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Asparagopsis taxiformis: potential and perspective for Vietnam seaweed industry to reduce CH_4 emission in animal husbandry

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ABSTRACT

Climate change has become a major issue for humanity nowadays, requiring comprehensive solutions on a global scale. The primary cause of climate change is the excessive absorption of solar energy due to the emission of greenhouse gases into the atmosphere. Alongside the main agent, CO_2, which accounts for two-thirds of global warming, other gases such as methane, nitrous oxide, and fluorinated gases are significant contributors. Methane emissions from livestock farming activities, primarily from cattle, play a crucial role. Although methane emissions are lower than CO_2, it has a much greater ability to absorb solar radiation than CO_2. In efforts to reduce methane emissions from livestock, scientists have conducted research on defauna of methanogens or inhibit the production of hydrogen, which is necessary for methane synthesis, by altering the composition or adding some ingredients to feed. Among the effective ways to reduce the methane emission, an important discovery is that the red algae *Asparagopsis*, including two species *Asparagopsis amata* and *Asparagopsis taxiformis,* which contain bromine compounds, when being added to feed, have a very strong inhibitory effect on methane production in bovine rumen. One of them, *A. taxiformis*, is distributed in many coastal provinces of Vietnam. With the high global consumption of cattle feed, the demand for *Asparagopsis* is substantial. However, due to its complex biological characteristic and life cycle, large-scale cultivation technology for this seaweed still faces many challenges. In this article, we summarize fundamental issues and related challenges in cultivating *A. taxiformis*. We cover the mechanism of methane production in the bovine rumen and methods to inhibit it, the biological characteristics and life cycles of the algae, nursery and cultivation techniques, as well as the climate conditions and challenges for developing the seaweed industry in Vietnam. Moreover, we also report preliminary results on sample collection and morphology analysis of *A. taxiformis* in Nha Trang, Khanh Hoa to support its potential, both nationwide and specially in Nha Trang.

Keywords: *Asparagopsis taxiformis*, methane, cultivation, rumen, Vietnam.

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INTRODUCTION

The global warming phenomenon, caused mainly by excessive CO_2 emissions from the combustion of fossil fuels, has been recorded for many decades to the present day. In addition to CO_2, other gases such as methane, nitrous oxide, and fluorinated gases also absorb much more the radiation energy from the sun and are therefore called Greenhouse Gases, GHG. Among GHGs, methane is second only to CO_2 in causing the greenhouse effect because it has a heat absorption capacity up to 20 times higher than that of CO_2 and is responsible for about 30% of global warming [1]. Human activities contribute about 63% of total global methane emissions [2], with agricultural activities including livestock farming, rice cultivation, and other activities accounting for 41% of methane emissions. Livestock farming is the main source, accounting for 73% of methane emissions in agriculture [3] and about 17% of global methane emissions. Besides the warming effect, methane production results in energy losses from feed to cattle ranging from 2–12% [4]. Therefore, reducing methane emissions in livestock farming is extremely important.

To decrease methane emissions from the digestion process of ruminant animals, many efforts have been made, including changing diets and adding ingredients to feed, such as saponins, tannins, flavonoids, lipids, essential oils, and algae. Among them, the red seaweed *Asparagopsis* has been found to strongly inhibit methane production in these animals. This seaweed contains many brominated compounds with high concentrations of 1–5% in the dry mass, including tribromomethane (bromoform), dibromochloromethane, dibromoacetic acid, bromochloroacetic acid, dibromomethane, tetrabromomethane and dibromonitromethane, in which tribromomethane $CHBr_3$ is considered the main inhibitors of methanogenic bacteria in the gut (enteric methanogenesis) [5]. With a very small percentage from 0.2% to 2.0% in feed, it can reduce methane production by 99.0% *in vitro* [6–7] or 98.0% *in vivo* [9]. These high inhibitory effects of methane reduction make research on *Asparagopsis* cultivation become very important.

Along with the development of the livestock industry worldwide to meet the increasing population's food needs, reducing methane emissions is imperative. The discovery of the inhibitory effect of bromine compounds in *Asparagopsis* on methane production opens up new prospects for addressing this issue. Therefore, research on propagation technology and biomass cultivation, laying the foundation for the development of *Asparagopsis* cultivation areas in Vietnam, is crucial because the demand for this seaweed will be significant for livestock industries worldwide. The total feed for dairy and beef in 2023 is estimated at 246.48 million tons [10]. Therefore, if the *Asparagopsis* mixing ratio is about 0.5%, the total amount of dry seaweed required is up to 1.23 million tons, equivalent to over 10 million tons of fresh seaweed. This represents a huge demand and a promising opportunity for the seaweed industry.

Coastal provinces in central Vietnam, characterized by a tropical climate, are suitable for natural development as well as seaweed cultivation due to their salinity, sunlight exposure, and stable temperatures. This is especially true for provinces from Quang Ngai to Ninh Thuan, where various types of natural seaweed are distributed [11]. The presence of *Asparagopsis* has been detected in these areas [12–14]. Residents in these coastal areas also have experience in seaweed cultivation such as *Gracilaria, Kappaphycus*, and recently, *Caulerpa lentillifera*.

Although the importance of this seaweed in reducing CH_4 emissions in livestock has been clearly demonstrated through many global studies, the development of this industry, from cultivation to final products, remains challenging. The first challenge lies in finding marine areas with favorable climates, neither too cold nor too hot, and with moderate sunlight. The second challenge is the availability of a skilled workforce, including not only experts but also local communities familiar with seaweed cultivation. Third, there is a need for a seaweed center capable of producing sufficient quantities of seed to support field cultivation. Finally, processing technologies are essential to produce dry seaweed products while maintaining high bromoform concentrations.

In this paper, we analyze the biological characteristics of *Asparagopsis* in relation to technological challenges in cultivation and the marine environment of central provinces in Vietnam to address the potential for the development of this seaweed, including large-scale aquaculture and processing. The samples collected in Vietnam were also compared morphologically with those originally found worldwide to identify both common and unique features.

Genus *Asparagopsis*

Genus *Asparagopsis* belong to Bonnemaisoniaceae, a family of the large phylum Rhodophyta. Since its inception, this genus has encountered considerable challenges in classification and identification [15]. Currently, only two species, *A. armata* and *A. taxiformis*, are widely accepted [16], although several other species have been proposed, such as *A. hamifera* (Hariot) Okamura and *A. svedelii* W.R. Taylor [17].

A. armata is a temperate species native to southern Australia and New Zealand [18], and is now found in various locations from the British Isles, the Canary Islands, Salvage, to Senegal [19]. *A. taxiformis* exhibits a distribution pattern typical of tropics and subtropics, being abundant in the tropical and warm-temperate areas of the Atlantic and Indian Oceans - Pacific Ocean [15, 18, 20]. Both species are considered introduced in the Mediterranean Sea [21].

Similar to other red algae, *Asparagopsis* spp. follows a triphasic life cycle (Fig. 1), including a haploid gametophyte, a diploid carposporophyte parasitic phase, and a diploid tetrasporophyte free-living phase, also known as the 'Falkenbergia' stage [16]. The life cycle of *Asparagopsis* begins with the germination of a haploid spore (1n). This results in the formation of the gametophytes, which constitute the majority of the life cycle. The gametophytes produce male and female gametes (on the same or different individuals). Fertilization of the female gamete results in the formation of a zygote, which then develops into the carposporophyte phase, characterized by a prolonged one-month duration. This stage is often referred to as the parasitic phase because the carposporophyte is attached to and sustained by the mature gametophyte [16]. The mature carposporophyte releases carpospores, and the germination of these carpospores gives rise to the tetrasporophyte, completing the life cycle of *Asparagopsis*.

In the gametophyte stage, *A. taxiformis* is easily distinguishable from *A. armata* by the absence of long hooked stolons/harpoon-like structure (indicated by the arrow in Figure 1 in [22]. Additionally, *A. taxiformis* has a dense rhizomatous structure for attachment to rocks or sediment layers [19]. On the other hand, the tetrasporophytes of 2 species are more difficult to distinguish because no morphological or habitat differences was reported. The only demonstrated difference is in the cell size at positions 30, 40, and 50 cells from the apex, which are smaller and shorter in *A. armata* compared to *A. Taxiformis* [15]. However, this does not ensure accurate classification, emphasizing the need for additional methods such as molecular biology for precise differentiation.

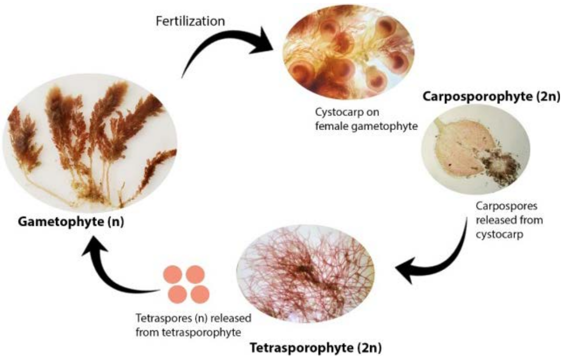

Figure 1. Asparagopsis life cycle (figure is drawn based on [22–23] using pictures taken from authors' observation)

In Vietnam, only *A. taxiformis* was found and known in Vietnamese language as "rong măng leo" or "rong hải tùng". It has been reported to be found in Con Co - Quang Tri [23], Ly Son - Quang Ngai [12], Truong Sa [13], from Nha Trang to Vung Tau [14], and Kien Giang [24]. Additionally, based on our research team's information, this seaweed is also present in Binh Dinh. According to data compiled from surveys conducted on Vietnamese islands in 2010–2011 by the Institute of Marine Research - Ministry of Agriculture and Rural Development, *A. taxiformis* falls into the group of seaweeds with a high encounter rate which was 73.7% [25]. However, the available data only extend to reporting on distribution and identification, lacking more in-depth studies on the life cycle, reproduction, or potential applications of *A. taxiformis* in Vietnam.

Reducing CH_4 emission methods in animal husbandry

The rumen contains a variety of microorganism distributed into key categories, including bacteria (domain Bacteria), methanogens (domain Archaea), protozoa (domain Eukarya), and anaerobic fungi (domain Eukarya). They build up rumen ecosystem with the complex relationship involved in digestion of feed and production of secondary metabolites. The main species of methanogens reported were *Methanobrevibacter gottschalkii* and *Methanobrevibacter ruminantium,* which accounted for 74% of all archaea in wild and domestic herbivores [28].

Related to mitigation of methane emission, ruminal methanogenic archaea have been intensively studied. They have strict association as ectosymbionts and endosymbionts with protozoa and bacteria, which produce H_2 and CO_2 for them to transform into methane [29, 30]. Therefore, the main strategy to reduce methane emissions is to inhibit the activities of bacteria and protozoa, which play a role in producing H_2 and CO_2.

There are many approaches to inhibit the methane emissions from ruminant, including dietary modifications, feed additives, microbiome manipulation and genetic selection [31]. However, adding ingredients to feed appears to be the most feasible option.

Among feed additives, substances such as saponins, tannins, flavonoids, lipid, essential oils and algae were used. Saponins can inhibit the development of protozoa by disrupting their cell membranes in the rumen. The structure of saponins consists of a hydrophilic sugar moiety and a hydrophobic steroid or triterpenoid aglycone, allowing them to lyse cells by forming complexes with sterols in cell membranes. Although saponins can suppress methane production, some can be toxic to ruminant. In addition, the effects of saponins depend on the source (plants), dose, diet and microbial community in rumen [32].

Tannins also have the effects on reducing methane by inhibiting H_2 production from the digestion of various substrates in feed. Tannins form complexes with proteins and carbohydrates under ruminal pH conditions, which reduces fiber degradation and increase propionate production from pyruvate, thereby consuming H_2 [33]. The effects of tannins on methane reduction are similar to those of saponins, meaning that their effectiveness depends on the source, chemical structure, dose, and diet composition. In addition, the ruminal microflora can develop resistance with long-term use of these substances, and they can be toxic at high doses [34].

Flavonoids are used in ruminant feed to increase productivity by elevating the ratio of propionate to acetate [35]. They were reported to reduce CH_4 production and suppress ciliate protozoa and hydrogenotrophic methanogens *in vitro* [36].

When introduced into feed, lipids can express the ability to inhibit methane production in the rumen. However, depending on the source, fatty acid composition, and the chemical structures of fatty acids such as the degree of saturation, fatty acid carbon chain lengths, the influence of lipids to methane reduction can vary [37–39]. Although the average methane reduction effects of lipids is about 14%, the side effects were also reported such as reduced fiber digestibility, milk fat synthesis, and inhibition of fermentation [40]. Besides lipids, plant essential oils such as garlic, eucalyptus, clove, rosemary, thyme, paprika, juniper, and ginger can also alter the microbial population and reduce the abundance of methanogens in rumen [41].

In general, there are many agents as mentioned above can influence methane production in the rumen when added into feed. However, their use needs more detailed studies because the effects depend on many factors such as sources and compositions, chemical structures, and doses. Moreover, increasing the dose in feed to enhance the effect can cause toxicity, inhibit digestion, and reduce the palatability for ruminants.

Application of *Asparagopsis taxiformis* in reducing CH_4

A. taxiformis has long been recognized for its rich nutritional content and valuable bioactive compounds. Samples collected from the Madeira Archipelago coastline showed iodine content around 3.37 g/100 g (DW), total phenol (TPC) 1.71 g GAE/100 g (DW), chlorophyll-a 45.96 mg/100 g (DW). Additionally, it contains lipids with a content of 2.05 g/100 g (DW) and carrageenan 21.18 g/100 g (DW) [42]. *A. taxiformis* also exhibits antifouling properties, deterring snails, showing antibacterial activity, and proving toxic to crustaceans without harming shrimp in aquaculture [43]. This seaweed also contains antioxidant properties, and the free radical scavenging activity may vary based on the extracting solvent [44].

Table 1. Summary of *A. taxiformis* application on CH_4 emission reduction from ruminants *in vitro* and *in vivo*

Animal	Duration (time)	Inclusion level (%)		CH_4 reduction (%)	Other observation	Reference
		Range	Optimum			
In vitro	72 h	16.7 (OM)		98.9	-	[48]
In vitro	72 h	0.07–16.7 (OM)	2.0 (OM)	99.0	-	[6]
In vitro	72 h	2.0 (OM)		99.0	-	[7]
In vitro	72 h	0.5–10 (OM)	2.0 (OM)	99.0	Negative impact on substrate digestibility with 10% inclusion.	[8]
Sheep	72 d	0.5–3 (OM)	3.0 (OM)	80.0	No changes in liveweight gain.	[49]
Beef steers	90 d	0.05–0.2 (OM)	0.2 (OM)	98.0	No negative effect on daily feed intake, feed conversion efficiencies, rumen function, no residues or changes in meat eating quality.	[9]
Beef steers	147 d	0.25–0.5 (OM)	0.5 (OM)	> 80.0	No differences in ADG, carcass quality, strip loin proximate analysis and shear force, or consumer taste preferences.	[46]
Dairy cows	28 d	0.25–0.5 (DM)	0.5 (DM)	65.0	Decreased dry matter intake, milk yield, and energy corrected milk yield. Increased concentrations of iodine and bromide in milk.	[50]
Dairy cows	22 d	0.44, 0.82, and 2.48% (DM); 0.24, 0.44, and 1.34% (OM)	-	-	Transfer of CHBr3 to the urine (10–148 μg/L) and milk (6 to 35 μg/L). Abnormal rumen wall. Animals refusal the feed or distinctive selection against *A. taxiformis*.	[47]

Notes: OM: organic matter; DM: dry matter.

Asparagopsis contains bromoform compounds ($CHBr_3$), considered the main agents for inhibiting enteric methanogenesis, the process by which bacteria produce methane in the gut. The bromine element is attached to vitamin B12, reducing B12 levels and subsequently inhibiting the methyl transfer activity of cobamide-dependent methyltransferase enzymes, essential for methanogens (methane-producing bacteria).

The content of $CHBr_3$ in *A. taxiformis* is 0.17–0.42% dry weight [45]. When *A. taxiformis* is incorporated into feed at small concentrations, it reduces methane emissions up to 99% both *in vitro* and *in vivo* (Table 1). The difference in *A. taxiformis* levels in feed between those studies was due to the variable content of bromoform in wild harvested strains and diet formulation. Although these studies have proven a promising application of *A. taxiformis* in CH_4 emission mitigation from meat-producing livestock because it did not cause any side effects on daily feed intake, animal growth, meat quality or consumer taste preferences [9, 46]. Conversely, the supplementation of dairy cows with *A. taxiformis* needs more consideration due to the presence of $CHBr_3$ in both urine and milk, with concentrations in milk ranging from 6 to 35 µg/L across all experimental treatments [47].

One of the challenges in processing *Asparagopsis* for being the ingredient in ruminant feed is the volatile property of bromoform from the seaweed after harvest. Therefore, the sun drying or hot air drying are not suitable for retaining bromoform in the seaweed. In this case, mild and cool drying methods, such as freeze drying, seems more appropriate. However, these drying techniques still take time and have high costs [51]. An alternative method is immersing the seaweed in vegetable oils, as canola or sunflower oil [52, 53]. During extraction, the bromoform is released into the oil. The oil enriched with bromoform is then separated from seaweed residue. This technique is simple and the bromoform-rich oils have been shown to reduce methane emission from ruminant when added into feed. However, the oil can influence the nutritional composition of the feed and the palatability for ruminant [54, 55].

Challenges in *A. taxiformis* cultivation and current status in Vietnam

Due to its triphasic life cycle, sexual and asexual propagation of *Asparagopsis* can be achieved at several stages including collecting and germinating of spores or fragmentation of gametophyte/tetrasporophyte to develop new thalli. The current best practice involves wild strain collection and inducing germination of carpospores to create tetrasporophytes [17] or tetraspores to create gametophytes [27]. The gametophytes and tetrasporophytes of *Asparagopsis* can also be reproduced asexually, with greater success for *A. Armata* [56–58]. Consequently, *A. armata* has been declared as capable of controlling the carpo-/tetra-spore release process, creating seedlings, and attaching to ropes for cultivation in large oceanic areas [22].

For *Asparagopsis taxiformis*, in general, both sexual and asexual reproduction are challenging. Observations in the natural environment on gametophytes suggest that asexual reproduction occurs in the form of hooked structures formed at the end of each ultimate branch, which, when detached, can give rise to new plants; however, successful cultivation of gametophytes in artificial environments has not been achieved [59]. Recent research attempting to culture the entire gametophyte of *A. taxiformis* in a laboratory setting has only succeeded for up to four weeks [60]. Asexual reproduction of *A. taxiformis* tetrasporophytes is achieved using a similar method to *A. armata* which is continuously cutting and subculturing shoot tips [61, 62]. The tetraspores are then induced under specific conditions, among which temperature, irradiance and nutrient supplementation played a pivotal role [63]. The germlings are then attached to a suitable substrates for the gametophyte to grow. When the gametophytes are large and resilient enought, they will be transfered to the ocean [22]. However, the successful implementation of the hatchery and nursery stages at commercial scale is yet to be demonstrated for this species [22] eventhough there was published manual for the native Australian strain [64].

In Vietnam, broodstock of *Asparagopsis taxiformis* has been reported to be successfully cultured in an outdoor system by the R&D company Greener Grazing [65]. Greener Grazing aims to produce *A. taxiformis* in the gametophyte forms by attaching the seedings to a twine and twisted around a rope, then deploying in the ocean for cultivation [22] but there are more challenges to be faced in the open sea that hinders the large scale production of this seaweed.

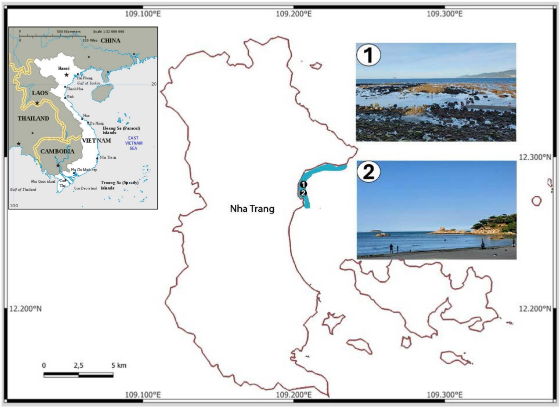

Figure 2. Study area along northern part of Nha Trang coastline. *A. taxiformis* were observed at 2 sites which are rocky and coral reef areas. The sea bottom were exposed under direct sunlight during low tide (example in site 1) and submerged under water in normal or high tide (example in site 2)

Recognizing the importance of *A. taxiformis*, our team in Nha Trang University conducted a survey along the coastline of northern Nha Trang city (Fig. 2) from 2022 to 2024. The investigation focused on rocky coral reef areas, and locations where other seaweed was present. The survey area extended from the coastline to 500 m offshore. The presence of *A. taxiformis* was monitored by routine snorkeling at least once every two weeks during low tide. As a results, *A. taxiformis* was found at 2 sites (named 1 and 2) in areas where other locally common seaweeds, such as *Sargassum*, *Turbinaria*, and *Ulva*, are distributed. Both gametophytes and tetrasporophytes of *A. taxiformis* were collected (Fig. 3a) during April-May and April-September, respectively. Gametophytes were visible to the naked eye due to their size (Fig. 3a), while the filamentous tetrasporophytes, characterized by a distinct 3-cell row structure, were examined under a stereo microscope (Figs. 3b, c).

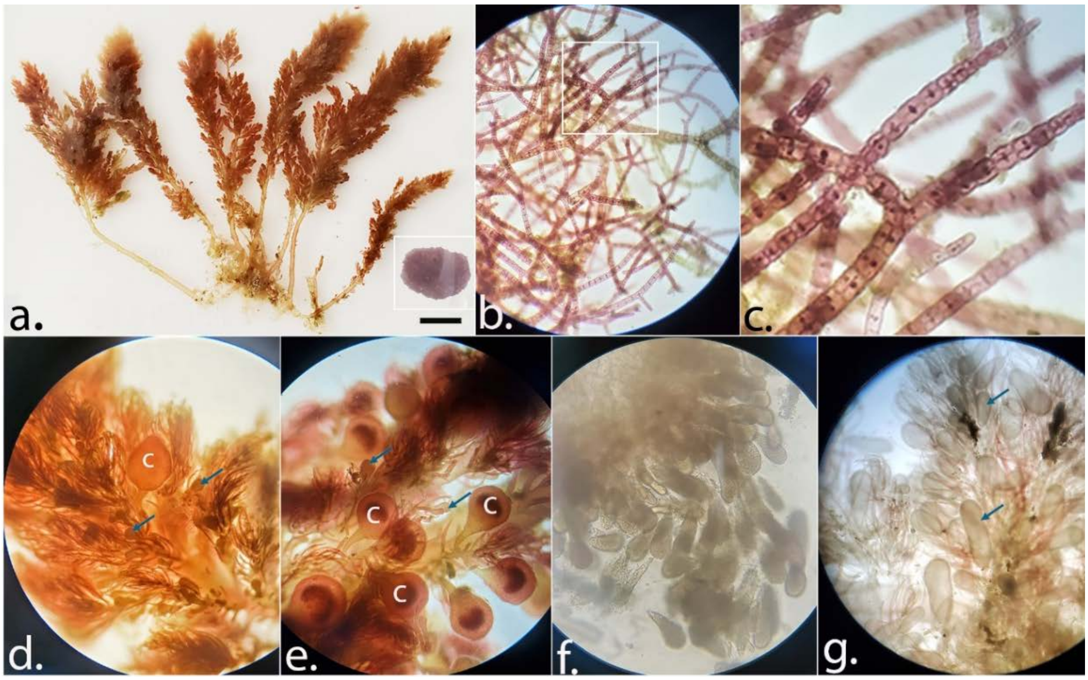

Figure 3. Asparagopsis taxiformis collected in Nha Trang, Khanh Hoa. (a) Two phases of *A. taxiformis* life cycle: bigger gametophytes and smaller filamentous tetrasporophyte, taken by digital camera on Samsung Galaxy note 10+; (b, c) Tetrasporophyte (100X magnification) with (c) is the zoom-in of (b); (d, e) Monoecious thallus with both cystocarp (c) and spermatangium (arrow) on the same frond; 40X magnification; (f) Carpospores released from cystocarp, 400X magnification; (g) Mature frond with only spermatangium, 40X magnification; b, d, e, f were taken by microscope (Optika, B130)

Interestingly, the gametophytic specimens exhibited cystocarps and spermatangia on the same frond (Figs. 3d, e), suggesting the monoecious nature of this alga. However, thalli bearing only spermatangia were also observed (Fig. 3g), indicating a possible dioecious nature. This inconsistency in the gametophyte stage of *A. taxiformis* - whether it is dioecious or monoecious - has also been reported previously. Several studies suggest that male and female gametangia are located on different thalli [65, 66] while Bonin and Hawk [16] reported the presence of only female plants. Conversely, research from Australia and New Zealand indicates that *A. taxiformis* is monoecious [66]. More recent studies have documented both male and female gametangia on the same thallus [68, 69]. Our findings showed the existence of both monoecious and dioecious phenotypes in *A. taxiformis* and provide further insight into the gametophyte stage of this alga in its natural habitat.

Our current progress involves examining the conditions for culturing this seaweed in the laboratory through both sexual and asexual reproduction. Sexual reproduction was attempted by isolating mature cystocarps, inducing spore release, and germinating spores to produce gametophytes. However, the results were limited due to a lack of technical information. This challenge may be addressed with the 2025 samples by applying the most recently published *A. taxiformis* hatchery and cultivation manual [64]. Additionally, asexual reproduction method was done by fragmenting tetrasporophytes. A major difficulty was cleaning the filamentous algae off many other epiphytic agents and very small mollusks that dominate the alga growth. Thus, before intensively culturing of *A. taxiformis*, it's neccessary to clean off as much as possible the contaminants. This is a labourous, high skilled and time-consuming step because of the very fragile and tiny tetrasporophyte. Another challenge was to determine the influencing factors to ensure large biomass production and long-term preservation.

Marine weather and human resource in coastal area in Vietnam

Vietnam has a long, narrow shape extending over 15 latitudes from north to south, resulting in diverse weather patterns. The northern part of Vietnam lies on the edge of the tropical climatic zone, with an annual average temperature is 23°C in the Hanoi. That number in Hue (central Vietnam) and Hochiminh city (south Vietnam) are 25°C and 27°C; respectively. The temperature range throughout the year in the north is wider than in the central and southern regions. The highest temperature in the north can be over 40°C in summer and down to a few degrees above freezing in winter. The average annual temperatures in the coastal areas are around 23°C, with the coldest month having a mean temperature of 16 to 17°C [70].

In the north-central region, the weather is warmer with average annual temperatures around 24 to 25°C and the coldest month having a mean temperature of 17 to 20°C. Average annual rainfall in coastal areas is approximately 2,000 to 2,900 mm. In the south-central region, the range of temperature is smaller, about 5 to 6°C, with average annual temperatures are around 25°C to 27°C. The coldest month has a mean temperature of 22 to 25°C and the hottest month has a mean temperature of 28 to 30°C. Average annual rainfall in coastal areas is approximately 1,900 mm although some areas in the southern parts of the region receive between 800 and 1,100 mm [70].

In the south, the average annual temperature in coastal areas is around 27°C, remaining fairly even throughout the year with little difference between the coldest and hottest months. The average annual rainfall in coastal areas is approximately 1,500 to 2,500 mm [70].

The conditions for seaweed culture are more favorable in the south central region compared to other areas, due to its temperature range throughout the year, rainfall, and sea water salinity. In the north and south, the sea bottoms are shallow, and salinity decreases during the rainy season due to the high water input from Red river (north) and Mekong river (south) [71]. In contrast, the south central region has deeper sea bottom and fewer small rivers, resulting in less fluctuation in salinity. Moreover, fishermen in coastal areas in the central region, from Hue to Ninh Thuan, have gained experience in cultivating and harvesting seaweed for food and agriculture use in a long time. The main seaweeds cultivated in this region are *Gracilaria, Kappaphycus, Caulerpa,* and *Porphyra*.

In particular, the fishing community in Nha Trang has extensive experience in seaweed cultivation and processing, especially with *Kappaphycus alvarezii* and *Caulerpa lentillifera*, making them a key human resource for *Asparagopsis* cultivation. Nha Trang is also home to several prominent marine research and education institutions, such as Nha Trang University (formerly the University of Fisheries), the Oceanographic Institute, and the Research Institute for Aquaculture III. Additionally, Nha Trang hosts many large seafood processing companies that are expected to contribute to the final stages of producing seaweed ingredients for animal feed.

CONCLUSION

In summary, despite the small quantities required, *Asparagopsis taxiformis* is highly effective as a feed ingredient for ruminants and can play a significant role in reducing methane emissions from livestock worldwide, thereby contributing to climate change mitigation. Given the vast global demand for livestock feed, the need for this seaweed to inhibit methane production will be substantial, requiring a robust value chain for its production, processing, and distribution globally. To build such a system, it is necessary to identify coastal countries with marine environments suitable for cultivating this seaweed.

Vietnam has the potential to establish and develop a *Asparagopsis taxiformis* industry due to the availability of natural resources, favorable marine climates—especially in the South Central coastal regions—and experienced human resources, including scientists and fishermen skilled in seaweed cultivation. By leveraging these advantages, Vietnam can become a major supplier of this seaweed on a global scale, contributing effectively to reducing methane emissions from ruminant livestock. However, the large-scale production of *A. taxiformis* remains an open question that requires the attention of both researchers and industry investors. With its rich history in fisheries studies, Nha Trang University is actively involved in this mission and has the potential to play a leading role in this endeavor.

REFERENCES

[1] A. Thorpe, “Enteric fermentation and ruminant eructation: The role (and control?) of methane in the climate change debate,” *Climatic Change*, vol. 93, pp. 407–431, 2009. DOI: 10.1007/s10584-008-9506-x.

[2] United States Environmental Protection Agency (EPA), *Methane and Nitrous Oxide Emissions from Natural Sources*. Washington, DC: USEPA Office of Atmospheric Programs, 2010.

[3] United States Environmental Protection Agency (EPA), *Global Mitigation of Non-CO_2 Greenhouse Gases: 2010–2030*. Washington, DC: USEPA Office of Atmospheric Programs, 2013.

[4] K. A. Beauchemin, E. M. Ungerfeld, R. J. Eckard, and M. Wang, “Fifty years of research on rumen methanogenesis: Lessons learned and future challenges for mitigation,” *Animal*, vol. 14, suppl. 1, pp. s2–s16, 2020. DOI: 10.1017/S175173 1119003100.

[5] N. P. Nørskov, A. Bruhn, A. Cole, and M. O. Nielsen, “Targeted and untargeted metabolic profiling to discover bioactive compounds in seaweeds and hemp using gas and liquid chromatography–mass spectrometry,” *Metabolites*, vol. 11, no. 5, 259, 2021. DOI: 10.3390/metabo11050259.

[6] L. Machado, M. Magnusson, N. Paul, R. Kinley, R. de Nys, and N. Tomkins, “Dose-response effects of *Asparagopsis taxiformis* and *Oedogonium* sp. on *in vitro* fermentation and methane production,” *J. Appl. Phycol.*, vol. 28, no. 2, pp. 1443–1452, 2015. DOI: 10.1007/s10811-015-0639-9.

[7] R. D. Kinley, R. de Nys, M. J. Vucko, L. Machado, and N. W. Tomkins, “The red macroalgae *Asparagopsis taxiformis* is a potent natural antimethanogenic that reduces methane production during *in*

vitro fermentation with rumen fluid," *Animal Production Science*, vol. 56, pp. 282–289, 2016. DOI: 10.1071/AN15576.

[8] R. D. Kinley, M. J. Vucko, L. Machado, and N. W. Tomkins, "*In vitro* evaluation of the antimethanogenic potency and effects on fermentation of individual and combinations of marine macroalgae," *American Journal of Plant Sciences*, vol. 7, pp. 2038–2054, 2016. DOI: 10.4236/ajps.2016.714184.

[9] R. D. Kinley, G. Martinez-Fernandez, M. K. Matthews, R. de Nys, M. Magnusson, and N. W. Tomkins, "Mitigating the carbon footprint and improving productivity of ruminant livestock agriculture using a red seaweed," *Journal of Cleaner Production*, vol. 259, 120836, 2020. DOI: 10.1016/j.jclepro.2020.120836.

[10] Alltech, *Agri-Food Outlook-2024*. USA: Alltech, 2024.

[11] T. V. Nguyen, N. H. Le, S. M. Lin, F. Steen, and O. De Clerck, "Checklist of the marine macroalgae of Vietnam," *Botanica Marina*, vol. 56, no. 3, pp. 207–227, 2013. DOI: 10.1515/bot-2013-0010.

[12] D. A. Duy, T. V. Huong, B. M. Tuan, N. V. Hieu, N. T. Mai, and D. D. Hong, "Marine species diversity around Ly Son Island, Quang Ngai," *Hue University Journal of Science: Natural Science*, vol. 128, no. 1A, pp. 51–72, 2019. [in Vietnamese].

[13] P. H. Tri, "Contribution to the study of seaweeds in the Truong Sa Archipelago (Big Truong Sa Island and Nam Yet Island)," *Compilation of Marine Research Studies*, vol. VII, pp. 147–162, 1996. [in Vietnamese].

[14] L. N. Tram, N. K. Duc, T. Kha, D. T. Nga, and L. T. Nga, "The agar (agar-agar) content in some red algae (Rhodophyta) species in the coastal areas from Nha Trang to Vung Tau," *Compilation of Marine Research Studies*, vol. I, pp. 33–41, 1978. [in Vietnamese].

[15] F. Chualáin, C. Maggs, G. Saunders, and M. Guiry, "The invasive genus *Asparagopsis* (Bonnemaisoniaceae, Rhodophyta): Molecular systematics, morphology, and ecophysiology of *Falkenbergia* isolates," *Journal of Phycology*, vol. 40, pp. 1112–1126, 2004. DOI: 10.1111/j.1529-8817.2004.03135.x.

[16] D. R. Bonin and M. W. Hawkes, "Systematics and life histories of New Zealand Bonnemaisoniaceae (Bonnemaisoniales, Rhodophyta): I. The genus *Asparagopsis*," *New Zealand Journal of Botany*, vol. 25, no. 4, pp. 577–590, 1987. DOI: 10.1080/0028825X.1987.10410088.

[17] P. Zhu, D. Li, Q. Yang, P. Su, H. Wang, K. Heimann, and W. Zhang, "Commercial cultivation, industrial application, and potential halocarbon biosynthesis pathway of *Asparagopsis* sp.," *Algal Research*, vol. 56, 102319, 2021. DOI: 10.1016/j.algal.2021.102319.

[18] G. A. Horridge, "Occurrence of *Asparagopsis armata* Harvey on the Scilly Isles," *Nature*, vol. 167, pp. 732–733, 1951. DOI: 10.1038/167732c0.

[19] N. Andreakis, G. Procaccini, and W. H. C. F. Kooistra, "*Asparagopsis taxiformis* and *Asparagopsis armata* (Bonnemaisoniales, Rhodophyta): Genetic and morphological identification of Mediterranean populations," *European Journal of Phycology*, vol. 39, pp. 273–283, 2004. DOI: 10.1080/0967026042000236436.

[20] W. H. Harvey, "Some account of the marine botany of the colony of Western Australia," *Transactions of the Royal Irish Academy*, vol. 22, pp. 525–566, 1855. DOI: 10.5962/bhl.title.112433.

[21] C. F. Boudouresque and M. Verlaque, "Biological pollution in the Mediterranean Sea: Invasive versus introduced macrophytes," *Marine Pollution Bulletin*, vol. 44, pp. 32–38, 2002. DOI: 10.1016/S0025-326X(01)00150-3.

[22] M. Zanolla, R. Carmona, L. Mata, J. De la Rosa, A. Sherwood, C. Navarro-Barranco, A. R. Muñoz, and M. A. Jeschke, "Concise review of the genus *Asparagopsis* Montagne, 1840," *Journal of Applied Phycology*, vol. 34, p. 10.1007, 2022. DOI: 10.1007/s10811-021-02665-z.

[23] D. A. Duy, D. V. Khuong, T. V. Huong, and D. T. Dat, "The current status of species diversity and marine resources around

the island of Con Co, Quang Tri," *Danang University Journal of Science and Technology*, vol. 17, no. 3, pp. 34–40, 2019. [in Vietnamese].

[24] D. A. Duy, D. T. Dat, and D. D. Tien, "Species biodiversity and distribution of algae in Nam Du archipelago, Kien Giang," *Can Tho University Journal of Science*, vol. 55, no. 4A, pp. 71–81, 2019. [in Vietnamese].

[25] D. A. Duy and D. V. Khuong, "The current status of marine species diversity on surveyed islands within the coastal regions of Vietnam," *Journal of Marine Science and Technology*, vol. 13, no. 2, pp. 105–115, 2013. [in Vietnamese].

[26] M. Zanolla and N. Andreakis, "Towards an integrative phylogeography of invasive marine seaweeds, based on multiple lines of evidence," in *Seaweed Phylogeography*, Z. M. Hu and C. Fraser, Eds. Dordrecht: Springer, 2016, pp. 187–207. DOI: 10.1007/978-94-017-7534-2_7.

[27] A. Mihaila, R. Lawton, C. Glasson, and M. Magnusson, "Early hatchery protocols for tetrasporogenesis of the antimethanogenic seaweed *Asparagopsis armata*," *Journal of Applied Phycology*, vol. 35, pp. 1–13, 2022. DOI: 10.1007/s10811-023-03029-5.

[28] G. Henderson, F. Cox, S. Ganesh, A. Jonker, W. Young, Global Rumen Census Collaborators, and P. H. Janssen, "Rumen microbial community composition varies with diet and host, but a core microbiome is found across a wide geographical range," *Scientific Reports*, vol. 5, 14567, 2015. DOI: 10.1038/srep14567.

[29] B. J. Finlay, G. Esteban, and K. J. Clarke, "Some rumen ciliates have endosymbiotic methanogens," *FEMS Microbiology Letters*, vol. 117, no. 2, pp. 157–162, 1994. DOI: 10.1111/j.1574-6968.1994.tb06758.x.

[30] M. Tokura, K. Ushida, and K. Miyazaki, "Methanogens associated with rumen ciliates," *FEMS Microbiology Ecology*, vol. 22, no. 2, pp. 137–143, 1997. DOI: 10.1111/j.1574-6941.1997.tb00365.x.

[31] B. Króliczewska, E. Pecka-Kiełb, and J. Bujok, "Strategies used to reduce methane emissions from ruminants: Controversies and issues," *Agriculture*, vol. 13, no. 3, 602, 2023. DOI: 10.3390/agriculture13030602.

[32] A. K. Patra and J. Saxena, "The effect and mode of action of saponins on the microbial populations and fermentation in the rumen and ruminant production," *Nutrition Research Reviews*, vol. 22, no. 2, pp. 204–219, 2009. DOI: 10.1017/S09544 22409990163.

[33] A. Jayanegara, F. Leiber, and M. Kreuzer, "Meta-analysis of the relationship between dietary tannin level and methane formation in ruminants from *in vivo* and *in vitro* experiments," *Journal of Animal Physiology and Animal Nutrition*, vol. 96, no. 3, pp. 365–375, 2011. DOI: 10.1111/j.1439-0396.2011.01172.x.

[34] A. Smith, A. Stirling, and F. Berkhout, "The governance of sustainable socio-technical transitions," *Research Policy*, vol. 34, no. 10, pp. 1491–1510, 2005. DOI: 10.1016/ j.respol.2005.07.005.

[35] M. Formato, G. Cimmino, N. Brahmi-Chendouh, S. Piccolella, and S. Pacifico, "Polyphenols for livestock feed: Sustainable perspectives for animal husbandry?," *Molecules*, vol. 27, no. 22, 7752, 2022. DOI: 10.3390/molecules27227752.

[36] E. Oskoueian, N. Abdullah, and A. Oskoueian, "Effects of flavonoids on rumen fermentation activity, methane production, and microbial population," *BioMed Research International*, vol. 2013, 349129, 2013. DOI: 10.1155/2013/349129.

[37] S. M. McGinn, K. A. Beauchemin, T. Coates, and D. Colombatto, "Methane emissions from beef cattle: Effects of monensin, sunflower oil, enzymes, yeast, and fumaric acid," *Journal of Animal Science*, vol. 82, no. 11, pp. 3346–3356, 2004. DOI: 10.2527/2004.82113346x.

[38] E. Jordan, D. K. Lovett, F. J. Monahan, J. Callan, B. Flynn, and F. P. O'Mara, "Effect of refined coconut oil or copra meal on methane output and on intake and performance of beef heifers," *Journal of Animal Science*, vol. 84, pp. 162–170, 2006. DOI: 10.2527/2006.841162x.

[39] K. A. Beauchemin, S. M. McGinn, and H. V. Petit, "Methane abatement strategies for cattle: Lipid supplementation of diets," *Canadian Journal of Animal Science*, vol.

87, pp. 431–440, 2007. DOI: 10.4141/CJAS07011.

[40] C. Grainger and K. A. Beauchemin, "Can enteric methane emissions from ruminants be lowered without lowering their production?," *Animal Feed Science and Technology*, vols. 166–167, pp. 308–320, 2011. DOI: 10.1016/j.anifeedsci.2011.04.021.

[41] R. J. Wallace, "Antimicrobial properties of plant secondary metabolites," *Proceedings of the Nutrition Society*, vol. 63, no. 4, pp. 621–629, 2004. DOI: 10.1079/PNS2004393.

[42] N. Nunes, S. Valente, S. Ferraz, M. C. Bareto, and M. A. A. P. de Carvalho, "Nutraceutical potential of *Asparagopsis taxiformis* (Delile) Trevisan extracts and assessment of a downstream purification strategy," *Heliyon*, vol. 4, no. 11, e00957, 2018. DOI: 10.1016/j.heliyon.2018.e00957.

[43] A. Manilal, S. Sujith, B. Sabarathnam, G. S. Kiran, J. Selvin, C. Shakir, and A. P. Lipton, "Bioactivity of the red algae *Asparagopsis taxiformis* collected from the southwestern coast of India," *Brazilian Journal of Oceanography*, vol. 58, no. 2, pp. 93–100, 2010.

[44] P. V. Neethu, K. Suthindhiran, and M. A. Jayasri, "Antioxidant and antiproliferative activity of *Asparagopsis taxiformis*," *Pharmacognosy Research*, vol. 9, no. 3, pp. 238–246, 2017. DOI: 10.4103/pr.pr_128_16.

[45] J. L. Hutchings, Y. Grebneva, S. J. Dilmetz, D. W. M. Pincher, and P. Hoffmann, "Analytical methods for the analysis of bromoform in red seaweed *Asparagopsis armata* and *Asparagopsis taxiformis*—A review," *Algal Research*, vol. 79, 103478, 2024. DOI: 10.1016/j.algal.2024.103478.

[46] B. M. Roque, M. Venegas, R. D. Kinley, R. de Nys, T. L. Duarte, X. Yang, and E. Kebreab, "Red seaweed (*Asparagopsis taxiformis*) supplementation reduces enteric methane by over 80 percent in beef steers," *PLoS ONE*, vol. 16, no. 3, e0247820, 2021. DOI: 10.1371/journal.pone.0247820.

[47] W. Muizelaar, M. Groot, G. van Duinkerken, R. Peters, and J. Dijkstra, "Safety and transfer study: Transfer of bromoform present in *Asparagopsis taxiformis* to milk and urine of lactating dairy cows," *Foods*, vol. 10, p. 584, 2021. DOI: 10.3390/foods10030584.

[48] L. Machado, M. Magnusson, N. A. Paul, R. de Nys, and N. Tomkins, "Effects of marine and freshwater macroalgae on *in vitro* total gas and methane production," *PLoS ONE*, vol. 9, no. 1, p. e85289, 2014. DOI: 10.1371/journal.pone.0085289.

[49] X. Li, H. C. Norman, R. D. Kinley, M. Laurence, M. Wilmot, H. Bender, R. de Nys, and N. Tomkins, "*Asparagopsis taxiformis* decreases enteric methane production from sheep," *Animal Production Science*, vol. 58, pp. 681–688, 2018. DOI: 10.1071/AN15883.

[50] H. A. Stefenoni, S. E. Räisänen, S. F. Cueva, D. E. Wasson, C. F. A. Lage, A. Melgar, M. E. Fetter, P. Smith, M. Hennessy, B. Vecchiarelli, J. Bender, D. Pitta, C. L. Cantrell, C. Yarish, and A. N. Hristov, "Effects of the macroalga *Asparagopsis taxiformis* and oregano leaves on methane emission, rumen fermentation, and lactational performance of dairy cows," *Journal of Dairy Science*, vol. 104, no. 4, pp. 4157–4173, 2021. DOI: 10.3168/jds.2020-19686.

[51] S. Tan, J. Harris, B. M. Roque, S. Askew, and R. D. Kinley, "Shelf-life stability of *Asparagopsis* bromoform in oil and freeze-dried powder," *Journal of Applied Phycology*, vol. 35, no. 1, pp. 291–299, 2023. DOI: 10.1007/s10811-022-02876-y.

[52] P. S. Alvarez-Hess, A. L. Thomson, S. R. O. Williams, A. Logan, C. Taylor, T. Singh, B. M. Roque, A. S. O. Neachtain, R. D. Kinley, and J. L. Jacobs, "The influence of feeding canola oil steeped *Asparagopsis armata* on resulting fatty acid profile and dairy processing properties of cow's milk," *Animal Feed Science and Technology*, vol. 310, 115924, 2024. DOI: 10.1016/j.anifeedsci.2024.115924.

[53] F. Sena, P. V. Portugal, M. T. Dentinho, K. Paulos, C. Costa, D. M. Soares, A. Oliveira,

H. Ramos, S. P. Alves, J. Santos-Silva, and R. J. B. Bessa, "Effects of sunflower oil infusions of *Asparagopsis taxiformis* on in vitro ruminal methane production and biohydrogenation of polyunsaturated fatty acids," *Journal of Dairy Science*, vol. 107, no. 3, pp. 1472–1484, 2024. DOI: 10.3168/jds.2023-23506.

[54] M. Magnusson, M. J. Vucko, T. L. Neoh, and R. de Nys, "Using oil immersion to deliver a naturally-derived, stable bromoform product from the red seaweed *Asparagopsis taxiformis*," *Algal Research*, vol. 51, p. 102065, 2020. DOI: 10.1016/j.algal.2020.102065.

[55] M. J. Vucko, M. Magnusson, R. D. Kinley, C. Villart, and R. de Nys, "The effects of processing on the in vitro antimethanogenic capacity and concentration of secondary metabolites of *Asparagopsis taxiformis*," *Journal of Applied Phycology*, vol. 29, no. 3, pp. 1577–1586, 2017, DOI: 10.1007/s10811-016-1004-3.

[56] M. D. Guiry and C. J. Dawes, "Daylength, temperature and nutrient control of tetrasporogenesis in *Asparagopsis armata* (Rhodophyta)," *Journal of Experimental Marine Biology and Ecology*, vol. 158, pp. 197–217, 1992. DOI: 10.1016/0022-0981(92)90227-2.

[57] J. T. Wright, E. J. Kennedy, R. de Nys, and M. Tatsumi, "Asexual propagation of *Asparagopsis armata* gametophytes: fragmentation, regrowth and attachment mechanisms for sea-based cultivation," *Journal of Applied Phycology*, vol. 34, pp. 2135–2144, 2022. DOI: 10.1007/s10811-022-02763-6.

[58] C. Haslin and M. Pellegrini, "Culture medium composition for optimal thallus regeneration in the red alga *Asparagopsis armata* Harvey (Rhodophyta, Bonnemaisoniaceae)," *Botanica Marina*, vol. 44, pp. 23–30, 2001. DOI: 10.1515/BOT.2001.004.

[59] O. P. Mairh, "Studies on *Asparagopsis taxiformis* (Delile) Collins and Harvey from Indian waters," *Journal of the Marine Biological Association of India*, vol. 19, pp. 97–106, 1977.

[60] M. M. Batista, "Reproduction and cultivation of *Asparagopsis taxiformis* (Delile) Trevisan," M.S. thesis, Aquaculture and Fisheries, Universidade do Algarve, Portugal, 2020.

[61] L. Mata, H. Gaspar, and R. Santos, "Carbon/nutrient balance in relation to biomass production and halogenated compound content in the red alga *Asparagopsis taxiformis* (Bonnemaisoniaceae): C/N balance in relation to halocarbons in *A. taxiformis*," *Journal of Phycology*, vol. 48, no. 1, pp. 248–253, 2012. DOI: 10.1111/j.1529-8817.2011.01083.x.

[62] L. Mata, R. J. Lawton, M. Magnusson, N. Andreakis, R. de Nys, and N. A. Paul, "Within-species and temperature-related variation in the growth and natural products of the red alga *Asparagopsis taxiformis*," *Journal of Applied Phycology*, vol. 29, pp. 1437–1447, 2016. DOI: 10.1007/s10811-016-1017-y.

[63] E. J. Theobald, M. B. Rule, T. L. Jackson, N. A. Rula, G. Diaz-Pulido, and E. L. Jackson, "Abiotic triggers for maximising germling numbers in *Asparagopsis taxiformis* (Rhodophyta, Bonnemaisoniales) via tetrasporogenesis," *Journal of Applied Phycology*, published online, 2024. DOI: 10.1007/s10811-024-03326-7.

[64] J. Statton, *Asparagopsis taxiformis Hatchery and Cultivation Manual*, May 13, 2024. [Online]. Available: https://agrifutures.com.au/product/asparagopsis-taxiformis-hatchery-and-cultivation-manual/, accessed: August 7, 2024.

[65] M. Tatarski, "An 'aquatic moonshot' in Vietnam aims to fight livestock methane with seaweed," *Mongabay News*, Oct. 2023. [Online]. Available: https://news.mongabay.com/2023/10/an-aquatic-moonshot-in-vietnam-aims-to-fight-livestock-methane-with-seaweed/, accessed: July 2, 2024.

[66] R. Barone, A. M. Mannino, and M. Mario, "*Asparagopsis taxiformis* (Bonnemaisoniales, Rhodophyta): first record of gametophytes on the Italian coast," *Bocconea*, vol. 16, no. 2, pp. 1021–1025, 2003.

[67] R. A. Marshall, D. B. Harper, W. C. McRoberts, and M. Dring, "Volatile bromocarbons produced by *Falkenbergia* stages of *Asparagopsis* spp. (Rhodophyta)," *Limnology and Oceanography*, vol. 44, no. 5, pp. 1348–1352, 1999. DOI: 10.4319/lo.1999.44.5.1348.

[68] M. Zanolla, R. Carmona, J. De la Rosa, N. Salvador, A. Sherwood, N. Andreakis, and M. Altamirano, "Morphological differentiation of cryptic lineages within the invasive genus *Asparagopsis* (Bonnemaisoniales, Rhodophyta)," *Phycologia*, vol. 53, pp. 233–242, 2014.

[69] M. Zanolla, R. Carmona, and M. Altamirano, "Reproductive ecology of an invasive lineage 2 population of *Asparagopsis taxiformis* (Bonnemaisoniales, Rhodophyta) in the Alboran Sea (western Mediterranean Sea)," *Botanica Marina*, vol. 60, pp. 627–638, 2017. DOI: 10.1515/bot-2017-0056

[70] Ministry of Construction (BXD), *QCVN 02:2021 - National Technical Regulation on Natural Physical and Climatic Data for Construction*, Hanoi, Vietnam, 2022. [in Vietnamese].

[71] T. P. Tuan, V. Thinh, U. D. Khanh, B. Q. Dung, and C. A. Dung, "The flattened seabed characters at the nearshore islands of Vietnam," *Vietnam Journal of Marine Science and Technology*, vol. 20, no. 3, pp. 245–254, 2020. DOI: 10.15625/1859-3097/20/3/12958.