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REVIEW ARTICLE

Potential of Macroalgae in Ruminant Nutrition

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ABSTRACT

Seaweeds broadly classified as brown, red, and green algae, are rich in proteins, essential amino acids, polyunsaturated fatty acids, vitamins, and minerals, along with bioactive polysaccharides such as laminarin, fucoidan, carrageenan, and ulvan. These compounds exert diverse biological effects, including antioxidant, anti-inflammatory, prebiotic, and immunomodulatory functions, thereby improving gut health, feed efficiency, and overall productivity of ruminants. of particular importance is their ability to mitigate enteric methane emissions. Certain red seaweeds, such as *Asparagopsis* species, contain halogenated compounds like bromoform, which inhibit methyl-coenzyme M reductase, the key enzyme in methanogenesis, leading to significant reductions in methane output while redirecting hydrogen toward propionate formation, an energetically favorable pathway. This dual role of enhancing nutrient utilization and reducing environmental burden underscores their significance. Despite these advantages, challenges remain, including variability in nutrient composition across species

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and seasons, presence of recalcitrant polysaccharides that hinder digestibility, risks of heavy metal accumulation, excessive iodine levels, and nutrient instability during processing. Addressing these constraints through standardized harvesting, processing, and supplementation strategies will be critical for large-scale adoption. Overall, macroalgae hold great promise as a renewable, nutrient-dense, and eco-friendly feed additive and their inclusion in ruminant diets can improve animal health and productivity, reduce reliance on conventional feed resources, and contribute to global efforts in climate change mitigation and sustainable livestock production.

KEYWORDS

• Macroalgae • Seaweed • Methane Mitigation • Prebiotic • Feed Additive

INTRODUCTION

The livestock production system occupies 30-40% of the world's cultivable land and 32% of the freshwater, thus competing with the human food production systems for resources (Mottet *et al.,* 2017). This competition between humans and animals can be counterproductive to human food security (Van Zanten *et al.,* 2019) and should be minimized as much as possible. With the increasing land degradation, depletion of fresh water, and climate change, the feed production system in the future may be severely affected, which can cause shortages of feeding resources for livestock. Hence, recognising new and alternative feeding resources with minimal competition as human foods and the more efficient utilization of the locally available feed resources would play a vital role in managing sufficient and quality feeding materials for sustainable livestock production in the future (Makkar *et al.,* 2016). Another major challenge to the livestock production sector is to minimize enteric methane emissions that mostly originate from the ruminant's digestive system via enteric fermentation of feeds. Ruminants are considered responsible for ~18% of total anthropogenic CH_4 releases a potent greenhouse gas with 28 times higher global warming potential than CO_2 (Mizrahi *et al.,* 2021). Enteric fermentation accounts for about 70% of the total CH_4 emissions from agriculture. The large livestock population in India is believed to contribute 9.25 Tg of CH_4 annually because of enteric fermentation. For every liter of CH4 generated, about 39.5 kilojoules of energy are squandered (Malik *et al.,* 2025). With a 28-fold greater potential for global warming than the most prevalent atmospheric carbon dioxide, methane is a powerful greenhouse gas. Reduction is not achievable without addressing the enteric CH_4 emissions. Apart from the global warming perspective, enteric CH_4 emissions also lead to a sizable loss of energy away from the host animal (Mohapatra *et al.,* 2025). India boasts an extensive coastline of approximately 7500 km, spanning nine states and four union territories, which presents a diverse array of seaweeds. In the Indian sea, approximately 844 species of seaweeds have been documented, comprising 434 red, 194 brown, and 216 green algae, with a potential availability of 58,000 tonnes (Malik *et al.,* 2025). The rich nutritional profile of seaweeds, like source of minerals, excellent sources of essential amino acids, a high content of prebiotic compounds, a rich source of carotenoid, and methane mitigating potential, makes them the best option for future feedstuffs.

SEAWEEDS: CLASSIFICATION

There are two major types of algae, i.e., macroalgae and microalgae. The term seaweed does not have any taxonomic value but is rather a popular term used to describe the common large marine algae (macroalgae). Macroalgae, are macroscopic and multicellular marine algae, are found in the littoral zone and can reach very enormous sizes as phytoplankton. Seaweeds are broadly classified into three groups based on pigmentation, i.e., phaeophyta (brown seaweeds), rhodophyta (red seaweeds), and chlorophyta (green seaweeds).

A) Brown algae:

Brown macroalgae, found from the upper intertidal to subtidal zones, can grow up to 45 m in length (Makkar *et al.,* 2016). They contain chlorophyll a, c, and fucoxanthin but generally have lower crude protein than green and red algae (Vieira *et al.,* 2018). Structurally, they are rich in alginates and fucoidan, while laminarin and mannitol serve as storage carbohydrates. Fucoidan exhibits diverse bioactivities, including anti-inflammatory, anti-tumor, antioxidant, anti-diabetic, and prebiotic effects (Shang *et al.,* 2017). Laminarin also shows anti-cancer, antimicrobial, antioxidant, and prebiotic functions (Zargarzadeh *et al.,* 2020). In addition, brown algae contain polyphenolic phlorotannins with bioactive potential (Gómez-Guzmán *et al.,* 2018). Common genera include Ascophyllum, Laminaria, Macrocystis, Nereocystis, Saccharina, Sargassum, and Undaria.

B) Green algae:

Green algae are usually found in the shallow waters and tide pools of the intertidal zone. Green algae have both chlorophylls a and b and carotenoids (Pereira 2016). Green macroalgae remain in the middle of red and brown species with a CP content of 5–33% of DM, Acrosiphonia, and Ulva spp., being the two richest species (Tayyab et al., 2016). Structural polysaccharides in green species are ulvan and cellulose, but they also contain a low amount of starch (1-4% of DM) (Zheng *et al.,* 2022). Some common genera of green algae: Chaetomorpha, Cladophora, Codium, Ulva.

C) Red algae:

Red algae spread from the low intertidal zone to a depth of 100m. Red algae, besides chlorophylls and carotenoids, are rich in phycobilins. Red macroalgae are well known for their abundance of carbohydrates, including carrageenan, agar, agarose, and agaropectin. Highest CP among macroalgae. Red seaweeds are rich in halogenated aliphatic organobromine compounds such as bromomethane, bromoform, and chlorine (Maschek and Baker 2008). Some common genera of red algae: Chondrus, Gracilaria, Palmaria, Prophyra, Pyropia, Kappaphycus, Asparagopsis.

Nutritional Profile of Seaweeds

The nutrient composition of seaweeds is not uniform; it varies with species, season of harvest, and environmental conditions such as water temperature, salinity, pH, light intensity, and nutrient availability in the surrounding water. A common feature across all seaweeds is their high moisture content, which generally accounts for 70–90% of their fresh weight. In terms of nutritional quality, red and green seaweeds usually provide more protein and less mineral matter compared to brown seaweeds, which are notable for their abundance of bioactive compounds. The chemical composition of some seaweeds are mentioned in Table 1.

A) Carbohydrates:

Carbohydrates make up the largest portion of seaweed dry matter (up to 70%), whereas lipids typically contribute less than 5% (Campos et al., 2019). Brown algae are particularly rich in complex polysaccharides such as cellulose, alginates, fucoidan, laminarin, and mannitol. Fibre fractions vary widely among species; for example, neutral detergent fibre levels range from 19.8–22.0% in *Ascophyllum* spp., 16.3–20.1% in *Laminaria* spp., 15.2–38.1% in *Undaria pinnatifida*, 25.9–41.5% in *Ulva* spp., and 33.5–40.8% in *Porphyra* spp. (Costa et al., 2021). Their total dietary fibre content is even higher, spanning from roughly 23% to nearly 58%, depending on the species.

B) Protein:

Protein concentration in seaweeds is highly variable. Brown algae such as *Laminaria* spp. are relatively poor in protein (0.6–16.1% of DM) (Tayyab et al., 2016), while red algae like *Porphyra* spp. can reach values of 24.1–44.0% DM. Across species, protein levels range from 5.6–12.1% in *Ascophyllum* spp., 15.7–22.2% in *Undaria pinnatifida*, 4.8–41.8% in *Ulva* spp., and 24.1–44.0% in *Porphyra* spp. (Costa et al., 2021). Red seaweeds generally offer higher-quality proteins, being rich in essential amino acids except for sulfur-containing ones. Seaweeds contain non-protein nitrogen, conventional crude protein estimates can be misleading; hence, nitrogen-to-protein conversion factors of 5.38 for brown algae, 4.92 for red, and 5.13 for green algae have been recommended (Guiry, 2014). Some species such as *Undaria pinnatifida* and *Palmaria palmata* possess amino acid profiles comparable to standard proteins, with essential amino acid indices of 95.9% and 103.7%, respectively, making them valuable for both human and animal nutrition. Methionine+cystine values in *Macrocystis pyrifera* and *Ulva* spp. are even higher than in soybean meal, supporting their potential as supplements for wool production. Seaweed proteins provide all major amino acids, with particularly high levels of glycine, alanine, arginine, glutamic acid, and aspartic acid, although their concentrations differ considerably between species. Nevertheless, lysine, methionine, and threonine are often limiting in seaweeds compared to conventional protein feeds, which may restrict their use in livestock diets. For example, lysine, methionine, and threonine contents in *Porphyra* spp. are 3.5–8.6%, 1.2–3.0%, and 5.8–8.7% of total amino acids, respectively (Costa et al., 2021).

C) Fat and lipids:

Seaweeds contain little crude fat, with levels ranging between 0.1% and 6.6% depending on the type, but are relatively high in ash due to their substantial mineral content. For instance, ash content varies from 0.8–30.9% in *Ascophyllum* spp. to as much as 73% in *Laminaria* spp. Carbohydrate storage also differs among groups: laminarin and mannitol are the main reserves in brown algae, Floridian starch predominates in red algae, and starch is the primary storage polysaccharide in green algae. Red algae also supply carrageenan, while green species provide ulvan and other sulfated polysaccharides (Lahaye & Robic, 2007).The lipid composition of seaweeds also shows interspecies variation. Their fatty acid profiles are dominated by polyunsaturated fatty acids, mainly omega-3 types such as 16:4n-3 and 18:4n-3, with some species also containing significant amounts of eicosapentaenoic acid (EPA, 20:5n-3) and, to a lesser extent, docosahexaenoic acid (DHA, 22:6n-3) (Kendel et al., 2015). Omega-6 fatty acids such as linoleic acid (18:2n-6) and arachidonic acid (20:4n-6) are also common. Reported EPA concentrations vary widely, from 0.4–2.6% in *Ulva* spp. to as high as 43% in *Porphyra*spp. (Costa *et al.,* 2021).

D) Minerals and Vitamins:

Mineral content in seaweeds is remarkably high, ranging from 10–50% DM, which is 10–20 times greater than in terrestrial plants (Moreda-Pineiro *et al.,* 2012). They are particularly rich in sodium, magnesium, calcium, potassium, iodine, and bromine, with certain brown algae like *Laminaria* spp. accumulating iodine at levels more than 30,000 times higher than seawater (Misurcová, 2012). While these minerals enhance their nutritional value, excessive intake of sodium, iodine, or bromine by livestock must be avoided (Morais *et al.,* 2020). The mineral content of some seaweeds are mentioned in table 1.

Seaweeds also supply essential vitamins. They contain both water-soluble (B_1, B_2, B_3, C) and fat-soluble (A, E, carotenoids) vitamins, with some species distinguished by their unusually high vitamin B_{12} levels, particularly *Ulva* spp. Vitamin E content is highest in *Laminaria* spp. (upto 2000 ppm), while vitamin C is abundant in *Ascophyllum* and *Laminaria* spp. (Costa *et al.,* 2021). Carotenoid composition also varies by group: green algae are rich in β-carotene and lutein, red algae in α- and β-carotene and zeaxanthin, and brown algae in fucoxanthin (Mikami & Hosokawa, 2013). These attributes make seaweeds a promising source of nutrients, minerals, and bioactive compounds for animal feeding.

Table 1: Chemical composition of seaweed species (all values on DM basis)

Analysis	*Ascophyllum nodosum*	*Macrocystis pyrifera*	*Laminaria and Saccharina sp.*	*Sargassum sp.*	*Palmaria palmata*	*Ulva sp.*
Crude protein (%)	5.3-10.7	7.8-12.4	7.6-12	6.7-10.3	13-25.2	11.3-25.9
Crude fibre (%)	4.1-6.8	5.5-10.5	5.5-7.7	7.7-12.5	1.5	2.8-11
NDF (%)	19.8-22.0	19.9	16.6	26.1-32.9	NA	20.8-31.6
ADF (%)	13.1	12.6	NA	16.9-25.7	NA	2.5-14.9
Lignin (%)	6.2-21.4	3.6	1.0-7.9	NA	NA	1.4-5.6
Ether extract (%)	2.3-5.5	0.4-0.8	0.5-1.0	0.3-2.1	NA	0.4-2.0
Ash (%)	20.4-24.6	22.5-41.5	24.0-39.0	23.1-48.7	17.5-31.5	15.6-30.4
Gross energy (MJ/kg)	14.5-14.7	8.6-9.4	NA	8.9-9.2	NA	12.1-17.3

table Cont....

Analysis	***Ascophyllum nodosum***	***Macrocystis pyrifera***	***Laminaria and Saccharina sp.***	***Sargassum sp.***	***Palmaria palmata***	***Ulva sp.***
Minerals						
Ca (g/kg)	20.0	12.6-15.6	8.8	1.2-6.4	NA	0.3-58.1
P (g/kg)	1.0	2.6-3.2	3.0	1.2-3.2	NA	0.6-4.8
K (g/kg)	24.0	45.1-89.9	59.5	15.9-76.6	NA	15.1-29.0
Na (g/kg)	NA	27-46.8	25.3	NA	3.0-3.6	NA
Mg (g/kg)	8.0	16.2-61.8	5.5	7.5-7.9	NA	13.5-19.9
Mn (mg/kg)	9.0-15.0	11.0	4.0-8.0	108.0-320.0	11.0	101.0
Zn (mg/kg)	67.0-295.0	12.0	41.0-181.0	63.0-365.0	143.0	28.0-61.0
Cu (mg/kg)	12.0-44.0	2.0	5.0-23.0	3.0-11.0	24.0	7.0-17.0
Fe (mg/kg)	98.0-170.0	117.0	0.0-466 .0	964.0-13618.0	153.0	1052.0-1440.0

Sources: Makkar *et al.* (2015)

Biologically Active Compounds in Seaweeds

Seaweeds are a valuable source of diverse biologically active compounds, including polysaccharides, proteins, polyunsaturated fatty acids, pigments, minerals, vitamins (A, D, E, K, B_{12}, and C), and a wide range of antioxidant molecules, particularly polyphenols (Michalak & Chojnacka, 2015).

A) Polysaccharides:

Seaweeds contain diverse bioactive polysaccharides that vary by algal group: brown algae (alginate, fucoidan, laminarin, cellulose), red algae (agar, carrageenan, porphyran, xylan), and green algae (ulvan, inulin, pectin, xylan). Among these, galactans, fucoidan, laminarin, and alginates are most significant due to strong biological activities. They act as prebiotics, improve digestion, and may comprise up to 76% of dry matter. Galactans and fucoidan possess anti-inflammatory, antioxidant, antiviral, and antitumor effects (Song *et al.,* 2012), while laminarin supports gut health and shows antioxidant, antibacterial, and antiviral properties (O'Doherty *et al.,* 2010). Alginates function as soluble fibres with thickening, stabilizing, antibacterial, and anti-inflammatory roles. Additionally, seaweed proteins such as lectins exhibit antibacterial, antiviral, and anti-inflammatory effects (Cunningham & Joshi, 2010).

B) PUFAs:

Seaweeds are further enriched with long-chain PUFAs, which are beneficial to both humans and animals. Species inhabiting colder waters typically accumulate higher PUFA concentrations than those from warmer seas, since low temperatures favor their synthesis (Holdt & Kraan, 2011). Important fatty acids present in seaweeds include linoleic acid (C18:2), α-linolenic acid (C18:3), arachidonic acid (C20:4), eicosapentaenoic acid (EPA, C20:5), and docosahexaenoic acid (DHA, C22:6), all of which contribute significantly to health.

C) Pigments:

Pigments represent another group of bioactives in seaweeds, mainly chlorophylls, carotenoids, and phycobiliproteins. Carotenoids, found in chloroplasts and chromoplasts, vary by species but typically include β-carotene (36–4500 mg/kg DM), fucoxanthin, and tocopherol (Holdt & Kraan, 2011). These compounds act as potent antioxidants by quenching singlet oxygen and scavenging free radicals (Li *et al.,* 2011). Phycobiliproteins, water-soluble pigments present in red and blue-green algae, demonstrate antioxidant, anti-inflammatory, antiviral, and neuroprotective activities (Holdt & Kraan, 2011).

D) Polyphenols:

Polyphenols are also abundant in seaweeds, particularly in *Ascophyllum* spp., where they neutralize free radicals by donating hydrogen atoms, thus producing non-reactive molecules. Brown seaweeds uniquely contain phlorotannins (e.g., eckol, dieckol), a class of tannins with multiple phenolic rings that act as electron traps for free radicals. Due to this structure, phlorotannins possess strong antioxidant and antimicrobial properties (Gupta & Abu-Ghannam, 2011).

Seaweeds as a Rich Source of Highly Bioavailable Mineral Elements

Seaweeds serve as valuable natural mineral supplements, often concentrating minerals 10–100 times more than terrestrial vegetables due to their bio-adsorptive and bio-accumulative capacities. Mineral uptake occurs through passive diffusion, active transport, and assimilation into cellular structures, and is influenced by functional groups in polysaccharides, proteins, and lipids, as well as environmental factors like pH, salinity, and temperature. Brown algae are particularly effective, with alginates and vanadium-dependent haloperoxidases enabling iodine accumulation up to 30,000-fold higher than seawater (Tsui *et al.,* 2006). Red algae (agar, carrageenan) and green algae (ulvans) also exhibit strong cation-binding and assimilation properties (Vasconcelos & Leal, 2001; Yaich *et al.,* 2011). Owing to their high mineral density and bioavailability, seaweeds are increasingly recognized as promising feed additives, capable of preventing mineral deficiencies, enhancing skeletal development, and enriching animal-derived products, as seen in the elevated iodine content of milk from cows supplemented with mixed seaweed diets.

Prebiotic Properties of Seaweeds

A wide range of prebiotics, both natural and synthetic, are commercially available; however, fructans such as inulin and fructo-oligosaccharides remain the most widely investigated and utilized (Neri-Numa *et al.,* 2020). Seaweeds, owing to their diverse polysaccharide composition including laminarin, fucoidan, carrageenan, agaran, ulvan, and alginate are considered one of the richest natural sources of prebiotics.

Alginate, a linear polysaccharide composed of β-D-mannuronic acid and α-L-guluronic acid residues, is particularly notable. When derived from seaweeds, alginate undergoes microbial fermentation in the gut, stimulating the growth of beneficial bacterial populations such as *Bacteroides, Bifidobacterium,* and *Lactobacillus.* At the same time, it suppresses harmful microorganisms like *Enterobacteria,* thereby reducing the production of potentially toxic putrefactive metabolites (Gotteland *et al.,* 2020).

Laminarin, the only soluble yet indigestible storage polysaccharide unique to seaweeds, consists of β-(1–3)-linked D-glucopyranose with occasional β-(1–6)-linked side chains. Gut microbes efficiently ferment laminarin into short-chain fatty acids, particularly butyrate and propionate. Its structural complexity, stabilized by interchain hydrogen bonds, renders it resistant to hydrolysis in the upper gastrointestinal tract. Laminarin further influences intestinal health by modifying mucus composition, regulating luminal pH, and modulating SCFA production (Devillé *et al.,* 2007).

Fucoidans are polysaccharides enriched with L-fucose and supplemented with sugars such as xylulose, glucuronic acid, mannose, and galactose. Their prebiotic effects, however, are inconsistent, making it challenging to establish definitive health benefits. Nonetheless, the European Food Safety Authority has recognized fucoidans as "novel foods" (Lynch *et al.,* 2010).

Carrageenans and **agarans**, two structurally related polysaccharides, differ primarily in their sulfation levels, with carrageenans exhibiting higher degrees of sulfation. Carrageenans, composed of repetitive β-D-galactopyranose and α-D-galactopyranose units, enhance SCFA production upon microbial fermentation. Agarans, on the other hand, are poorly fermentable. However, their hydrolyzed derivatives agarose oligosaccharides exhibit promising prebiotic potential, particularly in stimulating the growth of butyrate-producing bacteria, *Bifidobacterium* spp., and *Lactobacillus* spp.

Ulvan, a polysaccharide found in green seaweeds, is composed mainly of sulfated rhamnose, glucuronic acid, and small amounts of xylose and glucose (Lahaye & Robic, 2007). Due to its limited or negligible fermentation by gut microbes, ulvan is generally not regarded as a true prebiotic.

Experimental studies further highlight the prebiotic potential of seaweed-derived extracts and biomasses. For instance, an *in vitro* study demonstrated that supplementation with extracts from *Gelidium* and *Ascophyllum* increased the abundance of *Bifidobacterium* spp. while enhancing the production of SCFAs such as acetic and propionic acids (Ramnani *et al.,* 2012). Feeding *Chondrus* biomass to rats resulted in increased counts of beneficial bacteria, greater SCFA production, improved colonic histomorphology, enhanced fecal water-holding capacity, and elevated immune responses, as evidenced by higher IgA and IgG levels (Liu *et al.,* 2015). Similarly, the dietary inclusion of *Spirulina* biomass was associated with an increase in beneficial bacteria (*Lactobacillus casei, L.acidophilus, Streptococcus thermophilus,* and *Bifidobacterium*) and a decrease in harmful microbes (*Proteus vulgaris, Bacillus subtilis,* and *B. pumilus*) (Beheshtipour *et al.,* 2012).

Remarkably, even at relatively low inclusion levels (<2% of dietary dry matter), seaweed-derived polysaccharides can exert a strong prebiotic effect reported to be up to 5.5-fold greater than conventional reference prebiotics such as fructo-oligosaccharides or inulin. Moreover, specific polysaccharides like alginate provide an additional benefit by reducing populations of pathogenic bacteria such as Enterobacteriaceae and Enterococci (Wang *et al.,* 2006).

Seaweeds for Enteric Methane Mitigation

In the rumen, a diverse community of microbes degrades dietary carbohydrates and fibrous feed, leading to the production of CO_2, H_2, and volatile fatty acids (Min *et al.,* 2021). Figure 1 demonstrates the relationships among anti-methanogenic compounds, bioactive components in seaweed, and secondary metabolites as well as phytonutrients in plants. The release of H_2 occurs through reoxidation processes that involve several cofactors such as FADH, NADPH, and NADH. Both CO_2 and H_2 serve as key substrates for methanogenic archaea, which are widely recognized as the primary contributors to ruminal methanogenesis (Ellis *et al.,* 2008). This microbial interaction strongly influences the metabolic activity of rumen fermentative and acetogenic bacteria through interspecies hydrogen transfer (Stams and Plugge, 2009).

While most methanogens utilize CO_2 and H_2, other species can use substrates such as acetate, formate, methylamines, methanol, and alcohol (Ellis *et al.,* 2008). Berghuis *et al.* (2019) demonstrated that methanogenic archaea employ three major pathways for methanogenesis, with the CO_2 reducing hydrogenotrophic pathway being the most dominant. According to Cavicchioli (2007), the methyl-coenzyme M reductase (MCR) gene cluster is essential for CH_4 synthesis. A reduction in methanogenesis allows excess H2 to be redirected into alternative fermentation pathways that generate VFAs, especially propionic acid (C3) (Wanapat *et al.,* 2013). These VFAs not only provide an additional energy source for the host animal but also enhance feed utilization efficiency, thereby supporting improved growth and production of meat and milk. In particular, propionic acid (C3) is a critical precursor for gluconeogenesis, which is essential for glucose synthesis. Moreover, there exists a negative relationship between propionate formation and CH_4 emissions, since propionate competes with methanogens for available hydrogen (Wang *et al.,* 2023a, 2023b).

Dietary interventions, such as the supplementation of seaweed, have been shown to modify rumen fermentation pathways and suppress CH_4 production(Mohapatra *et al.,* 2024). As summarized in Figure 1, methanogenesis primarily occurs through three major routes: hydrogenotrophic, methylotrophic, and acetoclastic pathways. Certain plant secondary metabolites, including chloroform (CHCl3), bromoform, phlorotannins, and saponins, inhibit CH_4 synthesis by disrupting corrinoid enzyme activity and blocking MCR function (Min *et al.,* 2021). For instance, chloroform (10 mmol/L) effectively suppresses methane production from both H_2/CO_2 and acetate by inhibiting hydrogenotrophic and acetoclastic methanogens. Likewise, species of *Asparagopsis* are rich in bromoform, which acts as a competitive inhibitor of MCR, blocking the terminal catalytic step of methanogenesis. This inhibition is linked to interference with vitamin B_{12}-dependent methyl-transferase reactions, as bromoform cross-reacts with cobamide cofactors (Goel *et al.,* 2009). Fluoroacetate (FCH_2COO^-) specifically inhibits acetoclastic methanogenesis. Collectively, these halogenated compounds disrupt methyl-group transfer reactions, impair MCR function, and interfere with key enzymatic steps (Ungerfeld *et al.,* 2004).

Bromoform present in red seaweed (*Gracilaria* sp.) significantly reduces the abundance of methanogens. Additionally, compounds like bromochloromethane (BCM) impair MCR activity and affect vitamin B_{12} metabolism. Therefore, seaweeds rich in halogenated compounds hold great potential as natural anti-methanogenic agents, capable of mitigating CH_4 emissions by suppressing methanogen activity.

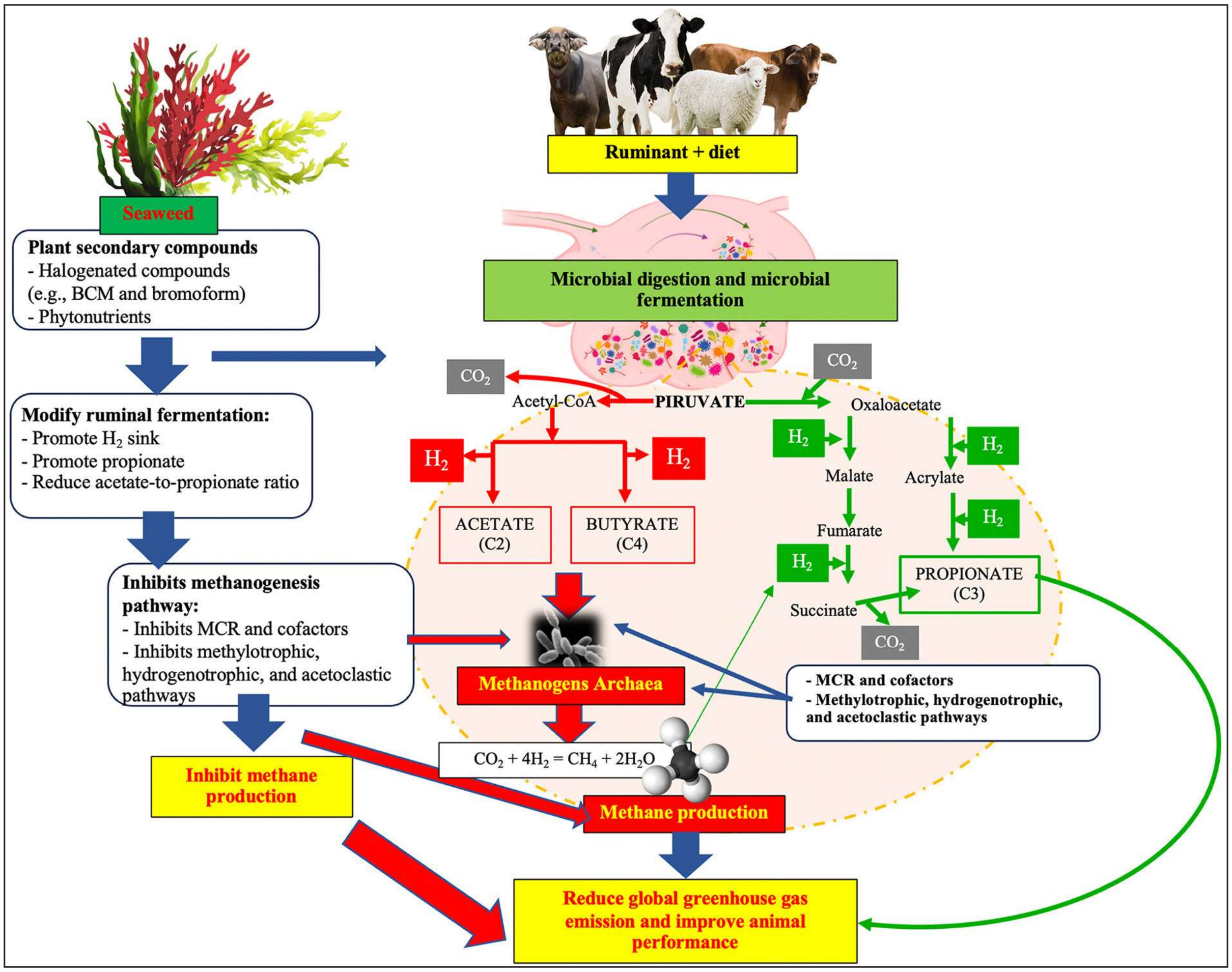

Figure 1: The diagram of the seaweed supplementation affects the pathways involved in methane (CH4) production within the rumen. BCM=bromochloromethane, MCR=methyl CoM reductase. (*Source:* sciencedirect.com)

Adapted from: Wang *et al.* (2023a, 2023b); Min *et al.* (2021); Roque *et al.* (2021); Machado *et al.* (2018); Patra (2014, 2012); Wanapat *et al.* (2013); Denman *et al.* (2007); Wood *et al.* (1968).

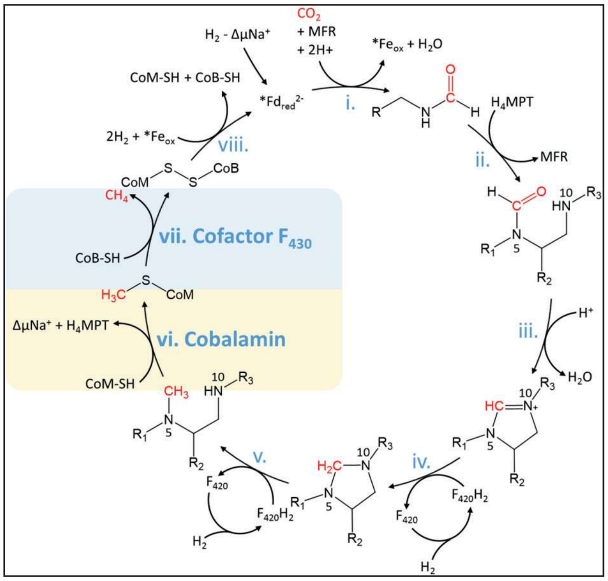

Figure 2: The Wolfe cycle for the reduction of CO_2 to CH_4 in hydrogenotrophic methanogenic archaea. Steps: i. CO_2 reacts with methanofuran (MFR) to produce formyl-MFR; ii. The formyl group is transferred to tetrahydromethanopterin (H_4MPT); iii.-v. Intramolecular imine formation and successive reductions; vi. Methyl transfer from methyl- H4MPT to CoM-SH catalysed by coenzyme M (CoM) methyl transferase (cobalamin); vii. Methyl group reduced to methane catalysed by methyl-CoM reductase (cofactor F430); viii. Ferredoxin mediated regeneration of CoM. *Source:* sciencedirect.com

Adapted from: Thauer *et al.* (2012)

Constraints of using seaweeds for animals

Although seaweeds are promising feed resources, several limitations restrict their direct use. Recalcitrant cell wall polysaccharides hinder digestibility by entrapping nutrients, while cation binding to anionic polysaccharides reduces mineral bioavailability (Overland *et al.*, 2019; Kumar *et al.*, 2008). Their strong bioaccumulation capacity also leads to heavy metal accumulation; aluminium levels up to 554 ppm have been reported, and brown algae often contain excessive iodine and arsenic, with *Laminaria digitata* accumulating toxic inorganic forms. Feeding trials with *Ulva rigida, Sargassum muticum,* and *Sacchoriza polyschides* increased arsenic in cow milk, though other metals remained unaffected (Morais *et al.*, 2020; Michalak & Marycz, 2019). Nutrient stability is another concern, as vitamins are highly heat-and UV-sensitive, with conventional sun-drying causing substantial losses, while solvent extraction has been proposed to mitigate degradation. Additionally, antinutritional compounds such as phenolics and sulfated polysaccharides can bind nutrients, restrict fermentation, and even generate harmful gut metabolites, further limiting their application in animal diets.

CONCLUSION

Overall, the available evidence suggests that seaweeds can serve as a valuable natural resource in animal nutrition. They are rich in essential minerals, exhibit prebiotic properties, enhance antioxidant activity, and strengthen the immune system. Certain calcareous seaweeds also act as effective rumen buffers, while others contribute to reducing methanogenesis. Taken together, these attributes highlight the potential of seaweeds as sustainable and multifunctional feed additives for improving ruminant production.

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