cows fed varying amounts (0, 57, 113, and 170 g/d) of the brown seaweed ASCO did not affect dry matter intake (DMI) and milk yield (Antaya et al., 2015, 2019; Silva et al., 2022). In contrast, DMI and milk yield decreased by up to 38 and 11.6%, respectively, in dairy cows fed incremental amounts [0, 0.5, and 1%; diet organic matter (OM) basis] of the red seaweed *Asparagopsis armata* (Roque et al., 2019). Both DMI and milk yield decreased by up to 7.1 and 6.5%, respectively, with feeding increasing levels [0, 0.25, and 0.5%; diet dry matter (DM) basis] of the red seaweed *A. taxiformis* to dairy cows (Stefenoni et al., 2021). Enteric CH_4 production decreased by 10.3% during the first period of the study (diet x period interaction) in grazing dairy cows supplemented with 113 g/d of ASCO meal but not thereafter (Antaya et al., 2019). Feeding the greatest level of *A. armata* (Roque et al., 2019) or *A. taxiformis* (Stefenoni et al., 2021) were much more effectively to reduce enteric CH_4 production (-67.2 and -34.4%, respectively) than ASCO meal likely because the presence of halogenated compounds (e.g., bromoform) in both red seaweeds.

Table 1. Predominant seaweed genera and species used as feed supplements to ruminants, chickens, swine, equine, fish, oyster, and shrimp.

Seaweed genera or species	**Seaweed type**	**Animal species fed**
Ascophyllum nodosum	Brown	Beef cattle, broiler chicken, dairy cattle, horse, fish, sheep swine
Laminaria	Brown	Dairy cattle, fish, sheep, swine
Lithothamnion	Red	Beef cattle, rabbit
Macrocystis pyrifera	Brown	Beef cattle, dairy cattle, goat, shrimp
Sargassum	Brown	Broiler chicken, dairy cattle, fish, goat, laying hen, sheep
Palmaria palmata	Red	Sheep
Ulva	Green	Broiler chicken, laying hen, fish, oyster, rabbit, sheep, shrimp
Asparagopsis taxiformis	Red	Beef cattle, dairy cattle, sheep
Asparagopsis armata	Red	Dairy cattle
Chondrus crispus	Red	Dairy cattle, laying hen

Another topic that attracts public attention regarding the use of seaweeds in dairy diets is the transfer of iodine and brominated metabolites to milk due to potential risks to human health (Brito, 2020; Fouts et al., 2022). Consequently, development of commercial algal-based feeds must consider tradeoffs between mitigation of enteric CH_4 emissions, and any human food safety, or environmental hazards linked to seaweeds (Vijn et al., 2020). Additional barriers to seaweed commercialization include production scalability and regulatory approval (Makkar et al., 2016; Vijn et al., 2020; Honan et al., 2021). One of the objectives of the present paper is to report the effect of the brown seaweed species ASCO and the red seaweed species *Chondrus crispus* on production performance, enteric CH_4 emissions, milk iodine concentration, and cow health. These seaweeds grow in the Atlantic coast of North America, and ASCO meal is commercially available in the US and popular among organic dairy producers in the country (Hardie et al., 2014; Antaya et al., 2015; Sorge et al., 2016; Snider et al., 2021), thus justifying research and review of both ASCO and *C. crispus*. A second objective of this paper is to review the effect of seaweeds with high CH_4 mitigation potential (i.e., *Asparagopsis* species) on production performance, enteric CH_4 emissions, milk iodine concentration, and cow health. It is beyond the scope of this paper to provide a systematic review of all seaweeds or seaweed mixtures that have been fed to ruminants including lactating dairy cows. The nutrient composition of 4 selected seaweed species (ASCO, *A. armata*, *A. taxiformis*, and *C. crispus*) is also reviewed.

Nutrient Composition of Selected Seaweeds

Table 2 shows the nutrient composition of selected seaweeds used in diets of lactating dairy cows. It was detected some variation in the nutrient composition of ASCO meal, particularly in the fibrous fractions (neutral detergent fiber, acid detergent fiber, and lignin) and minerals such as iron, zinc, and iodine. These discrepancies in nutrient composition may be associated with various sources of ASCO meal used in the studies, as well as different harvesting and processing procedures adopted by seaweed companies and seasonality (Evans and Critchley, 2014). It is important to note that ASCO is wild harvested in the US, which can lead to inconsistencies in nutrient composition due to less controlled conditions.

Concentration of crude protein was greater in the red seaweeds *A. armata*, *A. taxiformis*, and *C. crispus* than in the brown seaweed ASCO, with *A. armata* showing the greatest content (18.3%). Similarly, the red seaweeds had greater ash concentration than ASCO meal, particularly A. *taxiformis* that averaged 55.5% ash. *Asparagopsis taxiformis* also had the greatest concentrations of iron (4,964 mg/kg of DM) and bromoform (~10 mg/g of DM). Compared with *C. crispus*, ASCO meal had a greater proportion of the total crude protein constituted by soluble crude protein (Table 2). In general, the concentration of neutral detergent fiber was greatest in ASCO meal, intermediate in *C. crispus*, and lowest in both *Asparagopsis* species. As discussed above, variation in nutrient composition between brown and red seaweeds possibly reflect differences in methods used for harvesting, processing, and storage, as well as seasonality and geographical location.

The dietary inclusion of seaweeds ranged from about 0.27 to 1% in studies done with ASCO meal (Antaya et al., 2015, 2019; Silva et al., 2022), *A. armata* (Roque et al., 2019), and *A. taxiformis* (Stefenoni et al., 2021), suggesting that the contribution of macronutrients (e.g., protein, fiber) from algal feeds to meet amino acids and energy requirements of dairy cows is small. On the other hand, up to 6% (diet DM basis) of *C. crispus* was fed to dairy cows (Brito's Lab unpublished), and with similar or greater inclusion rate, diets need to be formulated considering the seaweed contribution to cows' nutritional requirements. Seaweeds bioaccumulate minerals as shown by their high concentration of ash (Table 2), which may require careful ration formulation to not overfeed certain minerals (e.g., iodine) while avoiding interactions between minerals and other dietary compounds in the gastrointestinal tract, which can ultimately impair mineral absorption (Goff, 2018).

Table 2. Nutrient composition [% of dry matter (DM), unless otherwise noted] of *Ascophyllum nodosum*, *Asparagopsis* species, and *Chondrus crispus* used in studies conducted with lactating dairy cows.

	Seaweeds			
Nutrient	*A. nodosum*[1]	*A. armata*[2]	*A. taxiformis*[3]	*C. crispus*[4]
Crude protein (CP)	10.2, 10.3, 7.65	18.3	14.6	12.8
Soluble CP, % of CP	57.0, 54.0, 39.5	-	-	22.7
Neutral detergent fiber	53.9, 39.2, 46.8	27.2	18.5	40.5
Acid detergent fiber	39.9, 20.8, 31.9	10.9	11.3	7.73
Lignin	20.0, 12.2, 16.3	2.83	-	2.60
Neutral detergent insoluble CP	5.50, 5.60, 5.40	-	-	-
Acid detergent insoluble CP	5.31, 5.10, 4.75	-	-	-
Ether extract	2.30, 2.40, 3.40	0.32	0.89	2.53
Starch	0.70, 0.40, 0.70	-	0.80	-
Ethanol soluble carbohydrates	3.30, 3.90, 0.95	-	-	-
Ash	25.9, 26.1, 22.9	50.4	55.5	36.9
Calcium	1.31, 1.28, 1.12	4.47	3.31	3.74
Phosphorus	0.25, 0,21, 0.16	0.27	0.22	0.23
Magnesium	0.69, 0.80, 0.89	1.38	1.56	0.91
Potassium	3.53, 2.57, 2.51	-	2.48	2.47
Sodium	3.90, 3.59, 3.42	9.36	10.2	4.40
Sulfur	2.84, 2.71, 3.37	-	-	5.40
Chloride	4.70, 4.73, 3.16	-	-	-
Iron, mg/kg of DM	287, 403, 234	1,188	4,964	1,570
Zinc, mg/kg of DM	9.00, 11.0, 33.5	66.3	21.0	53.7
Copper, mg/kg of DM	3.00, 4.00, 2.50	13.3	7.00	2.00
Manganese, mg/kg of DM	20.0, 24.0, 24.5	62.3	92.0	106
Arsenic, mg/kg of DM	28.3, -, 14.9	-	-	-
Iodine, mg/kg of DM	820, 727, 415	-	-	394
Bromoform, mg/g of DM	-,-,-	1.32	10[5]	-

[1] Data are mean values reported by Antaya et al. (2015), Antaya et al. (2019), and Silva et al. (2022), respectively.

[2] Data are mean values reported by Roque et al. (2019).

[3] Data are mean values reported by Stefenoni et al. (2021).

[4] Data are unpublished results from Brito's Lab.

[5] Value based on Figure 3 (experiment 4) reported by Stefenoni et al. (2021).

Effect of Selected Seaweeds on Production Performance in Lactating Dairy Cows

Ascophyllum nodosum

There are few controlled studies in which DMI was measured individually in lactating dairy cows supplemented with ASCO meal. Antaya et al. (2015) reported that DMI tended to increase quadratically (17.5, 18.1, 18.1, and 17.6 kg/d) in dairy cows fed incremental amounts (0, 57, 113, and 170 g/d) of ASCO meal. In 2 follow-up studies done at the University of New Hampshire, DMI (mean = 17.1 kg/d) did not change in dairy cows supplemented (113 g/d) or not with ASCO meal (Antaya et al., 2019) during the grazing season or in dairy cows (mean = 21.1 kg/d) receiving increasing levels (0, 57, 113, and 170 g/d) of ASCO meal or 300 mg/d of monensin (Silva et al., 2022). Similarly, Pompeu et al. (2011) feeding 56 and 132 g/d of ASCO meal and Cvetkovic et al. (2014) feeding 57 g/d of ASCO meal found no difference in DMI of dairy cows. Collectively, these results indicate that ASCO meal supplemented up to 170 g/d had no negative impact on DMI in Jersey (Antaya et al., 2015, 2019; Silva et al., 2022) or Holstein (Pompeu et al., 2011; Cvetkovic et al., 2014) cows.

Yields of milk yield, 4% fat-corrected milk (FCM), and energy-corrected milk (ECM) were not affected in dairy cows fed varying amounts of ASCO meal (Antaya et al., 2015, 2019; Silva et al., 2022), thus in agreement with Pompeu et al. (2011) and Karatzia et al. (2012). Whereas yields of 4%FCM and ECM did not change with feeding ASCO meal versus the control diet in the study of Cvetkovic et al. (2004), milk yield increased by 1.7 kg/d. Kellogg et al. (2006) reported a significant interaction between ASCO meal supplementation and breed for milk yield, with large-frame cows (mostly Holsteins) producing more milk (+2.3 kg/d) when offered ASCO meal (mean = 104 g/d) than those in the control diet, but no difference was observed for small-frame cows (mostly Jerseys, Milking Shorthorns, and Holstein × Jersey crosses). Positive milk yield responses in the experiments of Cvetkovic et al. (2004) and Kellogg et al. (2006) may be associated with beneficial effects of ASCO meal on alleviating heat stress in ruminants as this seaweed seems to regulate body temperature despite the mechanism not being fully elucidated (Allen et al., 2001). In fact, Pompeu et al. (2011) demonstrated that ASCO meal supplementation reduced body temperature to increasing ambient temperature in dairy cows during the hot summer months. Furthermore, Kellogg et al. (2006) showed decreased respiration rate in ASCO meal-fed cows over the summer. However, body temperature and respiration rate were not impacted with ASCO meal supplementation to heat-stressed (Cvetkovic et al., 2004) or grazing (Antaya et al., 2019) dairy cows, with both studies conducted in the summer. In all these experiments (i.e., Cvetkovic et al., 2004; Kellogg et al., 2006; Pompeu et al., 2011; Antaya et al., 2019), cows were not submitted to controlled heat stress conditions, thus data should be interpreted cautiously.

Concentrations and yields of milk fat and protein were not changed in cows supplemented with varying levels of ASCO meal (Antaya et al., 2015, 2019; Pompeu et al., 2011; Karatizia et al., 2012; Chaves Lopez et al., 2016; Silva et al., 2022). Cvetkovic et al. (2004) reported that milk fat concentration tended to decrease in cows offered ASCO meal possibly in response to a dilution effect caused by increased milk volume (+1.7 kg/d). In fact, milk fat yield did not change between treatments indicating no effect of diets on milk fat synthesis in mammary tissues (Cvetkovic et al., 2004). Whereas milk protein concentration was not affected by diets in the study of Cvetkovic et al. (2004), milk protein yield followed milk production and increased with ASCO meal supplementation. *Ascophyllum nodosum* is rich in phlorotannins, which are polyphenolic compounds known to make complexes with proteins and carbohydrates (Ragan and Glombitza, 1986). It is conceivable that ASCO-phlorotannins may have reduced protein degradation in the rumen, with escaped amino acids used for milk protein synthesis in the mammary gland. Kellogg et al. (2006) observed inconsistent treatment effect on milk fat concentration as it was lower for cows fed control versus ASCO meal in July but tended to increase with feeding ASCO during August. They attributed this discrepancy to temporal changes in milk fat concentration not related to dietary treatments. In contrast, milk protein concentration was not affected by ASCO meal supplementation in the experiment of Kellogg et al. (2006). Note that Kellogg et al. (2006) did not report production of milk components in their study.

Asparagopsis armata

This author is aware of only 1 published study (i.e., Roque et al., 2019) in which lactating dairy cows were fed *A. armata*. Roque et al. (2019) fed incremental amounts (0, 0.5, and 1%; diet OM basis) of *A. armata* to dairy cows in a 3 × 3 Latin square design (21-d periods) and reported a decrease in DMI of 3.0 and 10.6 kg/d comparing the control diets with 0.5 or 1% of *A. armata* supplementation, respectively. Authors hypothesized that decreased DMI may have been associated with the high concentration of minerals supplied by *A. armata* resulting in poor palatability. They also observed that while milk yield was 4.2 kg/d lower in cows receiving 1% *A. armata* than in those assigned to the control diet, no difference was detected between 0 and 0.5% *A. armata*. Reduced DMI (-3.0 kg/d) accompanied by similar milk yield with feeding control versus 0.5% *A. armata* implies mobilization of body reserves to keep up with milk synthesis. However, body weight (BW) change did not differ between these 2 diets, which may have been caused by limitations of short-term, changeover experimental designs to discriminate treatment differences for variables that represent altered nutrient partitioning such as BW change and retained N (Zanton, 2019).

Milk fat concentration averaged 3.84% and was not affected by diets with varying levels of *A. armata* (Roque et al., 2019). Contrarily, milk protein concentration was greatest, intermediate, and lowest in cows fed 0, 0.5, and 1% *A. armata*, respectively. Although milk protein yield was not reported by Roque et al. (2019), calculated milk protein yield decreased by 17% with feeding 1 versus 0% *A. armata*. As discussed above, DMI decreased by 38% in cows supplemented with 1% *A. armata* possibly leading to a reduced supply of rumen-degradable protein, which can ultimately impair microbial protein synthesis and availability of essential amino acids for milk protein synthesis. Overall, feeding *A. armata*, particularly at the greatest level of supplementation (i.e., 1% of the diet OM) negatively affected DMI, milk yield, and milk protein concentration. Therefore, further research is needed to better understand the use of *A. armata* for high-producing dairy cows.

Asparagopsis taxiformis

Research in which lactating dairy cows were fed diets containing *A. taxiformis* is scarce. Stefenoni et al. (2021) supplemented dairy cows with incremental amounts (0, 0.25, and 0.5% of the diet DM) of *A. taxiformis* and oregano leaves and observed that feeding 0.5% *A. Armata* led to the lowest DMI (-1.8 kg/d compared with the control diet).

Both yields of milk and ECM followed DMI and decreased by 2.6 and 2.4 kg/d, respectively, in cows fed 0.5% *A. taxiformis* relative to control. According to Stefenoni et al. (2021), decreased palatability with feeding 0.5% *A. taxiformis* was likely involved with the observed depression of DMI in their experiment. They also stated that the likelihood of sorting was negligible considering that *A. taxiformis* was finely ground and mixed into the total-mixed ration, further reinforcing a potential taste avoidance response. In fact, Muizelaar et al. (2021) reported that cows either frequently refused or selected against a concentrate mix containing *A. taxiformis*, dextrose, wheat, dehydrated beet pulp, and water. Whereas the concentrations of milk fat and milk protein were not affected with feeding *A. taxiformis*, their yields decreased by 6.2 and 6.3%, respectively, comparing 0.5% *A. taxiformis* versus control (Stefenoni et al., 2021). As discussed above for *A. armata*, further research is needed to better understand the processes underpinning the negative impact of *A. taxiformis* on production performance of high-producing dairy cows.

Chondrus crispus

While both *Asparagopsis* species discussed herein are not native of the US coast, the red seaweed *C. crispus* grows in the intertidal zone of the North Atlantic including the Gulf of Maine where it is wild harvested. In fact, a 3 × 3 Latin square design study was conducted at the University of New Hampshire (Brito's Lab unpublished) to evaluate the effect of incremental amounts of *C. crispus* (0, 3, and 6% of the diet DM) on DMI, milk production, and milk composition using 18 Jersey cows fed total-mixed rations with a 65:35 forage:concentrate ratio. Feeding *C. crispus* decreased DMI linearly (20.7, 19.3, and 18.9 kg/d for 0, 3, and 6% *C. crispus*, respectively). This reduction in DMI could be associated with palatability issues or sorting. *Chondrus crispus* used in the study was dried and milled into small flakes (mean particle size = 3.2 mm) and cows may have had the opportunity to sort. In fact, it was frequently observed small, harder pieces of *C. crispus* in the orts which appear to be the seaweed stipe (i.e., stem-like structure), indicating that cows selectively refused parts of the alga material. Despite the linear reduction in DMI, milk yield did not change and averaged 18.4 kg/d across treatments. Likewise, concentration (mean = 5.51%) and yield (mean = 1.01 kg/d) of milk fat, and concentration (mean = 3.64%) and yield (mean = 0.67 kg/d) of milk true protein were similar among diets. Overall, inclusion of up to 6% *C. crispus* in the diet DM negatively affected DMI but milk yield and composition remained unchanged.

Effect of Selected Seaweeds on Enteric Methane Emissions in Dairy Cows

Ascophyllum nodosum

Previous *in vitro* research revealed that phlorotannins extracted from ASCO dosed at 500 µg/L reduced CH_4 production in batch culture with forage (barley silage plus alfalfa hay) or ground barley as substrates (Wang et al., 2008). Similarly, Belanche et al. (2016) observed a quadratic decrease in CH_4 production during an *in vitro* batch culture study with vials dosed with incremental levels (up to 2 g/L) of ASCO meal. Therefore, ASCO meal has potential to suppress enteric CH_4 production *in vivo*. Table 3 shows the effect of ASCO meal, *Asparagopsis* species, and *C. crispus* on enteric CH_4 production, as well as mean percentage change when comparing the control diets versus those with the greatest inclusion of seaweeds.

To the best of this author knowledge, only 1 study (i.e., Antaya et al., 2019) was published to date evaluating the effect of ASCO meal on enteric CH_4 emissions in lactating dairy cows. Antaya et al. (2019) reported a diet × period interaction for enteric CH_4 production, which decreased by 10.4% in grazing dairy cows supplemented with 113 g/d of ASCO meal during the first period of the study (June) but not thereafter (July-September). This suggests a transient effect of ASCO meal on suppressing methanogenesis or an adaptation of the archaeal community to ASCO meal supply over time. Moreover, CH_4 yield and CH_4 intensity did not change and averaged 20 g/kg of DMI and 23.4 g/kg of ECM, respectively, between treatments (Antaya et al., 2019). Zhou et al. (2018) reported a linear decrease in the ruminal concentration (copies/g of DM) of archaea when rams received increasing dietary levels of ASCO (up to 5% of the diet DM), suggesting that ASCO meal should be supplemented at a greater amount than that fed by Antaya et al. (2019) to consistently inhibit ruminal methanogenesis. Nevertheless, unpublished results from Brito's Lab revealed no change in enteric CH_4 production (mean = 389 g/d), CH_4 yield (mean = 18.7 g/kg of DMI), and CH_4 intensity (mean = 13.8 g/kg of ECM) in dairy cows supplemented with 400 g/d of ASCO (~2% of diet DM) for 3 weeks. It is important to note that high dietary inclusion (>1% of the diet DM) of ASCO meal may not be feasible in commercial settings due to the risk of iodine toxicity and impairment of the thyroid function. Overall, based on limited *in vivo* research done with lactating dairy cows, it appears that ASCO meal has low enteric CH_4 mitigation potential.

Asparagopsis armata

Roque et al. (2019) reported that compared with the control diet (0% *A. amarta*), enteric CH_4 production decreased by 26.4 and 67.2% in dairy cows supplemented (diet OM basis) with 0.5 and 1% *A. armata*, respectively (Table 3). Similarly, CH_4 yield decreased by 20.3 and 42.7%, and CH_4 intensity by 18.2 and 60.1% with feeding 0.5 and 1% *A. armata*, respectively, relative to the control diet. *Asparagopsis armata* is known to bioaccumulate bromoform (Paul et al., 2006) that, in turn, has been shown to inhibit methanogenesis possibly in synergy with other halogenated or brominated compounds (Machado et al., 2018). In briefly, *A. armata* effectively suppressed CH_4 emissions, particularly at the greatest supplementation level. However, DMI, milk yield, and concentrations of milk fat and protein also decreased, which may limit the large-scale use of *A. armata* in dairy diets.

Asparagopsis taxiformis

Enteric CH_4 production (Table 3), CH_4 yield, and CH_4 intensity decreased by 34.4, 29.4, and 26.2%, respectively, in dairy cows fed (diet DM basis) 0.5% *A. taxiformis* versus the control diet (0% *A. taxiformis*) in experiment 3 of Stefenoni et al. (2021). However, no differences in enteric CH_4 production, CH_4 yield, and CH_4 intensity were observed between the control diet and 0.25% *A. taxiformis* (Stefenoni et al., 2021). According to Stefenoni et al. (2021), decreased CH_4 emissions in response to *A. taxiformis* supplementation was associated with the presence of bromoform and possibly other halogenated and brominated metabolites that accumulate in the tissues of this red seaweed. They also observed a decrease in the molar proportion of ruminal acetate and an increase in that of ruminal propionate with feeding 0.5% *A. taxiformis* versus control, thus indicating a shift in fermentation toward propionate, which is a hydrogen sink. Authors further reported that *A. taxiformis* (0.5% of the diet DM) was highly effective to suppress CH_4 yield in periods 1 and 2 of the study (mean = -55% reduction), but no treatment difference was seen on periods 3 and 4, possibly because of bromoform losses during storage over time. In contrast, Roque et al. (2021) demonstrated consisted suppression of CH_4 production and CH_4 yield in beef steers fed 0.5% *A. taxiformis* throughout the 21-week study, thus suggesting differences in the preservation of bromoform between batches of *A. taxiformis*. Overall, *A. taxiformis* has high potential as a dietary strategy to mitigate enteric CH_4 emissions in ruminants, but reduced production performance reported by Stefenoni et al. (2021) may limit producers' adoption.

Table 3. Enteric methane (CH_4) production and mean percentage change in lactating dairy cows fed *Ascophyllum nodosum* (ASCO) meal, *Asparagopsis* species, or *Chondrus crispus*.

Breed	**Basal diet[1]**	**Treatments**	**CH_4, g/d**	**Reference**
Jersey	Pasture + pTMR	0 g/d ASCO meal	371	Antaya et al. (2019)[2]
		113 g/d ASCO meal	363	
		Mean % change[3]	-2.16	
Holstein	TMR	0% *A. armata*	396[4]	Roque et al. (2019)
		0.5% *A. armata*	291[4]	
		1% *A. armata*	130[4]	
		Mean % change[3]	-67.2	
Holstein	TMR	0% *A. taxiformis*	349	Stefenoni et al. (2021)[5]
		0.5% *A. taxiformis*	350	
		1% *A. taxiformis*	229	
		1.77% oregano leaves	374	
		Mean % change[3]	-34.4	
Jersey	TMR	0% *C. crispus*	383	Brito's unpublished
		3% *C. crispus*	352	
		6% *C. crispus*	351	
		Mean % change[3]	-8.4	

[1] pTMR = partial total-mixed ration; TMR = total-mixed ration.
[2] A diet by period interaction was observed for enteric CH_4 production, which decreased by 10.3% with feeding 113 g/d of ASCO meal on period 1 but no change between diets thereafter.
[3] Mean % change comparing control versus diets with the greatest inclusion of seaweeds.
[4] Aproximate values based on Figure 1A and percentage reduction reported in the text.
[5] Data from experiment 3.

Chondrus crispus

As for both *Asparagopsis* species discussed above, there is limited *in vivo* research in which the enteric CH_4 mitigation potential of the red seaweed *C. crispus* was evaluated. It should be noted that the amounts of *C. crispus* fed *in vivo* during a study conducted at the University of New Hampshire (Brito's Lab unpublished) were based on results from preliminary *in vitro* research that showed moderate to high CH_4 mitigation potential in response to *C. crispus*. Cows fed incremental amounts (% of the diet DM) of *C. crispus* had a linear decrease in enteric CH_4 production (from 383 to 351 g/d; Table 3), thus in line with the linear reduction seen for DMI discussed previously. Compared with the control diet, enteric CH_4 production dropped by 8.4% with feeding 6% *C. crispus* (Table 3). However, CH_4 production was similar between 3% (352 g/d) and 6% (351 g/d) *C. crispus*, suggesting that it should not be fed in levels > 3% of the diet DM. Both CH_4 yield (mean = 18.4 g/kg of DMI) and CH_4 intensity (mean = 15.3 g/kg of ECM) did not differ across diets. Bromoform was not measured in *C. crispus* but based on a much less effective response on suppressing enteric CH_4 production compared with *A. armata* (Roque et al., 2019) or *A. taxiformis* (Stefenoni et al., 2021), it is conceivable that bromoform accumulation by *C. crispus* is minimal despite it having the enzymatic systems to synthesize this brominated metabolite (Thapa et al., 2020).

Effect of Selected Seaweeds on Milk Concentrations of Iodine and Brominated Metabolites and Human Health Implications

Milk iodine concentration

Iodine is a structural component of the thyroid hormones triiodothyronine (T3) and thyroxine (T4), and iodine deficiency is a public health concern that been linked to goiter and poor brain development as reviewed by Fuge and Johnson (2015). On the other hand, excess iodine intake can lead to thyroiditis, hyperthyroidism, hypothyroidism, and goiter in individuals with underlining thyroid issues or in vulnerable groups such as seniors, fetuses, and neonates (Pennington, 1990; Katagiri et al., 2017). Seaweeds (brown > red > green) bioaccumulate iodine through the uptake of iodide leached into the seawater based on the review of Fuge and Johnson (2015). Therefore, milk iodine concentration generally increases in response to seaweed supplementation to dairy cows. Table 4 shows the milk iodine concentration and mean percentage change comparing the control diets with those with the greatest dietary inclusion of seaweeds.

Milk iodine concentration increased linearly from 178 to 1,370 μg/L (Antaya et al., 2015) and from 383 to 1,228 μg/L (Silva et al., 2022) in dairy cows fed incremental amounts (0, 57, 113, and 170 g/d) of the brown seaweed ASCO (Table 4). Milk iodine concentration was, on average, 318% greater in grazing dairy cows supplemented with 113 g/d ASCO meal (mean = 481 μg/L) than in the diet without seaweed supplementation (mean = 118 μg/L; Antaya et al., 2019; Table 4). Similarly, feeding the red seaweeds *A. taxiformis* (Stefenoni et al., 2021) or *C. crispus* (Brito's Lab unpublished) increased the concentration of iodine in cow's milk. Specifically, Stefenoni et al. (2021) reported a 416% increase in milk iodine concentration comparing 0.5% *A. taxiformis* (mean = 2,966 μg/L) versus control (mean = 575 μg/L) as shown in Table 4. A linear increase in milk iodine concentration was observed in dairy cows fed increasing dietary levels of *C. crispus* (from 204 to 1,796 μg/L; Table 4). Furthermore, mean milk iodine concentration (1,021 μg/L) from cows fed 113 g/d of ASCO meal (~0.58% of the diet DM; Antaya et al., 2015; Silva et al., 2022) was 66% lower than that from cows fed the greatest amount (0.5% of the diet DM; ~118 g/d) of *A. taxiformis* (Stefenoni et al. (2021). This discrepancy in milk iodine concentration between ASCO meal and *A. taxiformis* despite similar amounts fed suggest differences in seaweed iodine concentration or iodine bioavailability. Note that Stefenoni et al. (2021) did not report the iodine concentration of the *A. taxiformis* used in their study. However, Roque et al. (2021) reported a mean iodine concentration of 2,270 mg/kg for *A. taxiformis* in their study, with this value being 177 and 447% greater than that obtained by Antaya et al. (2015) and Silva et al. (2022), respectively.

Table 4. Milk iodine concentration and mean percentage change in lactating dairy cows fed *Ascophyllum nodosum* (ASCO) meal, *Asparagopsis taxiformis*, or *Chondrus crispus*.

Breed	**Basal diet[1]**	**Treatments**	**Milk iodine, µ/L**	**Reference**
Jersey	TMR	0 g/d ASCO meal	178	Antaya et al. (2015)
		57 g/d ASCO meal	602	
		113 g/d ASCO meal	1,015	
		170 g/d ASCO meal	1,370	
		Mean % change[2]	+670	
Jersey	Pasture + pTMR	0 g/d ASCO meal	118	Antaya et al. (2019)[3]
		113 g/d ASCO meal	481	
		Mean % change[2]	+308	
Holstein	TMR	0% *A. taxiformis*	575	Stefenoni et al. (2021)[4]
		0.5% *A. taxiformis*	2,966	
		Mean % change[2]	+416	
Jersey	TMR	0 g/d ASCO meal	383	Silva et al. (2022)
		57 g/d ASCO meal	729	
		113 g/d ASCO meal	1,027	
		170 g/d ASCO meal	1,228	
		300 mg/d monensin	339	
		Mean % change[2]	221	
Jersey	TMR	0% *C. crispus*	204	Brito's unpublished
		3% *C. crispus*	848	
		6% *C. crispus*	1,796	
		Mean % change[2]	+780	

[1] pTMR = partial total-mixed ration; TMR = total-mixed ration.

[2] Mean % change comparing control versus diets with the greatest inclusion of seaweeds.

[3] A diet by period interaction was observed for milk iodine concentration, with the greatest difference in milk iodine between diets (+416%) being detected in period 2.

[4] Data from experiment 3.

According to the European Food Safety Authority (EFSA, 2013), milk iodine concentration should not exceed 500 µg/L to minimize risks of iodine toxicity in humans. Figure 1 shows the distribution of milk iodine concentration (n = 128 individual observations) from cows fed ASCO meal (Antaya et al., 2015, 2019; Silva et al., 2022) or *C. crispus* (Brito's Lab unpublished). Based on Figure 1, 80% (102 out of 128) of the individual observations was above the 500-µg/L threshold considered safe for humans' health (EFSA, 2013). Likewise, milk iodine concentration from cows fed *A. taxiformis* was 5.9-fold greater than 500 µg/L (Stefenoni et al., 2021). The 2020–2025 Dietary Guidelines for Americans recommends the consumption of 3 cups-equivalent (1 cup = 236.7 mL) of fat-free or reduced-fat milk daily for children and adolescents ages ≥ 9-18 and adults as part of a healthy diet (USHHS USDA, 2020). For examples, boys (age 9-13 years old) consuming 3 cups-equivalent of milk from cows fed 0.5% *A. taxiformis* would exceed their iodine recommended dietary allowance (i.e., 120 µg/d; US Institute of Medicine, 2001) by 17.6-fold and the iodine tolerable upper intake (i.e., 600 µg/d; US Institute of Medicine, 2001) by 3.5-fold assuming milk as the sole iodine source in their diet. Therefore, a hypothetical large-scale adoption of *A. taxiformis* by dairy producers across the US to mitigate enteric CH_4 emissions would require approaches to reduce iodine concentration of *A. taxiformis* such as washing procedures or using feeds containing goitrogenic compounds like canola meal or legumes (e.g., white clover).

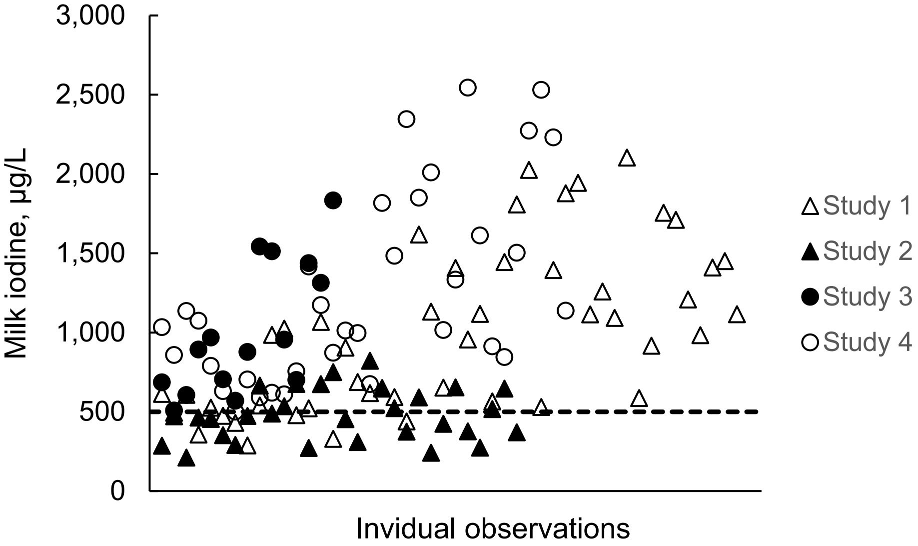

Figure 1. Individual milk iodine concentration observations (n = 128) from Jersey cows fed varying amounts of *Ascophyllum nodosum* meal (Study 1 = Antaya et al., 2015; Study 2 = Antaya et al., 2019; Study 3 = Silva et al., 2022) or *Chondrus crispus* (Study 4 = Brito's Lab unpublished). The dashed line represents the 500-µg/L threshold considered safe for human health according to the European Food Safety Authority (EFSA, 2013).

Weiss et al (2015) reported linear reductions in milk iodine concentration in dairy cows fed increasing amounts (from 0 to 13.9% of the diet DM) of canola meal and 2 levels (0.5 and 2 mg/kg) of supplemental iodine as ethylenediamine dihydroiodideiodine. On average, milk iodine concentration dropped by 43% (from 725 to 413 µg/L) and was below 500 µg/L in cows fed the greatest amounts of canola meal and supplemental iodine (Weiss et al., 2015). Antaya et al. (2019) observed that the milk iodine concentration of grazing dairy cows supplemented with 113 g/d of ASCO meal was below 500 µg/L (mean = 432 µg/L) in 2 out of 3 periods (diet × period interaction) likely associated with increased intake of goitrogenic compounds from grazed herbage. For comparison, milk iodine concentration from dairy cows in confinement supplemented with 113 g/d of ASCO meal averaged 1,015 µg/L (Antaya et al., 2015) and 1,027 µg/L (Silva et al., 2022). In addition to seaweed washing procedures and feeds with goitrogenic compounds, it may be necessary to eliminate the use of iodine-based solutions for milking hygiene procedures and feed iodine-free mineral/vitamin premixes if cows are to be supplemented with seaweeds with high CH_4 mitigation such as *A. armata* or *A. taxiformis*.

Milk concentration of brominated metabolites

As discussed earlier, red seaweeds accumulate several brominated metabolites, particularly bromoform (Paul et al., 2006). Therefore, bromoform along with bromide can be transferred to milk, thus raising human-health concerns (Roque et al., 2019). In fact, the US Environmental Protection Agency (US EPA, 2008) and the World Health Organization (WHO, 2017) have both set maximum standard concentrations for bromoform in drinking water at 80 and 100 µg/L, respectively. Regarding bromide, it has been suggested an acceptable daily intake of 0.4 mg/kg of BW, which would result in an acceptable total daily intake of 24 mg of this metabolite for an individual weighing 60 kg (EMEA, 1997).

Roque et al. (2019) reported no treatment differences in the milk concentration of bromoform, which averaged 0.11, 0.15, and 0.15 µg/L in dairy cows fed (diet OM basis) 0, 0.5, and 1% *A. armata*, respectively, in a 3 × 3 Latin square design with 21-d periods. Stefenoni et al. (2021) observed that the milk concentration of bromoform was not affected with feeding (diet DM basis) of 0.5% *A. taxiformis* to dairy cows despite a numerical increase of 75.2% when comparing the control diet (16.5 µg/L) with that containing seaweed (28.9 µg/L) in a 4 × 4 Latin square design with 28-d periods (experiment 3; bromoform measurements done on control and 0.5% seaweed diets only). The lack of treatment effect on milk bromoform concentration in the study of Stefenoni et al. (2021) may be associated with a high variation in animal response or in the analytical procedure or both considering that the standard error of the mean was 10.6 µg/L. Interestingly, milk bromoform concentration was 196-fold greater in cows fed *A. taxiformis* than in those receiving *A. armata*, but the reason for this discrepancy is not obvious based on data reported by Roque et al. (2019) and Stefenoni et al. (2021). Muizelaar et al. (2021) reported that on d 1 of their study bromoform was detected in the milk of most cows fed (diet DM basis) 67 and 133 g/d of *A. taxiformis* (mean = 9.1 and 11 µg/L, respectively), and it was again detected in the milk of only 1 cow supplemented with 333 g/d of *A. taxiformis* on d 9 (mean = 35 µg/L). No bromoform was found above the detection limit level (i.e., 5 µ/L) in the milk of all cows on d 10 and 17, which may be partially explained by animals inconsistently consuming the seaweed treatments and, at times, completely avoiding *A. taxiformis*.

The mean milk bromoform concentration (0.15 µg/L) reported by Roque et al. (2019) in cows fed both *A. armata* diets (0.5 and 1%) was, on average, 533- and 667-fold lower than the threshold levels considered acceptable for drinking water according to the US Environmental Protection Agency (80 µg/L; US EPA, 2008) and the World Health Organization (100 µg/L; WHO, 2017), respectively. As for *A. taxiformis*, using the milk bromoform concentration of 28.9 μg/L from cows fed the diet with 0.5% seaweed and the recommended 3 cups-equivalent of milk/d for children (USHHS USDA, 2020), it would result in a daily bromoform consumption of 20.5 μg, thus 3.9-. and 4.9-fold lower than the maximum bromoform concentrations set for drinking water by the US Environmental Protection Agency (US EPA, 2008) and the World Health Organization (WHO, 2017), respectively. Therefore, based on limited and variable data (Roque et al., 2019; Muizelaar et al., 2021; Stefenoni et al., 2021), milk bromoform concentration in dairy cows' milk appear to be safe for human consumption, but further research is needed to better understand the reasons behind discrepant milk bromoform results reported in the literature. Specifically, research is needed to improve knowledge on metabolism and pharmacokinetics of bromoform in dairy cows, while standardizing sample processing and analytical methods used to quantify bromoform across different biological matrices (e.g., milk, urine, blood, feces, tissues).

Stefenoni et al. (2021) measured bromide in milk and reported an average concentration of 40.4 mg/kg in cows fed 0.5% *A. taxiformis*, which was 692% greater than that found in milk from cows in the control diet (5.1 mg/kg). Following the recommended intake of 3 cups-equivalent of milk/d for children and adolescents ages ≥ 9-18 and adults based on the 2020–2025 Dietary Guidelines for Americans (USHHS USDA, 2020), it would result in a consumption of 28.7 mg/d of bromide if drinking milk from cows fed 0.5% *A. taxiformis*, thus slightly above the acceptable daily intake of 24 mg of bromide for an individual weighing 60 kg (EMEA, 2007). However, studies done with healthy volunteers dosed with up to 9 mg of bromide/kg of BW showed no detrimental effects on human health apart from incidental nausea episodes (Sangster et al., 1982, 1983). Further research is needed to better understand the variation in milk bromide concentration in response to varying dietary levels of *A. taxiformis*.

Effect of Selected Seaweeds on Iodine and Bromoform Metabolism in Dairy Cows

Iodine

There is scarce information on the effect of seaweeds on iodine metabolism in lactating dairy cows. Specifically, this author is aware of only 2 studies that investigated the effects of incremental amounts of seaweeds on iodine intake and output on milk, urine, and feces as shown in Table 5. On average, 140 and 61% of the iodine consumed was excreted via feces in cows supplemented with ASCO meal (Silva et al., 2022) or *C. crispus* (Brito's Lab unpublished), respectively, indicating that iodine was extensively recycled via the gastrointestinal tract as documented in earlier research (e.g., Miller et al., 1975). Interestingly, when cows were fed ASCO meal, the amount of iodine secreted on milk (mean = 19.5 mg/d) and excreted in urine (mean = 19 mg/d) was very similar. However, when iodine intake increased by an average of 7.1-fold comparing ASCO-fed with *C. crispus*-fed cows, urine became the dominant route for iodine excretion after feces (Table 5). These results suggest that the sodium-iodide symporter present in the lactating mammary gland (Cavalieri, 1997) likely saturated due to excess iodine supply shifting the output of iodine from milk to urine. It was also observed a quadratic increase in the urinary excretion of iodine in cows fed *C. crispus*, with the difference in the amount excreted being greater between 0 and 3% *C. crispus* (+45.3 mg/d) than between 3 and 6% (+13 mg/d). On the other hand, fecal excretion of iodine increased linearly following *C. crispus* supplementation (+128 and +96 mg/d comparing 0 vs. 3% and 3 vs. 6%, respectively) implying that as iodine intake largely surpassed requirement (from 3 to 6% *C. crispus*), iodine consumed was diverted from the urinary to the gastrointestinal tract. Potential environmental implications of excreted iodine need to be further investigated, particularly in a scenario of large adoption of seaweeds to mitigate enteric CH_4 emissions in both dairy and beef industries.

Table 5. Intake, milk secretion, and fecal and urinary excretion of iodine (mg/d) in dairy cows fed incremental amounts of *Ascophyllum nodosum* (ASCO) meal or *Chondrus crispus*.

	ASCO meal (g/d)[1]					*P*-value	
Item	0	57	113	170	SEM	Linear	Quadratic
Intake	8.60	28.7	48.6	68.9	2.34	<0.001	0.96
Milk	7.30	14.4	19.5	24.6	1.78	<0.001	0.44
Urine	5.10	14.1	18.0	24.8	1.98	<0.001	0.59
Feces	20.5	48.1	60.6	86.6	7.76	<0.001	0.92

	***C. crispus* (% of the diet DM)**					*P*-value	
Item	0	3	6	-	SEM	Linear	Quadratic
Intake	28.4	233	462	-	8.73	<0.001	0.20
Milk	4.48	15.0	31.4	-	2.12	<0.001	0.25
Urine	13.1	58.4	71.4	-	4.58	<0.001	<0.001
Feces	27.3	155	251	-	15.1	<0.001	0.21

[1] Adapted from Silva et al. (2022).

[2] Brito's Lab unpublished results.

Bromoform

It appears that the study conducted by Muizelaar et al. (2021) is the only one to this author knowledge that has investigated the effect of *A. taxiformis* on bromoform metabolism. In brief, bromoform was detect in urine of cows supplemented with *A. taxiformis* on d 1 and 10 of the experiment, but not on d 17 as it was below the limit detection level (<2 µg/L). Likewise, fecal bromoform concentration was not found in fecal samples because it was below the 20-µg/kg limit detection level. Overall, data from Muizelaar et al. (2021) should be interpreted cautiously due to cows either refusing or inconsistently consuming *A. taxiformis*, indicating that further research is needed to better understand bromoform metabolism in long-term experiments.

Effect of Selected Seaweeds on Iodine Intake and Iodine Toxicity Concerns in Dairy Cows

Excessive iodine intake can lead to toxicity in ruminants and associated symptoms such as excessive nasal and ocular discharge, hyperthermia, salivation, decreased milk production, coughing, and dry scaly coats according to the review of Paulíková et al. (2002). Iodine intake averaged 68.9 and 462 mg/d, respectively, in dairy cows fed 170 g/d of ASCO meal (Silva et al., 2022) or 6% of the diet DM as *C. crispus* (Table 5). Adequate iodine intake was calculated as 8.16 and 7.93 mg/d, respectively, for cows receiving 170 g/d of ASCO meal (mean = 450 kg of BW and 27.2 kg/d of milk) or 6% of *C. crispus* (mean = 489 kg of BW and 22.5 kg/d of milk) based on the Equation 7-34 [Dietary iodine = $0.216 \times \text{BW (kg)}^{0.528} + 0.1 \times$ milk yield (kg/d] reported in the NASEM (2021). However, actual iodine intake was 744 and 5,726% greater than estimated adequate iodine intake (NASEM, 2021) when feeding 176 g/d of ASCO meal or 6% *C. crispus*, respectively. Signs of iodine toxicity have been documented in dairy cows with estimated iodine intake ranging from 250 to 785 mg/d in diets containing ethylenediamine dihydroiodideiodine and time of supplementation varying from 1 month to 7 years (Olson et al., 1984). Ong et al. (2014) reported low-grade pyrexia, nasal discharge, respiratory distress, watery stools, and enlargement of the thyroid gland in 2 adult Holstein cows with estimated iodine intake averaging 10 mg/100 kg of BW. Despite excessive iodine intake in cows fed ASCO meal (Silva et al., 2022) or *C. crispus* (Brito's Lab unpublished), cows did not show signs of iodine toxicity. In addition, serum (Silva et al., 2022) and plasma (Brito's Lab unpublished) concentrations of T3 and T4 were not affected by diets even though cows were not exposed to long-term excess iodine intake as the experimental periods last 28 d (ASCO meal study) and 24 d (*C. crispus* study).

Neither Roque et al. (2019) nor Stefenoni et al. (2021) reported the concentrations of iodine for *A. armata* and *A. taxiformis*, respectively. Assuming an iodine concentration of 2,270 mg/kg for *A. taxiformis* (Roque et al., 2021), estimated iodine intake for dairy cows receiving 0.5% *A. taxiformis* (Stefenoni et al., 2021) would be 268 mg/d. Estimated adequate iodine intake using the NASEM (2021) Equation 7-34 (see above) averaged 10.7 mg/d for cows consuming 0.5% *A. taxiformis* weighing 635 kg and producing 42.2 kg/d of milk. Therefore, this estimated iodine intake was 2,405% greater than the estimated adequate iodine from NASEM (2021). Note that Stefenoni et al. (2021) did not report any iodine toxicity symptoms in their 4 × 4 Latin square design study with 28-d experimental periods.

Effect of Selected Seaweeds on Dairy Cow Health

Studies evaluating the impact of feeding the red seaweeds *A. armata*, *A. taxiformis*, and *C. crispus* on markers of dairy cow health are limited or not available. In contrast, the brown seaweed ASCO is likely the most studied algal feed as related to animal health based on reports in the literature [see review papers from Allen et al. (2001), Evans and Critchley (2014), and Makkar et al. (2016)]. However, most published research that have documented health benefits in response to ASCO meal supplementation such as modulation of body temperature, improved immune system, and decreased shedding of *E. coli* was done with beef, sheep, and pigs (Allen et al., 2001; Evans and Critchley, 2014; Makkar et al., 2016). Data on the effect of ASCO meal on mitigating heat stress are scarce and studies were not conducted under controlled conditions (e.g., Pompeu et al., 2011).

The algal feed ASCO meal is popular very among organic dairy producers in the US (Hardie et al., 2014; Antaya et al., 2015; Sorge et al., 2016; Snider et al., 2021), with up to 72.5% of organic grassfed dairies that participated in a national survey indicating the use of ASCO (Snider et al., 2021). According to a survey reported in Antaya et al. (2015), organic dairy producers feed ASCO meal for the following reasons: (1) it improves body condition and overall animal appearance, (2) it decreases somatic cell count, reproductive problems, and incidence of "pinkeye" (i.e., infectious bovine keratoconjunctivitis), and (3) it reduces incidence of nuisance flies. However, controlled studies are needed to corroborate these anecdotal claims.

Antaya et al. (2015) reported a linear decrease in the plasma concentration of non-esterified fatty acids in early- to mid-lactation dairy cows fed incremental amounts (0, 57, 113, and 170 g/d) of ASCO meal. They also observed a tendency for a linear decrease in the serum concentration of cortisol in response to ASCO meal supplementation. Similarly, Silva et al. (2022) saw a linear decrease in the serum concentration of cortisol with feeding varying amounts (0, 57, 113, and 170 g/d) of ASCO meal. However, the mechanisms behind these changes in blood non-esterified fatty acids and cortisol are not well understood and require further research. Cows in the study of Antaya et al. (2015) and Silva et al. (2022) were exposed to winter and summer conditions, respectively, which may have led to cold and heat stress that were alleviated by ASCO meal supplementation ultimately decreasing cortisol levels. In fact, ASCO meal and ASCO extracts have been associated with body's thermoregulatory control in beef cattle and sheep with concomitant reduction in circulating cortisol (Allen et al., 2001; Archer et al., 2007). Contrarily, serum cortisol concentration did not change in grazing dairy cows receiving 113 g/d of ASCO meal despite the study being conducted during the summer months when cows are more susceptible to heat stress (Antaya et al., 2019). Furthermore, plasma activities of the antioxidant enzymes superoxide dismutase (mean = 0.40 U/mL), glutathione peroxidase (mean = 50.3 nmol/min per mL), and catalase (mean = 8.03 nmol/min per mL) were not changed in cows supplemented with up to 170 g/d of ASCO meal in an experiment done from June to November (Silva et al., 2022). Chaves Lopez et al. (2016) observed a 44.5% reduction in milk somatic cells count (from 490,000 to 272,000) with feeding 100 g/d of ASCO meal compared with the control diet, thus suggesting improvement in milk quality and mammary gland health. Note that Chaves Lopez et al. (2016) used only 22 cows (n = 11/treatment) and their results should be interpreted cautiously. In general, ASCO meal appears to have some positive health benefits, but additional studies under strict conditions (e.g., controlled humidity and ambient temperature, immune system challenge, etc.) are needed to fully address the role of ASCO meal on improving dairy cattle heath.

Data on the effect of the red seaweeds *A. armata* and *A. taxiformis* on health of lactating dairy cows are limited. Roque et al. (2019) did not evaluate markers of animal health and did not report any adverse effect of *A. armata* on the health of 12 lactating dairy cows used in their experiment. Muizelaar et al. (2021) euthanized 2 lactating dairy cows that consistently consumed 67 g/d of *A. taxiformis* and observed loss or absence of papillae on parts of the ruminal wall in both cows. They also saw signs of inflammation in the ruminal wall of the 2 euthanized cows after histological examination of the ruminal papillae (Muizelaar et al., 2021). These histopathological changes in the ruminal wall and papillae of 2 cows were comparable to those found on 5 out of 10 sheep supplemented with increasing levels (0, 0.5, 1, 2, and 3%; diet OM basis) of *A. taxiformis* (Li et al., 2016). In contrast, no histopathological abnormalities and signs of inflammation were seen in 2 out of 2 euthanized sheep that had no access to *A. taxiformis* (i.e., control diet; Li et al., 2016). However, these histopathological changes detected in the ruminal wall and papillae of sheep and dairy cows could not be conclusively associated with *A. taxiformis* supplementation according to Li et al. (2016) and Muizelaar et al. (2021). Although Stefenoni et al. (2021) did not report any detrimental health effect in response to various levels of *A. taxiformis* supplementation to dairy cows, blood activity of the enzyme alanine aminotransferase decreased by 22.8% (from 57.5 to 44.4 U/L) with feeding 0.5% *A. taxiformis* versus control. This enzyme has been used as a marker of liver health and increased activity of alanine aminotransferase may be associated with liver damage and metabolic or infectious diseases as discussed by Stefenoni et al. (2021). Therefore, *A. taxiformis* may have some hepatoprotective effect, but Stefenoni et al. (2021) stated that they were not able to offer a reasonable explanation for the marked reduction seen for alanine aminotransferase activity in cows fed 0.5% *A. taxiformis*. It is clear based on these few reports that long-term studies are needed to properly assess the effect of *A. taxiformis* on health of high-producing dairy cows.

Summary and Implications

Feeding the brown seaweed ASCO meal had no negative effect on DMI. Milk yield response to ASCO meal supplementation varied, with some studies showing no effect on milk yield, whereas others resulting in improved milk production. In contrast, feeding the red seaweeds *A. armata*, *A. taxiformis*, and *C. crispus* decreased DMI, particularly when cows were fed the greatest amount of each seaweed. Milk yield followed DMI and decreased with feeding both *Asparagopsis* species, but not when cows were fed *C. crispus*. *Ascophyllum nodosum* meal did not consistently reduce or did not reduce enteric CH_4 production *in vivo*, but further research may be needed to fully address its effect on ruminal methanogenesis. On the other hand, enteric CH_4 production decreased in dairy cows receiving *A. armata*, *A. taxiformis*, and *C. crispus* even though the magnitude of CH_4 suppression varied with *A. armarta* ranking first (- 67.2%), and *A. taxiformis* (-34.4%) and *C. crispus* (-8.4%) second and third, respectively. Milk iodine concentration generally increased above the 500-μg/L threshold considered safe for human consumption when cows received seaweeds (i.e., ASCO meal, *A. taxiformis*, *C. crispus*) in their diets. Therefore, technologies to reduce iodine in seaweeds, especially in those with high CH_4 mitigation potential such as *A. taxiformis* and *A. armata* would be needed to reduce the risk of excess iodine intake in humans assuming large adoption of algal-based feeds by dairy producers. There are scarce data on the impact of ASCO, *Asparagopsis* species, and *C. crispus* on dairy cow health and results (either positive or negative) are not conclusive. Data obtained from cows fed the selected seaweeds reviewed in this paper came from short-term, changeover design studies, thus indicating the need for long-term, continuous design experiments to better understand the impact of these algal sources on production performance, enteric CH_4 production, and cow health. Costs and availability of seaweeds, producer adoption, environmental impact (e.g., urinary and fecal excretion of iodine and bromoform), governmental policies and subsidies, and consumers' willingness to pay premiums for dairy products with reduced carbon footprint will all interact to shape the success (or failure) of algal-based feed for high-producing dairy cows in the US and overseas.

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