonçalves 2022). The bioactive compounds of the seaweeds with anti-inflammatory effects can reduce the pro-inflammatory responses when included at a suitable level in the diet. The fucoidans from the seaweeds especially the brown seaweeds were shown to have anti-inflammatory activities (Ananthi *et al*. 2010). Polysaccharides from Enteromorpha seaweed effectively reversed the inflammation of the distal colon in constipated mice (Ren *et al*. 2017). The anti-inflammatory effect of fucoidan extract of *Fucus vesiculosus* was tested against the paw edema of rat and it was found that fucoidan based cream is shown to effectively reduce the paw edema (Obluchinskaya *et al*. 2021). Polysaccharides from the *Sargassum fulvellum* improved the viability of microphages treated with lipopolysaccharides (LPS) by decreasing the level of inflammatory mediators such as nitric oxide (NO), TNF-α, prostaglandin E_2 (PGE_2), IL-1 β, and IL-6 (Wang *et al*. 2021).

Antimicrobial activity: In recent years, the prophylactic usage of antibiotics in livestock has been banned by the many European countries, due to the growing concern about increased antimicrobial resistance (AMR) (Bennani *et al*. 2020). As a result of this, now researchers are working towards finding novel, risk-free, and natural compounds like prebiotics, herbal supplements, and phytogenic feed additives with antimicrobial properties as alternative agents to antibiotic growth promoters in livestock (Abdallah *et al*. 2019, Ranjan 2022, Paul *et al*. 2024). In this context, seaweed and its extracts gained good importance in recent years because of their antibacterial (Layana *et al*. 2019, Vennila *et al*. 2020), antifungal (Prabha *et al*. 2013), antiviral (Santos *et al*. 2019), antiprotozoal (Lane *et al*. 2009) effects. The primary or secondary metabolites of seaweeds are potential bioactive compounds associated with antimicrobial activities (Gupta and Abu-Ghannam 2011b). The antimicrobial compounds present in marine algal extracts are polysaccharides, fatty acids, peptides, phlorotannins, polyacetylenes, sterols, hydroquinones, bromophenols, terpenes, alkanes, alkenes, aldehydes, ketones and sesquiterpenes (Shannon and Abu-Ghannam 2016, Das *et al*. 2023). Phlorotannins present in brown seaweeds have been shown to exhibit antimicrobial activity against food-borne bacteria (Nagayama *et al*. 2002). The antimicrobial activity of the phlorotannins was due to their ability to bind with bacterial proteins such as enzymes and cell membranes and causes cell lysis (Shannon and Abu-Ghannam 2016). Out of the different extracts of brown seaweeds that were tested for their antimicrobial activity against the *Propionibacterium*, an alcohol substituent of phlorofucofuroeckol was shown to exhibit potent antimicrobial activity (Lee *et al.* 2014).

Immunomodulatory activity: The intensification of the livestock production system in recent years, put food animals under severe production stress. This stress further compromises the animal performance and health by causing damage to the immune system. It is well known that such immunocompromised individuals are much prone for infectious diseases. In such scenario, feeding natural plant-based products with immunomodulatory activity will be very much beneficial to activate the immune cells. The antioxidant compounds such as phenols and polyphenols present in seaweeds are responsible for the protection of immune cells from the oxidative damage in stress conditions (Michalak *et al*. 2022).

The immunomodulatory activity of seaweed polysaccharides was due to their ability to stimulate the release of cytokines and chemokines that further activate the immune cells (Leonard *et al*. 2011). The water soluble β-glucans (laminarin and porphyran) present in seaweeds can stimulate the host immune system by activating dectin-1 receptors present on the surface of monocytes, macrophages and neutrophils (Volman *et al*. 2008). Supplementation of *Sargassum spp*. enhanced the immunoglobulin (IgA) level in the intestines of goat kids indicating the immunostimulatory effect of the seaweed (Angulo *et al.* 2020). The circulatory and milk immunoglobulin (IgA and IgG) levels of lactating sows were enhanced on supplementation of seaweed polysaccharides (Bussy *et al*. 2019). The brown seaweed supplementation shown to improve the immunity of the Hanwoo steers by increasing the immunoglobulin (IgG) level in blood (Hwang *et al*. 2014).

Anti-cancer activity: Cancer is one of the major health related problems worldwide for humans as well as animals. Despite of several decades of research, still there is no full effective treatment strategy available for treating and managing the cancer (Zugazagoitia *et al*. 2016). So, there is a need to develop some novel anticancer agents with minimal or no side effects to improve the quality of life of a cancer patient. Now, the focus turned towards the marine organisms, such as seaweeds as a potential source of several functional compounds with anticancer activity (Gutierrez-Rodriguez *et al*. 2018). The *in vitro* anticancer activity of three selected brown seaweeds namely, *Saccharina cichorioides, Saccharina japonica,* and *Fucus evanescens* were tested against human colorectal and breast adenocarcinoma cells and it was found that the sulfated compounds (Laminarin) of brown seaweeds effectively inhibited the proliferation, colony formation and migration of cancer cells (Malyarenko *et al*. 2017). Phlorotannins of brown algae also exhibit anticancer activities (Athukorala *et al*. 2006). The fucoidan from brown seaweed was also found to have beneficial effect in the treatment and prevention of some cancers (Gamal-Eldeen *et al*. 2009). The *in vitro* antitumor activity of the fucoidan extracted from the brown algae (*Cladosiphon okamuranus*) was found to be satisfactory when tested against the human stomach cell lines (Kawamoto *et al*. 2006).

Seaweed in ruminant diet: The macroalgae have already been identified as an alternative feed resource for ruminants from ancient days (Makkar *et al*. 2016, Morais *et al*. 2020). The use of seaweeds in ruminant diet mainly depends on the chemical composition of algae and adaptation of animal to particular algal species. Seaweeds are usually incorporated in the diet of ruminants either as feed supplement or feed additive. Effect of seaweed supplementation in cattle and buffaloes under Indian conditions is depicted in Table 2. The brown seaweed *Ascophyllum nodosum* is most commonly fed to the ruminants due to their large size and is found to improve the growth rate in ruminants (Allen *et al*. 2001, Makkar *et al*. 2016). The beneficial effects of seaweed bioactive compounds in small ruminants in terms of improved antioxidant status and immunity have been reported by many researchers (Kannan *et al*. 2007, Angulo *et al.* 2020). The inclusion of brown seaweed (*Undaria pinnatifida*) at 2% level in the diet of Hanwoo steers improved growth rate by increasing average daily gain (ADG) with improved feed efficiency (Hwang *et al*. 2014). The improved growth rate in ruminants on supplementation of brown seaweed is attributed to their phlorotannin content which helps in better utilisation of protein by ruminants (Hwang *et al*. 2014).

Seaweeds are also known to reduce the methane production and the anti-methanogenic property of seaweed is proved by many *in vitro* and *in vivo* experiments (Machado *et al*. 2016, Roque *et al*. 2019a). The use of seaweeds in animal diets can be a viable option to reduce the carbon foot print of ruminant animals and to increase the production of efficiency of livestock (Roque *et al*. 2021). The naturally synthesized halogenated compounds such as bromoform present in seaweeds are responsible for their antimethanogenic activity (Roque *et al*. 2019b). The effect of brown seaweed extracts on the rumen fermentation and methane yield was assessed by an *in vitro* experiment and it was found that the seaweed extracts can modify the rumen fermentation characteristics by increasing DM digestibility and VFA concentration in rumen and decreasing methane yield (Choi *et al*. 2021). The *L. japonica* as a feed additive (20% of basal diet) shown to improve the *in vitro* VFA concentration without having any effect on methane production, and the same seaweed when used as feed by replacing 20% of concentrate shown to reduce the methane yield with some detrimental effects on rumen fermentation (Ahmed *et al*. 2022). Goats supplemented with brown seaweeds are shown to emit lesser methane as compared to non-supplemented group (Nirmala *et al*. 2018).

The bioactive compounds present in seaweeds not only improve the performance and health status but also can enhance the milk production (Sharma *et al*. 2022). The feeding of seaweed to the lactating cows and buffaloes had been shown to improve the milk yield with good protein and fat content (Singh *et al*. 2017, Maheswari *et al*. 2021). Several research studies proved that supplementation of seaweeds at lower doses have the ability to enhance milk quantity, quality and performance; however, at higher doses shown to have adverse effects in terms of reduced feed intake, milk production and performance (Roque *et al*. 2019a). The bioactive compounds of seaweeds deposited into the muscles and tissues of the animals and can improve the quality of meat (Hwang *et al*. 2014). Overall, it can be inferred that at optimum inclusion of seaweed in the diet of ruminants can improve the lactation efficiency, health, performance and quality of milk and meat.

Seaweed in swine diet: Effect of seaweed supplementation in swine is presented in Table 3. In swine nutrition, novel alternative feed supplements are needed to improve the health and welfare of the pigs. Especially during post-weaning phase, the gastrointestinal tract of piglets undergoes undesirable morphological and physiological changes which make the piglet more susceptible for gut related infections. In order to control such conditions, it is more essential to develop some novel, safe, natural feed ingredients with antimicrobial, antioxidant and immunostimulatory properties (Rattigan *et al*. 2020). Marine algae is one such feed supplement that can be incorporated into the swine diet because of the presence of a variety of bioactive compounds and their associated health benefits. In recent years, the use of seaweed in pig nutrition has given promising results in terms of improved growth performance (Heim *et al*. 2014a, 2014b, Draper *et al*. 2016, Ruiz *et al*. 2018), nutrient digestibility (O'shea *et al*. 2014), and prebiotic (Corino *et al*. 2019), antioxidant, anti-inflammatory, and immunomodulatory activities (Bussy *et al*. 2019). The use of seaweeds and their extracts in swine diets as an alternative to feed antibiotics was studied and beneficial effects were also reported (Corino *et al*. 2019).

Especially the indigestible seaweed polysaccharides such as laminarin, fucoidan, alginate and ulvan were mostly explored in swine studies to test their efficacy on performance, gut health and immunity of pigs. Laminarin and fucoidan, from brown seaweeds are of particular importance due to prebiotic action they exert positive effect on gut health in pigs (Choi *et al*. 2017). The inclusion of laminarin and fucoidan in the diet of weaned piglets increased the coefficient of apparent total tract digestibility (CATTD) of dry matter (DM), crude protein (CP), and neutral detergent fiber (NDF) (McAlpine *et al*. 2012). Brown seaweed supplementation in the piglets stimulated the growth of health-positive bacteria such as *Lactobacillus* and *Bifidobacteria* species and reduced the population of *Escherichia coli* (Mukhopadhya *et al*. 2012, Murphy *et al*. 2013, Wan *et al*. 2016). Improved gut microbial status and enhanced immunity were observed when the swine diet was supplemented with seaweeds (O'Doherty *et al*. 2010). Maternal supplementation of seaweed powder showed to improve the immune status of the suckling piglets through the transfer of immunoglobulins from lactating sow to piglets via milk (Azizi *et al*. 2018). The inclusion of seaweeds in swine diets can greatly replaces the use of feed antibiotics, organic acids and other growth promoters and can improve the production of swine industry without any adverse effects.

Seaweed in poultry: Seaweed has been in use as an alternative feed resource in poultry ration and many countries approved the use of seaweed as poultry feed. Results of seaweed supplementation in poultry. Seaweed polysaccharides have prebiotic properties that positively influence the gut microbiota and reduce the pathogenic bacteria and improve the overall gut health status (Cherry *et al*. 2019). Maintaining a healthy gut is very much important in poultry production otherwise it may adversely

Table 2. Effect of seaweed supplementation in cattle and buffaloes under Indian conditions

Seaweed spp.	Animal	Outcome	Reference
Kappaphycus alvarezii, Gracilaria salicornia, and *Turbinaria conoides*	Murrah buffaloes	No effect on nutrient intake and digestibility	Chugh *et al*. (2021)
Sargassum wightii	Sahiwal cows	No effect on mineral metabolism and blood-milk mineral profile	Singh *et al*. (2016)
Sargassum wightii	Sahiwal cows	Increased milk yield without causing any changes in the milk composition	Singh *et al*. (2017)
Kappaphycus alverazii, Gracilaria salicornia, Turbinaria conoides	Crossbred calves	Improved the concentration of Hb, lymphocytes, and L: N ratio, and serum concentration of globulin	Munde *et al*. (2018)
Kappaphycus alverazii, Gracilaria salicornia, Turbinaria conoides	Murrah buffaloes	Improved antioxidant status, immunity, and milk yield	Maheswari *et al*. (2021)
Kappaphycus alverazii, Gracilaria salicornia, and Eucheuma spinosum	Crossbred calves	Improved immune response without showing any effect on antioxidant status, serum metabolites, and growth performance	Anderson *et al*. (2023)

Table 3. Effect of seaweed supplementation in swine

Seaweed spp.	Animal	Dose	Outcome	Reference
Laminaria spp. extract (Laminarin and Fucoidan)	Pregnant sow	10 g/d	Improved IgG in colostrum. Elevated IgG and IgA in suckling piglets.	Leonard *et al*. (2010)
Laminaria spp.	Pregnant sow (from 83rd day to weaning)	10 g/d	Improved ADG of suckling piglets. Increased villus height in ileum.	Heim *et al*. (2014a)
Brown seaweed (Alginic acid oligosaccharide)	Weaned piglets	100 mg/kg	Improved ADG. Enhanced superoxide dismutase (SOD), catalase (CAT) and total antioxidant levels, and reduced lipid peroxidation. Improved immune profile.	Wan *et al*. (2016)
Ecklonia cava	Weaned piglets	0, 0.05, 0.1 and 0.15% of basal diet	Improved growth performance. ↑ *Lactobacillus* count ↓*Clostridium* and *E. coli*	Choi *et al*. (2017)

affect the growth performance and the overall economic potential of the farm. A healthy intestinal microbial profile determines the health status of gut. Seaweed polysaccharides as prebiotics can selectively improve the health-beneficial microbes. Some researchers have found that the supplementation of seaweed in a poultry diet did not show any adverse effect on the palatability and intake of the feed (Abudabos *et al*. 2013, Kulshreshtha *et al*. 2014; 2017). However, the level of seaweed inclusion in poultry ration is comparatively lower than the other animal diets due to the presence of higher levels of indigestible fiber and minerals.

In poultry diets, seaweeds can be used as a source of macro and micronutrients (Azizi *et al*. 2021) and have the potential to be used as an antibiotic replacer (Balasubramanian *et al*. 2021). Seaweeds can improve the immune status of birds and can reduce the pathogenic bacteria in the gut through their antimicrobial activity (Paul *et al*. 2024). The supplementation of red seaweed in the diet of layer chicken shown to improve the growth performance, egg laying, and gut health status through its probiotic activity (Kulshreshtha *et al*. 2014). Seaweed is known to reduce egg cholesterol and improve the overall health of the chicken (Carrillo *et al*. 2009). The red seaweed (*Chondrus crispus*) supplementation at 4% level in poultry ration was shown to protect the laying hens from *Salmonella enteritidis* colonization and improved the immune status of the birds by enhancing IgA levels (Kulshreshtha *et al*. 2017). Wang *et al*. (2013) found enhanced activity of amylase in the duodenum of broilers supplemented with *Enteromorpha prolifera*. When seaweeds are used at right doses in poultry ration, can improve health status by enhancing antioxidant and immune status, decrease the harmful microbial load in the gut and can improve the quality of meat and eggs (Abudabos *et al*. 2013, Karimi *et al*. 2015).

Marine macroalgae or seaweed could be an important feed supplement for livestock because of their nutritive value and health-promoting effects. The use of seaweeds in the animal diet not only improves animal food security but also improves overall health status and maintain productivity. Recent studies have shown that the bioactive components of seaweeds can have a beneficial effect on gut health by improving intestinal mucosal metabolism, which in turn helps in better absorption and utilization of nutrients,

Table 4. Effect of seaweed supplementation in chicken

Seaweed	Inclusion level	Finding	References
Red seaweed *Palmaria palmata*	0.6%, 1.2%, 1.8%, 2.4% and 3% in broiler chicken	↑ *Bifidobacterium* ↑ *Lactobacillus (ileum)* ↓*Clostridium perfringens* ↑ IgA and G Best response at 1.8% level The increasing trend in the size of villus height, width, villus surface area, and mucosal depth	Karimi *et al*. (2015)
Brown and green seaweeds	90.30% in broiler chicken	Apparent ileal digestibility of CP and CF is higher in brown seaweed-fed chicken than in green seaweed-fed group	Azizi *et al*. (2021)
Red seaweed *Palmaria palmata*	0%, 0.05%, 0.10%, 0.15% and 0.25% broiler chicken	Increased total tract DM digestibility with increasing dose. Improved faecal *lactobacillus* and decreased *E. coli* and *Salmonella spp* Enhanced villi height and width and reduced faecal gas emissions (NH_3 and H_2S)	Balasubramanian *et al*. (2021)
Green seaweed *Ulva* spp.	0%, 2%, 2.5%, 3%, and 3.5% in Boschveld chickens	Increased feed intake Improved body weight gain No effect on nutrient digestibility	Nhlane *et al*. (2020)

and have other beneficial effects such as antimicrobial, antioxidant, anticancer, and immunomodulatory effects which ultimately helps in better health status and improved productivity of livestock.

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