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Review Article

Application of the brown macroalga *Saccharina latissima* (Laminariales, Phaeophyceae) as a feed ingredient for livestock: A review

Sachin Dhakal [a], Alexander Oliver Jüterbock [b], Xingen Lei [c], Prabhat Khanal [a, *]

[a] *Animal Science, Production and Welfare Division, Faculty of Biosciences and Aquaculture (FBA), Nord University, Steinkjer 7713, Norway*
[b] *Algal and Microbial Technology Division, Faculty of Biosciences and Aquaculture (FBA), Nord University, Bodø 8049, Norway*
[c] *Department of Animal Science, College of Agriculture and Life Sciences (CALS), Cornell University, Ithaca, NY 14853, USA*

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ABSTRACT

In recent years, marine macroalgae have been recognized as potential alternative and sustainable feeding resources for livestock. Differences in nutritional values and biomass yield across macroalgal species are critical factors while aiming to utilize them as animal feed components. A brown macroalga, *Saccharina latissima*, also known as sugar kelp, has a promising biomass yield and high nutritional and bioactive compounds that can benefit both ruminant and monogastric animals. For example, the dietary inclusion of *S. latissima* in dairy and beef cattle can enhance milk yield, meat quality, and iodine content in milk and meat while reducing enteric methane emissions in vitro. However, high iodine content and the presence of some potentially toxic elements (arsenic, cadmium, etc.) lead to critical challenges, demanding careful consideration while determining the inclusion level of *S. latissima* in the livestock feed. To address these challenges, effective post-harvest biomass processing techniques, particularly hydrothermal treatments, have shown promise in reducing heavy metals and minerals of concern (e.g., iodine) and enhancing their safety as animal feed. It is thus essential to evaluate the sustainability of post-harvest processing techniques as they are usually energy-demanding and can negatively influence nutrient utilization in animals as certain digestible fractions can disappear during processing. Furthermore, variations in the nutritional and bioactive composition of *S. latissima* due to seasonal and spatial factors can create challenges for commercial exploitation. In this context, multiple harvesting of biomass and choosing the appropriate harvesting seasons can maximize the nutritional potential of *S. latissima*. In conclusion, *S. latissima* can be a novel feed ingredient for livestock, but year-round biomass availability and identifying cost-effective and energy-efficient post-harvest biomass processing methods that optimize both nutritional values and digestibility of *S. latissima* are critical for improving animal production, performance, and health.

1. Introduction

With a projected figure of 9.7 billion people by 2050, demands for animal-derived proteins are expected to rise (Bikker et al., 2020; Boland et al., 2013; Cole et al., 2018). Currently, animal feed industries are facing higher prices of conventional feedstuffs due to a reduction in the global supply of agricultural products as a consequence of COVID-19 and the ongoing Russia–Ukraine conflict (Donnellon-May and Teng, 2022; Okolie and Ogundeji, 2022). In addition, the undesirable impacts of global warming on agricultural crop production (Abbass et al., 2022) have threatened the supply of feed ingredients to livestock. In this context, exploring alternative

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* Corresponding author.
E-mail address: prabhat.khanal@nord.no (P. Khanal).
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and environment-friendly feed sources for sustainable livestock production is crucial to ensure future food security and self-sufficiency. Among various novel animal feed ingredients, marine macroalgae, also called seaweeds, are viewed as potentially viable and sustainable feeding resources for production animals (Bikker et al., 2020; Pandey et al., 2021; Van Den Burg et al., 2021). Marine macroalgae offer various benefits over terrestrial farming, such as the utilization of salt water as a substitute for fresh water, adoption of sea-based agriculture over land-based, elimination of the need for industrial fertilization, and high productivity in terms of biomass generated per unit of surface area (Buschmann et al., 2017). Thus, the cultivation and utilization of various macroalgae species for different food and feed purposes present a promising and sustainable strategy to address potential food and feed security risks, underscored by a notable surge in global macroalgae biomass production.

The global yield of macroalgae was 35.8 million metric tons in 2019, where 1.1 million metric tons came from wild harvesting (approximately 3%), and the remaining 34.7 million metric tons (approximately 97% of the total biomass) were produced through cultivation (Cai et al., 2021; Hurtado et al., 2022). The global cultivation of seaweed has consistently increased over the past decade (Hurtado et al., 2022); however, wild harvest remained almost stable (Fig. 1). Compared to Asia, which produces 97% of the global farmed seaweed biomass (Zhang et al., 2022), Europe harvested 98% of total macroalgae production from the wild in 2016, where 225 companies were involved (Araújo et al., 2019, 2021). In recent years, utilizing macroalgae for food, feed, and other pharmaceutical purposes is also becoming more popular in Europe, which can assist in achieving several European Policy Goals for Blue Growth (Buschmann et al., 2017; Ktari et al., 2022). Historically, employing seaweed as livestock feed has been a well-established and widespread tradition in northern Europe. Countries such as Iceland, Norway, and Scotland notably fed seaweed to sheep as a regular practice, even when these animals suffered from diseases (Chapman, 2012; Mæhre et al., 2014). Therefore, while aiming to exploit macroalgal biomass as animal feed, it is essential to select suitable macroalgae species as approximately 10,000 species of macroalgae have been identified (Collins et al., 2016; Pereira, 2021) and possess unique nutritional characteristics based on their types or species. According to their pigmentation, macroalgae are broadly divided into three major groups: brown algae (Phaeophyta), red algae (Rhodophyta), and green algae (Chlorophyta) (Dawes, 1998; Lobban and Wynne, 1981). Among them, brown macroalgae have high biomass yield and are rich in nutritional composition and bioactive compounds, including polysaccharides, essential amino acids, minerals, vitamins, polyphenols, etc., with health-promoting properties (Jang et al., 2024; Lozano Muñoz and Díaz, 2020). Particularly, *Laminaria/Saccharina* are the most cultivated and commercialized brown macroalgae species in the world; thus, this review aims to evaluate the potential of one of the important and most cultivated brown macroalgae species, *Saccharina latissima*, for future animal feed applications. In addition, we highlight different production and processing parameters for optimal commercial utilization. In particular, this review aims to provide important perspectives on the research and development gaps that must be bridged before including brown macroalgae in the feedstuffs at a commercial scale.

2. Brown macroalgae

Brown macroalgae are naturally available in wider sea environments, including the Northern Hemisphere coastal regions, and are easily characterized by their large size, especially kelps (Laminariales), and high productivity. In particular, temperate climatic conditions provide optimal environments for brown macroalgae growth due to their cold and high saline water and nutrient-rich extensive coastlines (Sjøtun et al., 2015). Brown macroalgae are also identified as potent environmentally-friendly novel feed ingredients for livestock and fish feed due to their unique nutritional properties and health benefits for various production animals (Makkar et al., 2016; Øverland et al., 2019). Certain brown

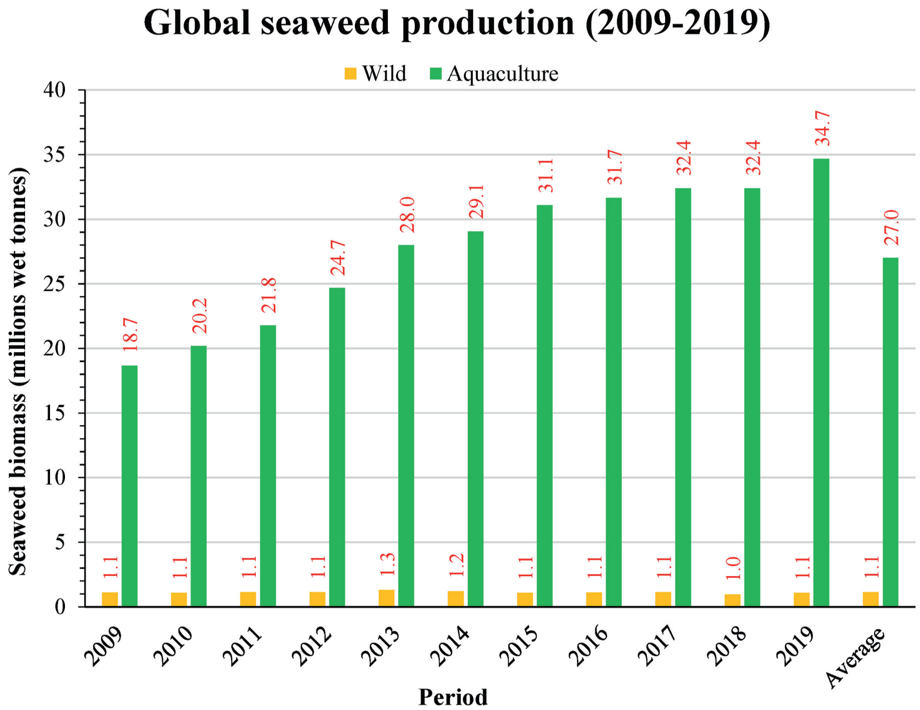

Fig. 1. Global production of macroalgae (wild and aquaculture) from 2009 to 2019 (Hurtado et al., 2022).

macroalgae are rich in essential nutrients ranging from bioavailable proteins and trace minerals to polyunsaturated fatty acids, soluble and insoluble dietary fiber, phenolic compounds, and polysaccharides that are essential for biological activities (Macartain et al., 2007; Reboleira et al., 2019). Therefore, brown macroalgae, such as *S. latissima*, generate impressive biomass and yield and possess unique carbohydrates and bioactive compounds for animal feeding.

2.1. *Saccharina latissima*

The brown macroalga *S. latissima* (Laminariales: Laminariaceae), also referred to as sugar kelp or royal kombu, is a cold-water, perennial species that can thrive on hard bottom substrate in protected waters (Fig. 2A) (Sharma et al., 2018). The holdfast, the stipe, and the blade together determine the adult sporophyte morphology (Fig. 2B). The length, width, and thickness of different morphological parts vary with hydrodynamic exposure (strong water current or protected area), temperature, and nutrient availability (Vettori and Nikora, 2017; Visch et al., 2020). *S. latissima* is one of the kelp species with the highest rate of growth and one of the most cultivated brown macroalgae in terms of both the volume of biomass production and the number of companies in European seas (Araújo et al., 2021) and also in Norway (Norderhaug et al., 2020). *S. latissima,* is widespread in the Northern Hemisphere, occurring from the intertidal zone to the bottom of the photic zone (Bolton et al., 1983). In 2019, 16.4 million metric tons of brown macroalgae biomass had been cultivated globally, which is ca. 47.3% of total macroalgae cultivation. *Laminaria*/*Saccharina* biomass accounted for 35.4% of global macroalgal production (Cai et al., 2021). As outlined below, *S. latissima* has promising nutritional value with a significant potential for exploitation as an alternative animal feed resource.

3. Nutritional potential of the brown macroalga *S. latissima*

Fresh macroalgae generally contain about 70% to 90% of water and are rich in various macro- and micronutrients (Biancarosa et al., 2018). Carbohydrates (e.g., alginate, mannitol, laminarin, and cellulose), proteins, and salts are principal components of *S. latissima*, even though their compositions vary with seasonal fluctuations (Pandey et al., 2022; Sterner and Edlund, 2016). Protein and mineral contents are generally higher during winter or spring (Tayyab et al., 2016), while carbohydrates and polyphenols have been reported to be highest during summer or autumn (Schiener et al., 2015). In addition, *S. latissima* is a source of bioactive polysaccharides, polyphenolic compounds, beneficial minerals, and amino acids (Marinho et al., 2015a). The organic matter (OM) digestibility of *S. latissima* in ruminants remains unchanged in the biomass harvested in spring and autumn (Pandey et al., 2022). Despite having low protein and high iodine concentrations, recent findings have suggested that sugar kelp may still be a viable option as sustainable animal feedstock. The nutritional composition (Table 1) and mineral profile (Table 2) of *S. latissima* are summarized based on the previous studies on *S. latissima.*

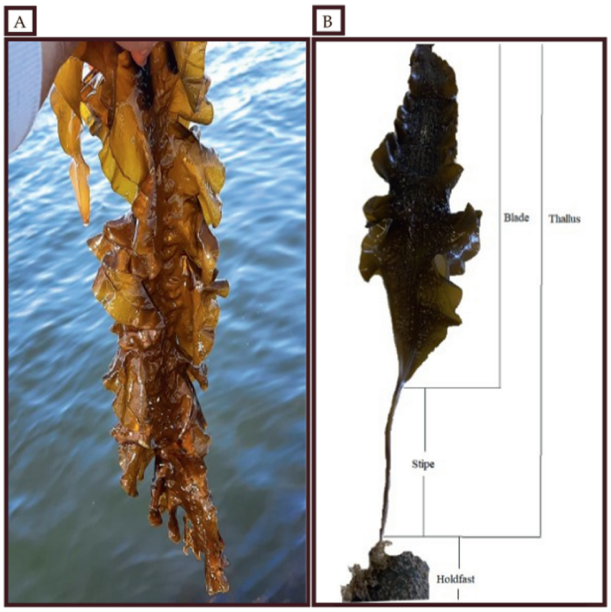

Fig. 2. Figure showing (**A**) the matured blade and the (**B**) general morphology of *Saccharina latissima.*

Production animals require essential amino acids, along with other nutrients to support their growth and performance. Macroalgae exhibits a relatively high protein quality due to its great proportion of essential amino acids (EAA) for livestock (Angell et al., 2016). Up to 69% of the essential amino acid index was reported in the biomass of *S. latissima* (Marinho et al., 2015a; Dawczynski et al., 2007), making it a suitable species for both human food and animal feed. Although a few studies have reported the digestibility of different macroalgal species in vitro (Pandey et al., 2021), there is relatively limited research on in vivo nutrient digestibility, including proteins. The in vitro protein digestibility of *S. latissima* appears to be slightly lower (approximately 80% of the total CP content) compared to red macroalgae (approximately 85%) (Tibbetts et al., 2016). Therefore, diet optimization should be done with a focus on fulfilling EAA requirements and considering digestibility parameters.

Complex carbohydrates, mainly alginate, fucoidan, and laminarin, are found in *S. latissima*, while their digestibility is limited in monogastric animals, they possess prebiotic effects, improving gut health (O'Sullivan et al., 2010). These polysaccharides are partially or fully fermented in the hindgut of monogastric animals by gut-specific commensal bacteria, resulting in the production of short-chain fatty acids, which can inhibit the proliferation of harmful gut pathogens (Braden et al., 2004). Brown macroalgae, such as *S. latissima*, serve as a significant source of both macro- and microminerals, with concentrations found to be 10 to 20 times greater than those typically observed in terrestrial plants and freshwater algae (Pereira, 2011). *S. latissima*, in particular, has high iodine content and may serve as a natural source of iodine for both livestock and humans, preventing iodine deficiency (Baňoch et al., 2010). Since this is a promising macroalgal species for animal feed applications, obtaining sufficient biomass of a high nutritional value is critical. The nutritional quality of *S. latissima* is dependent upon various production and processing factors as discussed below.

3.1. *Effects of cultivation conditions, harvesting seasons, and post-harvest processing on the nutritional values of S. latissima*

3.1.1. *Cultivation conditions*

S. latissima grows best at temperatures between 10 and 15 °C and the growth is generally retarded below 5 °C and above 20 °C (Fortes and Lüning, 1980; Nepper-Davidsen et al., 2019). *S. latissima* is well adapted to oceanic salinity (30 to 35 practical salinity unit) (Gerard et al., 1987; Spurkland and Iken, 2011). Therefore, the Norwegian coast is home to about half of the world's natural *S. latissima* kelp beds (Moy et al., 2006) as it provides favorable temperatures (10 to 17 °C) and salinities (30 to 35 practical salinity

Table 1
The nutritional composition of fresh *Saccharina latissima* (DM basis).

Item	Content	Reference
Moisture, %	77.5 to 89.8	Lytou et al. (2021), Marinho et al. (2015a), Schiener et al. (2015)
Ash, %	2.7 to 41.1	Bojorges et al. (2022), Lytou et al. (2021), Manns et al. (2014), Marinho et al. (2015a), Pandey et al. (2022), Schiener et al. (2015), Sharma et al. (2018), Tibbetts et al. (2016)
Mannitol, %	2.5 to 23.3	Manns et al. (2014), Schiener et al. (2015), Sharma et al. (2018), Vilg et al. (2015)
Laminarin, %	4.0 to 39.0	Schiener et al. (2015), Vilg et al. (2015)
Alginate, %	16.0 to 36.0	Manns et al. (2017), Schiener et al. (2015)
Total carbohydrates, %	15.3 to 63.1	Bojorges et al. (2022), Lytou et al. (2021), Schiener et al. (2015), Sharma et al. (2018), Tibbetts et al. (2016), Vilg et al. (2015)
Nitrogen, %	0.8 to 1.6	Schiener et al. (2015), Tibbetts et al. (2016)
Protein, %	1.3 to 11.2	Bojorges et al. (2022), Marinho et al. (2015a), Pandey et al. (2022), Schiener et al. (2015), Tibbetts et al. (2016), Vilg et al. (2015)
Total amino acids, %	1.5 to 12.7	Manns et al. (2014), Marinho et al. (2015a)
Crude fat, %	2.6 to 5.5	Bojorges et al. (2022), Tibbetts et al. (2016)
NDF, %	19.1 to 51.7	Pandey et al. (2022)
TPC, mg PGE/g	4.3 to 16.5	Pandey et al. (2022), Tibbetts et al. (2016), Vilg et al. (2015)
TPC, g PGE/kg	0.7 to 1.4	Sharma et al. (2018)
TPC, %	0.4 to 0.7	Schiener et al. (2015)

DM = dry matter; NDF = neutral detergent fiber; TPC = total polyphenol content; PGE = per gallic acid equivalent.

Table 2
The mineral profile of fresh *Saccharina latissima*.

Item	Content	Reference
Sodium, % of DM	2.0 to 3.3	Bruhn et al. (2019), Pandey et al. (2022), Sharma et al. (2018)
Potassium, % of DM	4.0 to 7.0	Bruhn et al. (2019), Pandey et al. (2022), Sharma et al. (2018)
Calcium, % of DM	0.8 to 1.7	Cabrita et al. (2016), Pandey et al. (2022), Sharma et al. (2018)
Magnesium, % of DM	0.5 to 0.7	Bruhn et al. (2019), Cabrita et al. (2016), Pandey et al. (2022), Sharma et al. (2018)
Phosphorus, % of DM	0.1 to 0.2	Cabrita et al. (2016), Sharma et al. (2018)
Iron, mg/kg of DM	16.0 to 1280.0	Bruhn et al. (2019), Cabrita et al. (2016), Pandey et al. (2022), Schiener et al. (2015), Sharma et al. (2018)
Iodine, mg/kg of DM	39.0 to 6568.0	Bruhn et al. (2019), Cabrita et al. (2016), Jordbrekk Blikra et al. (2021), Lüning and Mortensen (2015), Nielsen et al. (2020), Schiener et al. (2015), Sharma et al. (2018), Stévant et al. (2018b)
Bromine, g/kg of DM	0.4 to 1.5	Arlov et al. (2024), Sharma et al. (2018)
Chlorine, g/kg of DM	67.7 to 178.0	Arlov et al. (2024), Sharma et al. (2018)

DM = dry matter.

unit) (Kerrison et al., 2015). Generally, *S. latissima* is cultivated and deployed between October and February (Rørstad, 2019).

The predominant cultivation system for *S. latissima* is sea-based open cultivation, which is economically viable and can exploit natural marine environments while generating a high biomass yield. In addition, *S. latissima*, cultivated as a component of integrated multitrophic aquaculture (IMTA) under sea-based open cultivation, can harness the nutrients released or lost from feeds provided to other aquaculture species, such as finfish, shrimp, or salmon (Granby et al., 2020). This can ultimately assist in generating a net positive environmental impact by absorbing excess nutrients from the surrounding water (Venolia et al., 2020). However, such an open-sea cultivation approach can result in variable biomass quality of *S. latissima* and can be susceptible to various environmental challenges, including high disease risks in coastal and shallow ocean areas (Barbier et al., 2019; Buschmann et al., 2017; Visch et al., 2020; Ward et al., 2020). In the IMTA system, sugar kelp can benefit primarily from the utilization of inorganic nitrogen, specifically in the forms of ammonia and nitrate, which are released from fish feed, leftovers, and excreta (Lazzari and Baldisserotto, 2008). The concentration of these nutrients in IMTA systems is influenced by fish activity, distance from the fish cage, and other environmental parameters (Jansen et al., 2018; Rugiu et al., 2021). Consequently, fluctuations in nutrient concentrations absorbed by the kelp biomass may contribute to variations in the growth and nutritional quality of sugar kelp. In addition, there is also a higher risk of bioaccumulation of toxicants in farmed and wild kelps due to fishpond effluents, industrial discharges, chemical leaching from agricultural operations, and other human activities (Filippini et al., 2021). The concentration of such heavy metals in exposed *S. latissima* biomass depends on several environmental parameters such as water temperature, pH, and concentration of the contaminants in the environment (Banach et al., 2020). Arsenic, cadmium, lead, and mercury are heavy metals primarily common in *S. latissima* (Shaughnessy et al., 2023). Therefore, careful attention should be given when selecting cultivation sites and conditions for growing *S. latissima* commercially to ensure that the final seaweed products are safe for consumption.

Different biotic and abiotic factors can affect the cultivation of *S. latissima*. The fluctuating abiotic conditions such as light, temperature, water current, depth of cultivation, and nutrient availability throughout different seasons are expected to result in variations in phenology, growth, and biochemical composition (Marinho et al., 2015a; Schiener et al., 2015). These differences, in turn, will impact the cultivated *S. latissima* biomass in open-sea environments and ultimately influence the quality of the end products. Forbord et al. (2020) have shown that cultivation at a shallow depth (1 to 2 m) generally resulted in higher production in terms of frond length and biomass yield of *S. latissima*. Ideally, the cultivation of sugar kelp should be limited to the upper 10 m of the water column, where strong water currents provide a higher supply of nutrients, subsequently leading to increased biomass production (Skjermo et al., 2014). *S. latissima* exhibits greater biomass per individual when grown in areas with strong water currents compared to sheltered sites (Peteiro and Freire, 2013). On the other hand, sugar kelp grown in deeper water (8 to 9 m) tended to have higher levels of protein, ash, Q_N (quantitative tissue nitrogen), and I-DIN (intracellular nitrate) (Forbord et al., 2020). Thus, optimal water depth is critical to balance the biomass yield and nutritional quality of *S. latissima,* while targeting animal feed production.

In addition, a few studies indicate that *S. latissima* cultivated in nutrient-enriched waters near a fish farm in an IMTA system have significantly higher fatty acid content (60% more) with higher eicosapentaenoic acid (20:5) and a lower n-6/n-3 ratio than wild harvested samples (Barbosa et al., 2020). However, another study found no significant differences in lipid and fatty acid content between *S. latissima* cultivated within or outside IMTA (Marinho et al., 2015b), suggesting that further research is needed to understand the role of IMTA on the nutritional compositions of *S. latissima* biomass.

3.1.2. *Harvesting seasons*

Harvesting is the initial step after cultivation to collect the biomass of the cultivated macroalgae for further processing. *S. latissima* is either harvested from the cultivated aquaculture farm or the wild. In Europe, 68% of the production units rely on harvesting from wild stock, and the remaining 32% utilize aquaculture farming systems (Araújo et al., 2021). Kelp species, including *S. latissima*, are harvested (either wild or cultivated) using seaweed trawls, Scoubido boats, paddle wheels, or water-jet-driven seaweed cutters equipped for mechanical harvest (Kadam et al., 2015). The harvesting season of *S. latissima* usually starts from mid-April till the end of June (Nilsen, 2018; Zhang, 2018). Multiple partial harvesting of mature kelp plants, instead of harvesting the whole biomass, can be a beneficial practice to reduce production costs (Bak et al., 2018; Van Den Burg et al., 2016) and mitigate biofouling issues associated with kelp farming.

As mentioned earlier, the time of harvesting (season/month), among others, plays a critical role in the nutritional value of *S. latissima* biomass (Adams et al., 2011; Black, 1950; Schiener et al., 2015). *S. latissima* shows lower carbon and hydrogen levels in spring than in summer, along with decreased carbohydrate contents compared to those harvested in summer (June) (Monteiro et al., 2021). Additionally, lipid and ash content tended to decrease over the harvesting period from April (spring) to June (summer). Protein content did not vary over the same harvesting months (Monteiro et al., 2021). In contrast, a higher content of protein, minerals, NDF, and lipids was found in wild-harvested *S. latissima* in spring (May) (Pandey et al., 2022; Rioux et al., 2009) and summer (June) compared to late-summer and autumn. Lipid content in *S. latissima* appears to be lower in summer than in winter (December), when the kelp showed increased total fatty acid (FA) levels (Barbosa et al., 2020; Marinho et al., 2015b). Therefore, harvesting before the peak summer is the best season to obtain high-quality biomass for animal feed.

3.1.3. *Post-harvest processing techniques*

Freshly harvested *S. latissima* contains a high amount of moisture (up to 92% wet basis) and has a short life span after harvesting due to enzymatic deterioration, lipid oxidation, and microbial proliferation (Enríquez et al., 1993). As mentioned earlier, *S. latissima* often contains high levels of iodine and toxic elements such as cadmium, lead, mercury, and inorganic arsenic (Biancacci et al., 2022; Cheney, 2016; Olsson et al., 2020). Hence, it is essential to remove excess minerals and heavy metals by applying suitable post-harvest processing techniques before using *S. latissima* biomass for various animal feed applications, as summarized in Table 3.

After harvesting, the harvested *S. latissima* is typically washed to remove any impurities, such as sand, shell debris, or epiphytes, which may have attached to the harvested biomass (Kadam et al., 2015). After washing, hot water blanching of biomass i.e., immersion of fresh biomass in boiled water for a short time could be an effective method to reduce excess iodine and harmful elements of brown algae, including sugar kelp (Blikra et al., 2022a; Pandey et al., 2023). For example, blanching of sugar kelp at 30 to 80 °C for 30 to 300 s could reduce the iodine content up to 85% to 93%, while increasing the total phenolic content (TPC) and radical scavenging effects (Nielsen et al., 2020; Trigo et al., 2023). In addition, blanching of harvested sugar kelp at 60 °C for 300 s increased polyunsaturated fatty acid (omega-3 and omega-6) contents (Nielsen et al., 2020), and the essential to total amino acid ratio. However, it may also reduce the bioactive potential of *S. latissima*, e.g., by removing pigments like fucoxanthin. Therefore, optimal hot water blanching can be an effective post-harvest processing technique to reduce excess iodine and harmful elements in *S. latissima,* improving its nutritive values and subsequent utilization as an animal feed ingredient.

Apart from blanching, additional hydrothermal treatments have been considered to remove the toxic minerals from the harvested biomass of *S. latissima*. Soaking treatments can lead to the stress-induced leaching of nutrients by uptaking the water via osmosis (Stévant et al., 2017). Thus, soaking fresh *S. latissima* biomass in warm water (32 °C) could reduce >87% of the iodine in under 1 h, and 49% of ash, and 75% to 77% of Na and K after 22 h (Stévant et al., 2018b), making it suitable for animal feed applications.

Drying reduces the water content by evaporation, which hinders the growth and multiplication of microbes (Beuchat et al., 2013). The drying rate of fresh/frozen macroalgal biomass depends on several parameters such as temperatures, tissue thickness, surface area, etc. (Lewicki and Jakubczyk, 2004). Various methods, including sun, freeze-drying, oven-drying, and, more recently, microwave drying, can be used to dry harvested biomass. However, only a few of these methods (air-drying and freeze-drying) are mostly used by companies to process *S. latissima*. Air-drying of *S. latissima* at temperatures between 25 and 70 °C gave similar nutritional (total carbohydrate, polyphenols, protein, and free amino acid) content as freeze-drying, however, the iodine content was significantly reduced in freeze-dried samples (Stévant et al., 2018a). According to Sappati et al. (2017), low-temperature (40 °C) drying might preserve the highest possible nutrient profile and textural qualities of *S. latissima*. In addition, drying at low humidity (25%) can enhance drying rates (Sappati et al., 2017). Since freeze-drying is less applicable at a commercial scale due to its higher equipment and operational costs, as well as slower drying rates, low-temperature (40 to 60 °C) air drying could be an acceptable drying method when the aim is to produce biomass for animal feed production (Stévant et al., 2018a).

To ensure that *S. latissima* is safe for animal feed applications, it is critical to employ appropriate post-harvesting techniques that are beneficial from both economic and nutritional points of view. Pulsed electric fields (Blikra et al., 2022b), and novel blanching and drying (e.g., microwave and ultrasonic) techniques that are under application in food industries (Dibanda et al., 2020), might also be energy-efficient and can retain most nutritional and bioactive components whiling processing *S. latissima* as animal feed ingredients.

4. Application of *S. latissima* as an animal feed ingredient

A comprehensive overview of the specific impacts of varying dietary inclusion levels of *S. latissima* in both in vitro and in vivo settings across different animal species is presented in Tables 4 and 5, respectively. These tables provide detailed information on the observed effects of the *S. latissima* inclusion on various parameters, such as nutrient digestibility, growth performance, and methane production, demonstrating the potential benefits and limitations of using *S. latissima* in animal feeding.

Table 3
Different post-harvest processing techniques for *Saccharina latissima* biomass.

Processing techniques (temperature/time)	Response	Advantages	Disadvantages	References
Blanching (30 to 80 °C for 30 to 300 s)	Reduced iodine (up to 93%); increased TPC content and radical scavenging effect; increased the essential to total amino acid ratio, omega-3 and omega-6 contents	Simple, inexpensive, remove excess minerals, etc.	Leaching of water-soluble beneficial nutrients, high energy consumption, etc.	Nielsen et al. (2020), Trigo et al. (2023)
Soaking (32 °C for 22 h)	Reduced >87% of the iodine after 1 h; reduced 49% of ash, and 75% to 77% of Na and K after 22 h	Simple, inexpensive, removes excess salt and minerals, etc.	Time-consuming, leaching of water-soluble beneficial nutrients, etc.	Stévant et al. (2018b)
Oven-drying (40 °C for 24 h)	Preserved most nutrients and texture quality	Simple, effective at reducing moisture content, produces lightweight, etc.	Heat-sensitive compounds might be destroyed, require a long drying time, etc.	Sappati et al. (2017)
Freeze-drying (−50 °C for 72 h)	Reduced iodine content and increased polyphenol content	Preservation of color and heat-sensitive compounds, effective at reducing moisture content, reduces microbial load, etc.	Time-consuming, expensive, high-energy consumption, less applicable on a commercial scale, etc.	Stévant et al. (2018a)

TPC = total polyphenol content.

Table 4
In vitro studies showing the effects of dietary inclusion of *Saccharina latissima* inclusion on digestibility and fermentation characteristics.

Rumen fluid (inoculum) source	Inclusion level	Incubation period	Response	Reference
Cows	Intact (whole) macroalga	72 h	Reduced OM and nitrogen digestibility	Bikker et al. (2020)
Cows	20% DM	NA	Similar impacts on total gas and VFA production compared to maize silage	Pandey et al. (2022)
Cows	17% DM	48 h	Reduced VFA production (summer season) when incubated with grass silage	Thorsteinsson et al. (2023a)
Cows	25% DM	24 h	Decreased total gas production; increased VFA production	Maia et al. (2016)
Cows	25% DM	8 days	Increased DM and OM digestibility, and decreased protein digestibility, did not affect gas and methane production	Maia et al. (2019)
Cows	15%, 30%, and 45% DM	48 h	Increased total organic matter digestibility with increasing inclusion level	Ramin et al. (2019)
Cows	15%, 30%, and 45% DM	NA	Increased OM digestibility and protein utilization with increasing inclusion level	Ramin et al. (2017)
Goats	150 g/kg fresh matter	144 h	Increased VFA production compared to the control diet	de la Moneda et al. (2019)
Sheep	Intact macroalga	NA	Increased OM digestibility (up to 97%)	Greenwood et al. (1983)

OM = organic matter; DM = dry matter; VFA = volatile fatty acids; NA = not available.

4.1. Inclusion level of S. latissima in animal diets

In contrast to most terrestrial plants, macroalgae possess higher levels of polysaccharides, proteins, minerals, and vitamins (Urbano and Goñi, 2002). Given that macroalgae have a high mineral content (up to 30% to 39% of DM) (Schiener et al., 2015), adding either naturally collected or enriched macroalgae (Chojnacka, 2008) to the diet appears to be a potential mineral supplement for livestock feed. Due to the high mineral (ash) content of the macroalgae, their possible uses, such as mineral sources for livestock animals, would depend on their elemental composition and specific animal requirements (El-Said and El-Sikaily, 2013; Rey-Crespo et al., 2014). The dietary inclusion of *S. latissima* in animal feed presents a promising opportunity to enhance the nutritional values and overall quality of feed formulations. Rey-Crespo et al. (2014) found that dairy cattle that had been fed with a mixture of macroalgae supplements (including *S. latissima*) had better mineral status, particularly iodine and selenium levels in blood and milk, suggesting a high bioavailability of macroalgae-based minerals. As mentioned earlier, *S. latissima*, among brown macroalgae, has been found to have relatively high mineral content, especially the iodine level, which can limit its inclusion as an animal feed ingredient.

How much sugar kelp can be included in animal feed may depend on the nutritional requirements of the animal species, the nutritional quality of the sugar kelp, and regulations or guidelines for using macroalgae in animal feed in the respective countries or regions. For example, a 1% DM inclusion of *S. latissima* in the cattle feed positively impacted dry matter intake and protein, fat, and iodine contents in the milk (Ueland, 2022). However, a 5% DM inclusion of ensiled *S. latissima* as a mineral supplement in cattle showed mineral-based toxicity (Hammer, 2020). Mineral poisoning typically causes anorexia, weight loss, diarrhea, and impaired animal performance (NRC, 2005). Therefore, the amount of kelp ingredient should be carefully monitored to avoid adverse effects of macroalgae on animal health and production. The dietary inclusion of *Saccharina lattisima* in diets for poultry, horses, and ruminants is mainly limited by the iodine content and for pigs by the bromide content (Cabrita et al., 2016), as outlined in Table 6.

4.2. Impacts of dietary inclusion of S. latissima on digestion, metabolism, and animal performance

Various studies have demonstrated the positive effects of the dietary inclusion of macroalgae on the production performance and health of different monogastric and ruminant species. In general, even a minimum level of brown macroalgae inclusion or its constituent parts (such as concentrated protein or polyphenol extract) in the diet increased the nutritional value of feed and enhanced the

Table 5
In vivo studies showing the effects of *Saccharina latissima* inclusion in feed on digestibility and animal performance.

Targeted animals	Age/production stage	Inclusion	Duration of feeding trial	Response	Reference
Poultry (broiler)	14 to 22 days	10% DM of silage or silage residue	8 days	Higher FI and FCR, no difference in BWG, OM, and ash digestibility	Stokvis et al. (2021)
Poultry (parent stock)	30.5 weeks	Meal (0.6%) and extract (0.08%) DM	7 weeks	High iodine in eggs, percentage of fat pad increased	Kling (2021)
Cows	Lactation	1% DM	8 weeks	Increased DM intake, milk production, high protein, fat, and iodine in milk, no effect on nutrient digestibility	Ueland (2022)
Cows	Lactation	5.7 g DM/d per cow	12 weeks	Increased milk iodine content and reduced calcium content	Qin et al. (2023)
Cows	Lactating	4% ensiled DM	12 weeks	No effects on methane production, DMI, or milk production	Thorsteinsson et al. (2023b)
Calves	Weaning	5% DM	15 days	Showed symptoms related to iodine toxicity and reduced growth rate	Hammer (2020)
Pre-weaning calves	Pre-weaning	5% DM	40 days	No significant effect on health status and performance	Samarasinghe et al. (2021a)
Calves	Pre-weaning	5% DM	28 days	Increased innate immune response	Samarasinghe et al. (2021b)
Castrated ram	30 months	162 g/kg DM	32 days	Lower nitrogen digestibility (due to complex formation with phlorotannin, lower microbial activity, and proved by less VFA production)	Gülzari et al. (2019)
Piglets	Post-weaning	10.5% DM (mixed *S. latissima* and *Ascophyllum nodosum*)	8 weeks	No significant differences in performance and health compared to negative control piglets without supplemented ZnO	Satessa et al. (2020)
Piglets	Weaner	2.5% FRS	8 weeks	Increased microbial diversity in colon and gut-immune modulation	Hui et al. (2021)

DM = dry matter; BWG = body weight gain; FI = feed intake; FCR = feed conversion ratio; OM = organic matter; DMI = dry matter intake; VFA = volatile fatty acids; FRS = lactobacilli fermented rapeseed-seaweed blend (*Ascophyllum nodosum* and *Saccharina latissima*); ZnO = zinc oxide.

Table 6
The maximum level of inclusion of *Saccharina lattisima* in the diets of different animal species (g/100 g diet, DM basis).[1].

Species	Maximum level of inclusion	Elements responsible for the maximum limit of inclusion
Poultry	31.3	Iodine
Swine	36.2	Bromide
Horse	0.5	Iodine
Cattle/sheep	5.2	Iodine

DM = dry matter.

[1] Adapted from Cabrita et al. (2016) based on NRC (2005).

performance of the fed animals (Rajauria, 2015). However, data are limited regarding the nutritional value of *S. latissima* as dietary ingredients for food animals, and only a few studies have evaluated the impacts of dietary inclusion of *S. latissima* on animal health, production, and performance (Table 5). As mentioned earlier, sugar kelp is rich in dietary fiber, such as alginate and laminarin. These complex carbohydrates can promote gastric motility, decrease gastric clearance, and increase intestinal bulk and nutrient absorption (Lange et al., 2015). In addition, studies have shown that alginate inhibits the activities of enzymes such as pepsin and pancreatic lipase which decreases the intestinal absorption of glucose, cholesterol, and triglycerides (Brownlee et al., 2005; Chater et al., 2015). Fucoidan and alginate present in *S. latissima* can also act as a prebiotic that exerts beneficial health effects in monogastric animals by modulating gut microbiota (Gibson et al., 2017; Huebbe et al., 2017). Such effects include activation of the immune system, vitamin synthesis, decreased fat mass, and weight gain in obese animals (Gibson et al., 2017; Huebbe et al., 2017). Similarly, phlorotannin present in brown sugar kelp has antioxidant properties (Liu et al., 2017), which can scavenge free radicals and reduce oxidative stress in the gastrointestinal tract. This can help to protect the intestinal mucosa from damage and inflammation, leading to improved digestion and nutrient absorption in ruminants and monogastric animals.

In vitro rumen fermentation studies (Table 4) indicate that *S. latissima* could be utilized as an important nutritional and anti-methanogenic dietary ingredient for ruminants. Studies on the use of *S. latissima* as a feed ingredient for ruminants and its ability to influence rumen fermentation and methane generation are limited, and the outcomes varied with the formulation of the basal diets (Maia et al., 2016). Maia et al. (2016) found that at 25% inclusion in the meadow hay, *S. latissima* reduced in vitro methane and total volatile fatty acid production. However, other studies that incorporated *S. latissima* at a 25% DM into a single total mixed ration diet (Maia et al., 2019) or 20% DM on maize silage (Pandey et al., 2022) found no harmful impacts on the *in vitro* rumen fermentation parameters, indicating *S. latissima* as a viable alternative feed ingredient for ruminant nutrition.

The in vitro experiment that evaluated the digestibility of OM in *S. latissima,* using rumen fluid from sheep, revealed a significantly high digestibility rate up to 0.97 (Greenwood et al., 1983; Makkar et al., 2016). Additionally, Ramin et al. (2017) found that increasing the proportion of a protein-enriched fraction of *S. latissima* in an in vitro trial led to higher levels of OM and protein digestibility. However, in an in vivo experiment, lower protein digestibility of *S. latissima* was reported compared with soybean meal-based feed when included at 16.2% DM of protein in the Norwegian white sheep (Gülzari et al., 2019). The poor protein digestibility of *S. latissima* might be associated with the formation of insoluble complexes with phlorotannin, protein, and fiber, which could restrict rumen fermentation and further hinder the absorption of nutrients in the small intestine (Arnold and Targett, 1998; Gaillard et al., 2018; Macartain et al., 2007). Brown macroalgae, including sugar kelp, offer advantages due to their rich content of omega-3 polyunsaturated fatty acids, essential minerals, and vitamins and can be used in meat-producing ruminants as a natural feed ingredient (Pinotti et al., 2023). Incorporating *S. latissima* into the lamb's growing-finishing diet (up to 5%) has demonstrated favorable effects on meat quality traits, including decreased cooking loss and shear force, elevated iodine levels, and stabilization of selenium levels in the meat (Grabež et al., 2023). Therefore, when aiming to utilize *S. latissima* as an animal feed component, the inclusion level needs to be optimized to prevent overdosing on iodine and heavy metals and the overall digestibility of the feed mixture should be evaluated.

Although macroalgae supplementation has been approved as chicken feed in various countries, their inclusion rate in poultry diets is relatively limited compared to other animals. Depending on the macroalgae species and animal age, it has been suggested that macroalgae can replace up to 10% to 15% of poultry diets and serve as an effective pellet binder (Rajauria, 2015). Dietary inclusion of up to 2% to 3% DM of brown macroalgae in feed can enhance pellet hardness of layers diets without negatively affecting egg production, egg quality, or hen growth performance (Al-Harthi and El-Deek, 2011). However, research focusing on the dietary supplementation of *S. latissima* in poultry feed is scarce. Recent findings suggest that the inclusion of 0.6% DM of intact *Saccharina* biomass, or 0.08% DM of its extract in ROSS 308 parent stock diet enhanced iodine content in the egg but did not change other egg quality parameters and overall performance (Kling, 2021). The addition of *S. latissima* into diets for pigs increased the immunological response in pigs and had a beneficial effect on the gut health and microbiota (McDonnell et al., 2010).

Therefore, *S. latissima* biomass and its bioactive compounds have the potential to be a beneficial dietary supplement and a tool for ruminant methane reduction. Further investigation is needed to evaluate whether adding *S. latissima* can enhance nutrient digestion, performance, and health in both ruminants and monogastric animals.

5. Future perspectives

S. latissima has been traditionally used as a food and feed source by people of coastal regions worldwide. Recently, *S. latissima* has gained increasing interest as a sustainable and nutritious feed source. However, fluctuations in chemical composition, including minerals and secondary metabolites of *S. latissima* in response to growing seasons, result in variations in its nutritional properties, as mentioned earlier. Ensuring a high-quality biomass with a consistent nutritional composition of *S. latissima* becomes challenging due to seasonal fluctuations (Holdt and Kraan, 2011; Pandey et al., 2022). Another critical challenge of utilizing *S. latissima* in animal feed is the upscaling of cultivation and production to ensure that sufficient biomass is available to feed industries throughout the year. Cultivation methods such as monoculture or IMTA can help conserve marine biodiversity while providing a sufficient renewable feed source. In Europe, transitioning from wild harvesting to commercial cultivation of kelp is essential to meet increasing global demands for kelp biomass sustainably (Smale et al., 2013). Promising species like *S. latissima* show rapid growth and resilience to harsh conditions, with countries like Norway and Ireland leading cultivation efforts (Yarish et al., 2017). The possibility of employing kelp biomass, including *S. latissima*, as a feed ingredient may become more likely to depend on commercial-scale production at a relatively low cost in the future. While the large-scale cultivation of *S. latissima* biomass is increasing, research and development should be focused on its commercial utilization as animal feed, which will ultimately help the technological advances towards upscaling of *S. latissima* biomass. In this context, product diversification of *S. latissima* is critical, potentially employing biorefinery approaches, which could assist in maximizing the use of whole *S. latissima* biomass for multiple applications, including within the animal feed sector. To create an economically viable kelp-based value chain, a cascading biorefinery method should focus on valorizing both the liquid extract (protein-rich) and the solid fibrous fraction. The protein-rich extract of sugar kelp has been tested as an animal feed ingredient in the form of protein concentrate for both monogastric and ruminant animals (Gülzari et al., 2019). Furthermore, pretreatments such as the use of enzymes before exposing *S. latissima* biomass to a biorefinery process would aid in hydrolyzing the poorly digestible polysaccharides, increasing the digestibility of the solid fraction (organic matter) compared to intact *S. latissima* biomass (Bikker et al., 2016; Ramin et al., 2017).

One of the main bottlenecks for the development and expansion of the sugar kelp aquaculture industry in Europe is biofouling (Rolin et al., 2017), which usually starts around May and becomes most intense in June. Loss of commercial value, decreased productivity owing to breaking fronds and reduced development due to poor nutrient uptake and limited light availability are all consequences of biofouling (Visch et al., 2020). Thus, efforts are underway to develop *S. latissima* cultivars with enhanced traits such as high biomass output, increased nutrient content, and low affinity for biofouling (Forbord, 2020; Rolin et al., 2017). Similarly, utilizing local genetic resources and employing technologies to prevent hybridization between cultivated and wild populations (Goecke et al., 2020), are crucial for ethical and sustainable kelp use. Nordic countries, like Norway, emphasize the conservation and utilization of local cultivars (Goecke et al., 2020). By preventing such hybridization, it is possible to harness genetic diversity for traits like improved growth rate, protein content, resistance to organisms, and reduced mineral levels. Therefore, appropriate site selection for the cultivation and growth of biofouling-resistant sugar kelp strain farming is vital for stable production and supply of high-quality biomass by protecting against unwanted hybridization and biofouling.

Nutrient-rich *S. latissima* can be used as a nutritional and bioactive, e.g., antioxidant and prebiotic, feed ingredient for livestock (Michalak et al., 2022; Pradhan et al., 2022). The extraction and utilization of various bioactive compounds from *S. latissima* can lead to antimicrobial properties against bacterial and fungal infection in farm animals (Cusson et al., 2021; Mohammed, 2023), along with anti-inflammatory and immunomodulatory effects (Kraan, 2022; Stefaniak et al., 2019). Future research and development efforts must focus on identifying and extracting various bioactive compounds in an environmentally-friendly manner. Similarly, as sugar kelp contains an extremely high concentration of iodine, the effective use of *S. latissima* as food and feed additives could help to prevent iodine deficiency in Europe (Lazarus, 2014).

Table 7
The composition of potentially toxic elements of fresh *Saccharina latissima* (mg/kg DM).

Toxic elements	Content	Reference
Arsenic	39.1 to 92.5	Bruhn et al. (2019), Cabrita et al. (2016), Jordbrekk Blikra et al. (2021), Schiener et al. (2015), Sharma et al. (2018)
Cadmium	0.2 to 3.0	Bruhn et al. (2019), Cabrita et al. (2016), Jordbrekk Blikra et al. (2021), Sharma et al. (2018), Stévant et al. (2018b)
Mercury	0.02 to 0.1	Bruhn et al. (2019), Cabrita et al. (2016), Jordbrekk Blikra et al. (2021), Sharma et al. (2018)
Lead	0.2 to 2.2	Bruhn et al. (2019), Cabrita et al. (2016), Jordbrekk Blikra et al. (2021), Schiener et al. (2015), Sharma et al. (2018)
Aluminum	11.0 to 1877.0	Cabrita et al. (2016), Sharma et al. (2018)

DM = dry matter.

However, the high content of iodine and the abundance of potentially toxic elements, such as arsenic, cadmium, lead, mercury, etc., is also another limiting factor for using *S. latissima* as an alternative feed additive for livestock feed (Table 7). Thus, it is important to utilize various approaches to minimize the levels of toxic and critical minerals in *S. latissima* biomass, for example, by employing simple post-harvest hydrothermal treatments (Pandey et al., 2023) and choosing appropriate cultivation sites or harvesting seasons (Duinker et al., 2020). Overall, *S. latissima* has a massive potential of using both nutritional and bioactive feed ingredients within the animal feed sector which may not only assist to improve animal production and performance but also can combat issues associated with animal health and multidrug antimicrobial resistance within the livestock sector.

Nowadays, methane emissions from ruminants have become a serious global issue, and several methane mitigation strategies are already being implemented including the use of macroalgae for their anti-methanogenic potential (McGurrin et al., 2023). However, different studies have reported variable results in methane production regarding the use of seaweeds as an anti-methanogenic feed additive. To date, *Asparagopsis taxiformis* and *Asparagopsis armata,* two red macroalgae species have demonstrated anti-methanogenic properties by reducing methane production by up to 95% in vitro and up to 80% in vivo, primarily due to the presence of halogenated compounds such as bromoform (Roque et al., 2021; Chagas et al., 2019). Similarly, brown macroalgae also have methane-mitigating potential, but their anti-methanogenic capability appears to be lower compared to red macroalgae (Pandey et al., 2022, 2021). This difference is likely due to the differences in the composition of bioactive compounds such as phenolics and halomethanes between the macroalgal species (Nørskov et al., 2021). Thus, a detailed characterization of species-specific secondary bioactive compounds using the metabolomics approach and their application in feeding trials with production animals should be performed. In addition to compound identification, determining whether to use whole seaweed biomass or only the extract containing beneficial compounds, establishing the optimum inclusion level in the diet, and assessing the impact of seaweed addition on the ruminal microbiome have yet to be fully explored. Therefore, extensive in vivo studies are needed to ascertain the nutritional and anti-methanogenic potential of *S. latissima* as ruminant feed.

Another potential area for utilizing *S. latissima* would be in feed manufacturing industries to produce better pellet quality. The ability of macroalgae to bind pellets and improve their physical quality is attributed to their polysaccharide composition, which varies based on the specific species (Rajauria, 2015). Alginate, a core component found in *S. latissima* biomass (16% to 36% DM), is commercially extracted and sold as a gelling agent for food industries (Albers et al., 2021). Alginate's gelling and water-holding properties can be used as a pellet binder for better pellet quality (Cruz Suárez et al., 2008). Adding 3.5% kelp to the feed improved pellet texture and led to increased feed consumption in shrimp (Cruz Suárez et al., 2008). El-Deek and Brikaa (2009) found that up to 3% DM inclusion of macroalgae improved feed quality based on the hardness of pellets. Thus, there is also potential for using *S. latissima* to improve the physical structure of animal feed pellets. Such improvements in pellet quality can enhance feed intake, reduce feed spillage, and lead to better animal weight gain and feed conversion ratios (FCR) (Abdollahi et al., 2013; Glover et al., 2016). Future studies should evaluate the impacts of including components, e.g., alginate from *S. latissima* on nutrient digestibility and animal performance, in addition to beneficial effects on the physical structure of pelleted diets. However, the seasonal variation of alginate level in *S. latissima* could be a concern when aiming for commercial application of alginate in the animal feed industry.

6. Conclusion

Considering the limited availability of traditional and domestic feedstuffs, many studies have highlighted the potential role of the brown macroalga *S. latissima* as a promising sustainable nutrient source for animal feed applications. The high biomass yield, presence of several bioactive compounds, and various carbohydrate contents of *S. latissima* make it an attractive feed ingredient/additive for livestock. Nevertheless, further research is required to better understand the appropriate inclusion levels and nutrient digestibility specific to various farm animals, considering the content of complex polysaccharides, high iodine content, and toxic minerals in *S. latissima*. Future research should prioritize the development of cost-effective methods to increase the supply of high-quality *S. latissima* biomass for sustainable, environmental-friendly, and economically viable livestock feed production. Particularly, optimizing cultivation conditions, harvesting strategies, and post-harvest processing techniques should be considered. Furthermore, in vivo data are required to confirm the beneficial effects of *S. latissima* on nutrient digestibility, feed intake, animal health and performance, and environmental sustainability of the livestock sector, mainly ruminant production. Overall, *S. latissima* has the potential to be an integral component of circular economy-based livestock production in the future.

Credit Author Statement

Sachin Dhakal: Writing-Original Draft. **Alexander Oliver Jüterbock, Xingen Lei** and **Prabhat Khanal:** Writing-Review and Editing, Supervision.

Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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