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Diverse Roles of Seaweed in the Blue Carbon Economy and Sustainable Development: A Comprehensive Review

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Abstract: The imperative to replace fossil fuels with renewable fuels, such as marine ecosystem-derived fuel and food, has spurred the development of a blue carbon economic model. Seaweed emerges as a pivotal element in this framework, demonstrating potential as a substantial carbon sink. Seaweed serves multiple purposes, encompassing climate change adaptation and mitigation and contributing to advancing a bioeconomy by reducing dependence on fossil fuels. Seaweed also holds promise as a source of human food, cattle feed, biofuels, renewable feedstocks, and other versatile applications. Numerous contemporary scientific publications, reputable organizations, and business resources offer illuminating insights and fresh perspectives on how seaweed can effectively contribute to the growing blue carbon economy, providing innovative tools for combating long-term climate change. This comprehensive review delves into the multifaceted potential of seaweed, concentrating on its contributions to carbon sequestration, its role as a blue carbon precursor, and the carbon-neutralization capabilities of both wild seaweeds and seaweed farming. Moreover, it explores the specific role of seaweed in the blue carbon economy, mainly as cattle feed in ruminant diets. In addition, seaweed cultivation has the potential to mitigate global climate change, promote economic development, and support sustainable livelihoods, offering a versatile solution to address pressing environmental and socioeconomic challenges.

Keywords: blue carbon economy, carbon sequestration, seaweeds, carbon sink, global warming, climate change mitigation

1. Introduction

Interest in carbon storage techniques has intensified as concerns about climate change and carbon emissions grow. The combustion of fossil fuels, a significant source of anthropogenic carbon dioxide (CO_2) emissions, is expected to contribute to a further increase in the coming years due to rising energy demands. The accumulation of CO_2 in the atmosphere enhances the greenhouse effect, resulting in elevated atmospheric temperatures. Approximately 25% of annual anthropogenic CO_2 emissions are absorbed by the ocean, serving as the primary natural carbon sink [1, 2]. However, this absorption comes at a cost, leading to carbonic acid formation in seawater.

Ocean acidification, a consequence of elevated CO_2 concentrations in the atmosphere, has increased by 30% since the industrial revolution [3]. This phenomenon threatens non-swimming marine organisms, including zooplankton, bacteria, and benthos, particularly at depths of 1000 m or more, and is believed to have detrimental effects on marine life. The Paris Agreement was introduced to reduce carbon emissions and remove carbon from the atmosphere to combat the threat of climate change. The United Nations Framework Convention on Climate Change has advocated for measures to mitigate carbon emissions as part of a strategy to limit global warming below 2°C above preindustrial levels [4, 5].

In light of these environmental imperatives, the international community has initiated the blue carbon initiative, driven by the necessity to transition away from fossil fuels in favor of marine ecosystem-derived resources for fuel and food. This initiative places a specific emphasis on carbon sequestration and storage in deep waters and sediments. Coastal ecosystems, including seagrasses, salt marshes, and mangroves, have emerged as central components of the blue carbon strategy, as they are ten times more effective in sequestering CO_2 per unit area per year than boreal, temperate, or tropical forests and twice as effective as land-based biomass storage [6–10]. These ecosystems occupy only 2% of the global area while providing considerable benefits, including shoreline protection, seafood production, and water quality enhancement [11].

Regrettably, coastal blue carbon ecosystems have been diminishing alarmingly, with an estimated one-third of the global total lost over recent decades [12]. The primary drivers of this degradation include anthropogenic factors such as deforestation, coastal population growth, urban development, agriculture, aquaculture, sedimentation, siltation, sea level rise, and extreme weather events [7]. The degradation of these ecosystems not only nullifies their capacity to serve as carbon sinks but also contributes to carbon emissions by releasing previously stored carbon into the atmosphere. This has resulted in a global annual loss of blue carbon ecosystems ranging between 0.7 and 7%, with

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projections suggesting that these ecosystems release between 0.15 and 1.02 billion tons of carbon into the atmosphere each year, thus making a substantial contribution to anthropogenic climate change [12]. The maximum mitigation benefits of mangrove, seagrass, and salt marsh restoration are unlikely to exceed 2% of current total CO_2 emissions. It is important to note that carbon is also stored in marine animals, and the extraction of fish from the sea contributes to blue carbon release [13].

Among the array of potential solutions, macroalgae or seaweed stands out as a promising option due to its multifaceted benefits and applications. Seaweed cultivation and utilization offer multiple advantages within the blue carbon framework. Firstly, seaweed serves as a robust carbon sink, effectively sequestering CO_2 from the atmosphere and contributing to climate change adaptation and mitigation efforts. Secondly, seaweed holds promise as a valuable resource for advancing a bioeconomy, reducing dependence on finite fossil fuel reserves [14]. It can be employed as a renewable feedstock for biofuel production and as a sustainable source of both human and cattle nutrition [15]. Furthermore, seaweed exhibits remarkable versatility in its applications, offering opportunities to develop innovative and sustainable products.

This comprehensive scientific review embarks on exploring the multifaceted potential of seaweed, with a particular focus on its significant contributions to carbon sequestration, its role as a blue carbon precursor, and the carbon-neutralization potential of both wild seaweeds and seaweed farming. This focus is grounded in the urgency of contemporary environmental issues, such as climate change and ocean acidification, where seaweed's pivotal role in mitigating these challenges is evident. Additionally, this field represents an emerging and rapidly evolving area of research, underscoring the importance of reviewing it. As we approach a critical juncture in global environmental and economic transitions toward sustainable, low-carbon solutions, understanding seaweed's potential for carbon sequestration and carbon neutralization is not only pertinent but also crucial in addressing these challenges.

Moreover, methane a potent greenhouse gas (GHG) is notably emitted from the livestock industry, particularly from ruminant animals. Seaweed has emerged as a promising solution to reduce methane production in the digestive systems of these animals, offering a practical means of mitigating climate change. This review in addition will delve into the specific contribution of seaweed to reduce methane emissions, particularly in its role as a cattle feed in ruminant diets. By addressing this issue, we not only contribute to lowering GHG emissions but also promote sustainable livestock farming practices that have both environmental and economic benefits.

Overall, seaweed emerges as a promising candidate for addressing pressing environmental challenges and promoting a carbon-neutral future, offering a comprehensive solution within the overarching context of the blue carbon economy.

2. Seaweed as a Carbon Sequester

Carbon dioxide (CO_2) significantly contributes to global GHG emissions, accounting for approximately 76% of the total [16]. Its detrimental impact on living organisms and the environment is well-documented. Models developed by the U.S. climate change science program indicate that within the next century, to stabilize atmospheric CO_2 at 550 parts per million (ppm) – twice the preindustrial level and 45% higher than the 2007 concentration – a reduction of over 75% in annual global emissions is required [17]. Consequently, carbon sequestration and stabilization of atmospheric CO_2 levels have become essential for effective carbon management.

Defining "sequestration" is of paramount importance. Traditionally, the term referred to temporary measures, such as holding assets until a court's decision or debt repayment (asset sequestration). In the context of carbon management, sequestration involves separating and securing the storage of dangerous substances, such as carbon dioxide, to prevent their release into the atmosphere.[1] The Intergovernmental Panel on Climate Change typically considers a time span of 100 years when assessing the global warming potential of GHGs [18]. However, sequestration efforts often focus on much longer time scales, ranging from thousands to millions of years from a geological perspective.

It is important to note that most of the carbon captured by seaweeds is held transiently as biomass before being utilized or decomposed [19]. The equilibrium of CO_2 within seawater can take months to years to reach due to factors such as water mixing, changes in wind patterns, salinity variations, temperature fluctuations, and carbon equilibration processes, as well as the ongoing photosynthesis and respiration activities of marine organisms in the water column. The impact of seaweed farming on carbon uptake and the implications for accurately quantifying the amount of carbon sequestered and the duration of sequestration remain challenging and require further investigation. However, defining sequestration in the context of carbon dioxide storage and understanding the dynamics of carbon capture by seaweeds, including the duration and effects of seaweed farming, present ongoing challenges that warrant further research and investigation.

3. Seaweed as a Precursor to Blue Carbon

Blue carbon refers to the organic carbon absorbed and stored within coastal ecosystems and the ocean [20].[2] Seaweeds have emerged as a particularly promising candidate for addressing climate change and reducing atmospheric carbon due to their significant contributions to carbon sequestration (illustrated in Figure 1), carbon storage, coastal protection, food security, and their potential to manage localized ocean acidification, and deoxygenation [15]. Effectively managing production processes associated with seaweed cultivation is essential to minimize carbon-emitting activities and ensure the successful implementation of seaweed-based blue carbon strategies.

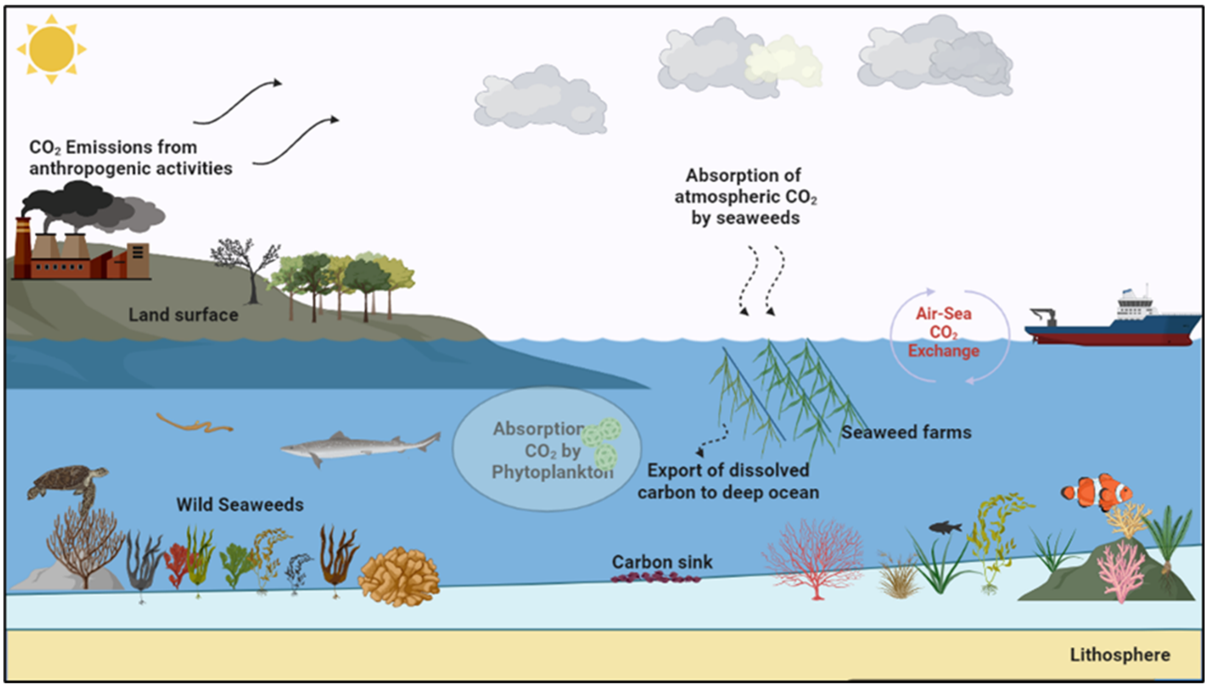
As indicated by a recent meta-analysis, macroalgae growing in soft sediments globally exhibit a carbon burial rate of approximately 6.2 Teragrams (Tg) of carbon per year [21]. Seaweed aquaculture demonstrates a high potential for carbon sequestration, with an intensity of around 1500 tonnes of CO_2 per square kilometer per year [14]. However, the current scale of seaweed aquaculture remains insufficient to significantly mitigate climate change on a global scale.

By the year 2022, the global production of seaweed in aquaculture had surged to 34.74 million tonnes of fresh weight, as reported by the Food and Agriculture Organization of the United Nations [22]. This significant quantity holds the potential for substantial carbon drawdown, contingent upon how the harvested seaweed biomass is managed. The theoretical carbon drawdown could reach a maximum of 3.16 million tonnes of CO_2 per year if all 34.74 million tonnes of fresh weight contribute to carbon sequestration. On the other hand, the minimum carbon drawdown could be as low as zero tonnes if all seaweed biomass is entirely

[1] Selin, N. E. (2023). Carbon sequestration. Retrieved from: https://www.britannica.com/technology/carbon-sequestration

[2] NOAA Climate.gov. (2022). Understanding blue carbon. Retrieved from: https://www.climate.gov/news-features/understanding-climate/understanding-blue-carbon

Figure 1
An illustrated representation of seaweeds' role as carbon sinks in ocean ecosystems



allocated for human consumption, subsequently releasing carbon back into the environment. These estimates assume of a dry weight content of approximately 10% of the fresh weight and an average carbon content of about 24.8% of seaweed dry weight [14].

In the scenario where seaweed biomass is fully consumed, such as in the production of food products and carrageenan, there could be an unintentional carbon sequestration rate of approximately 11%. Under the assumption that this estimate is also applicable to seaweed aquaculture, it implies that around 358,000 tonnes of CO_2 may have been sequestered unintentionally in oceanic sink sites during the farming process in 2019. It is important to note that the assessment of carbon sequestration is limited to the seaweed farming season, which varies by location, and this estimate does not encompass potential carbon sequestration through seaweed-based products [23].

However, it is crucial to acknowledge that this estimate, while substantially contributing to CO_2 sequestration, represents just a fraction of the overall potential. Precisely, it constitutes only 0.04% of the anticipated average of 841 Teragrams (Tg) of CO_2 projected to be sequestered annually by 2030 from all other blue carbon habitats [24]. The current infrastructure for seaweed aquaculture is predominantly basic and predominantly situated in sheltered coastal areas. Nonetheless, the potential for seaweed aquaculture expansion could experience significant growth if cost-effective and sustainable offshore aquaculture beyond the continental shelf becomes a viable option [25].

Further research is imperative, particularly in understanding the ecological impacts and associated risks and evaluating emerging technologies for both inshore and offshore operations. These efforts are pivotal in determining the potential scale of seaweed aquaculture in contributing to climate change mitigation at local and global levels. Therefore, it becomes necessary to carefully consider the balance between carbon storage by seaweeds and the overall carbon output to preserve and restore marine ecosystems that play a crucial role in long-term climate change adaptation.

3.1. Wild seaweeds: Potential and challenges in carbon sequestration

The wild-grown seaweeds possess enormous potential in terms of their carbon sequestration. However, there is still limited knowledge about wild seaweed resources, requiring caution when making global quantitative estimates [19]. Current research mainly focuses on commercially valuable genera in specific geographic areas of interest to governments and businesses. Estimates indicate that kelp beds encompass a global area ranging from 1 to 5 million square kilometers and are distributed along approximately 25% of the world's coastlines [26]. However, accurately estimating subtidal algal beds using satellite imagery remains challenging [27].

The significance of brown alga kelp beds in blue carbon storage has primarily been associated with coastal systems, including salt marshes, mangroves, and seagrass beds. Restoring or expanding seaweed and kelp beds is being proposed as a strategy for carbon storage [28–30]. However, the feasibility of establishing seaweed beds is often overlooked, as local and regional factors such as exposure to waves, ocean currents, water depth, nutrient dynamics, predation, implementation costs, zoning regulations, and societal acceptance play crucial roles [19]. Furthermore, seaweed beds exhibit significant seasonal variations in standing stock, further complicating their carbon storage potential assessments [31].

Several organizations are actively involved in restoring kelp forests to combat climate change. These organizations, including SeaTrees, the Bay Foundation's kelp restoration project, and the Kelp Forest Foundation, work on research and conservation efforts to protect and restore kelp ecosystems for their climate benefits.

Table 1
Coastal restoration organizations and their accomplishments

Organization name	Project endeavors	Noteworthy achievements	References
SeaTrees	SeaTrees focuses on establishing coastal restoration projects, known as blue carbon projects, spanning a range of ecosystem types, including mangrove forests, kelp forests, seagrass meadows, coral reefs, and coastal watersheds. SeaTrees collaborates closely with local non-profit partners in each project location to oversee and execute the critical work associated with restoration and protection efforts, thereby delivering a wide array of invaluable benefits to both the local environment and its communities	SeaTrees has successfully restored and preserved 539,514 square feet of kelp ecosystems across project sites located in California and Australia. This effort contributes to the protection and revitalization of these crucial blue-carbon coastal ecosystems, furthering our mission to combat climate change	[32, 33]
The Bay Foundation (TBF)	The mission of TBF is centered on the restoration and improvement of Santa Monica Bay through a combination of targeted initiatives and collaborative partnerships. These efforts are dedicated to the enhancement of water quality, the preservation and revitalization of natural resources, and safeguarding the valuable benefits associated with the Bay	TBF is at the forefront of global kelp forest restoration, focusing on the vibrant kelp forest ecosystems along the southern California coast. These ecosystems are renowned for their exceptional diversity and productivity, serving as vital habitats and food sources for more than 700 marine species, including kelp bass, California spiny lobster, abalones, marine mammals, birds, and various fish. TBF actively supports international partnerships, method development, and technological innovation. To date, TBF successfully restored more than 58 acres of kelp in Santa Monica Bay	[34, 35]
Kelp Forest Foundation (KFF)	The foundation's primary objective is to bridge the existing gaps in scientific understanding concerning the ecosystem services provided by kelp forests. The KFF is dedicated to increasing awareness about the significant economic and ecological value of kelp forests, driving research initiatives, expanding knowledge, and advancing scientific understanding related to the restoration of natural kelp forests and the cultivation of kelp afforestation	The organization's primary focus is on raising public awareness about the ocean and supporting academic research through the Blue House program, which offers scholarships to further these goals. Additionally, the KFF plays a vital role in the maintenance of the Macrocystis seed bank, a critical initiative aimed at preventing the loss of giant kelp. The establishment of giant kelp spore banks is essential for the preservation of heirloom strains, the conservation of biodiversity, and the restoration of ecosystems. These spore banks operate similarly to seed banks used for terrestrial species, safeguarding the genetic diversity of kelp for future research and applications	[36, 37]

Their contributions are instrumental in enhancing our understanding and implementation of kelp forest restoration initiatives to mitigate carbon emissions and promote ecosystem resilience (Table 1).

3.2. Farmed seaweeds: Opportunities and challenges in carbon sequestration

Cultivated seaweed species demonstrate rapid growth rates and possess the potential to sequester substantial amounts of carbon. Nonetheless, it is important to recognize that the standing stock of seaweed within a seaweed farm varies over time. It may peak during a specific period before declining to zero when the seaweed is harvested. The carbon dynamics associated with seaweeds are intricate, as they also release carbon through the fragmentation of particulate organic matter and dissolved organic matter [19].

Sunlight penetration is a critical limiting factor influencing the vertical and three-dimensional development of seaweeds, with most production concentrated near the surface waters. The pursuit of large-scale seaweed farming warrants careful consideration due to various factors, including water dynamics, nutrient constraints, adverse temperature and salinity conditions, and factors related to social acceptability and legal regulations [38]. Biomass losses within seaweed beds can occur due to phenomena like storm-induced water movements and insect grazing [39].

The fate of seaweed particles within carbon cycles remains uncertain, as only a small proportion (approximately 10%) of these particles will resist degradation by organisms [40]. While the deliberate sinking of seaweed biomass into the deep ocean is an intriguing concept, economic considerations come into play. Questions arise regarding potential buyers of seaweeds for sinking purposes and the compensation mechanisms involved in such actions. Typically, market forces influence the utilization of seaweeds toward the most financially lucrative applications. Instead of letting the seaweed biomass get deprived in the ocean, more resource-efficient methods should be employed to exchange the traditional manufacturing methods of animal feed, fertilizers, medicines, cosmetics, and high-value-added products. Recent research has highlighted the suitability of *Kappaphycus alvarezii* as a cattle feed on Pulau Bidong Island, Malaysia [41]. The nutritional profile of seaweeds makes them highly suitable for applications in fish feed, oyster feed, and poultry feed [42]. For instance, the inclusion of seaweed in poultry diets has been shown to significantly improve n-3 fatty acids in egg yolk and their color to satisfy customer's expectations [43].

4. Seaweed-Based Ruminant Diets: A Systematic Approach to Mitigating Methane Emissions and Advancing Blue Carbon Initiatives

The need to enhance efficiency in the agricultural and food industry has become increasingly crucial in the face of climate change. Among the contributors to GHG emissions, the livestock sector, particularly ruminant supply chains, accounts for a significant portion, responsible for 44% of anthropogenic methane (CH_4) emissions, equivalent to 3.1 gigatonnes CO_2-eq of CH_4 annually [44]. Methane is produced during the fermentative process in the rumen, where methanogens utilize hydrogen to generate CH_4. The alarming levels of methane emissions from cattle pose a substantial environmental concern, with each cow emitting an estimated 154–264 pounds of methane gas annually. Extrapolating this to the global population of 1.5 billion cattle raised for meat production, the total methane emissions from cattle reach a staggering 231 billion pounds annually[3] [45].

In recent years, certain seaweed species, including *Asparagopsis taxiformis*, *Alaria esculenta*, *Ascophyllum nodosum*, and *Chondrus crispus*, have shown promising potential in reducing CH_4 emissions from ruminants [46–49]. Notably, *A. taxiformis* has demonstrated remarkable efficacy in minimizing CH_4 production, with reductions of up to 98% observed when included at a mere 0.2% of dry matter intake in steer diets [50]. Several other seaweeds, such as *Cladophora patentiramea*, *Cystoseira trinodis*, *Dictyota bartayresii*, *Gigartina spp.*, *Padina australis*, and *Ulva spp.*, have also exhibited significant mitigation potential *in vitro*, with over 50% reduction in CH_4 emissions [51–53]. However, the results from these initial studies need to be further validated through *in vivo* investigations.

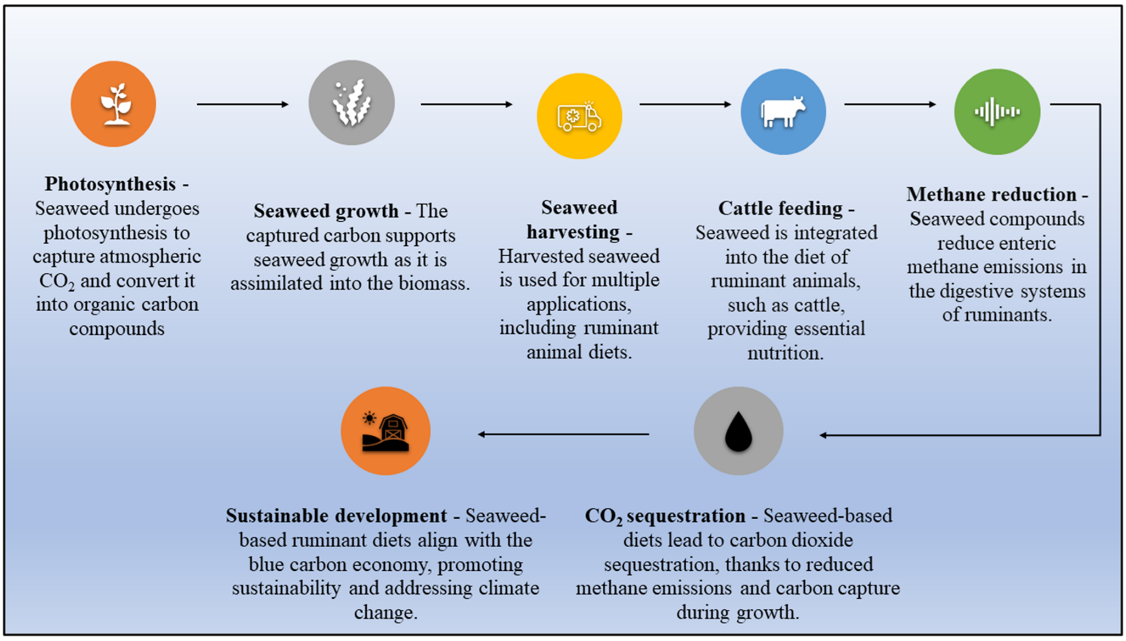
Seaweed-based ruminant diets offer a systematic approach to mitigating methane emissions, providing a viable pathway for addressing the environmental challenges posed by the livestock sector. This approach not only contributes to the reduction of methane emissions but also aligns with the objectives of the blue carbon economy. By utilizing seaweed as a cattle feed, we not only mitigate GHG emissions but also tap into the potential of marine resources to sequester carbon, thereby advancing the blue carbon initiatives aimed at combatting long-term climate change and fostering sustainable development (Figure 2).

The economic feasibility of integrating seaweed into cattle diets is indeed a pivotal concern. As outlined by Vijn et al. [54], introducing financial incentives may become imperative for seaweed adoption, particularly if the enhanced beef or milk yields resulting from seaweed inclusion do not outweigh the associated feed costs. Feed expenses constitute a substantial portion of a farmer's budget, making it a significant factor to consider [55]. Nevertheless, it is essential to acknowledge that, at present, there is a noticeable absence of comprehensive scientific studies delving into the economic implications for farmers when integrating seaweed into cattle feed [56].

While short-term animal trials and *in vitro* studies are essential for evaluating seaweed's potential to reduce methane emissions and its impact on animal productivity, feed intake, health, product quality, and manure composition, longer-term trials are required to comprehensively assess selected seaweeds' effects on methane emissions, productivity, health, product quality, nutrient digestibility, active compound residues in manure, and manure-related GHG

[3]United States Environmental Protection Agency. (2020). Agriculture and aquaculture: Food for thought. Retrieved from: https://www.epa.gov/snep/agriculture-and-aquaculture-food-thought

Figure 2
Seaweed-based ruminant diet carbon cycle



emissions [54]. Furthermore, the estimate by Vijn et al. [54] that using seaweed as 1% of the diet for all U.S. cattle would require approximately 3.2 million metric tons of dry seaweed annually, which is more than half of the current global seaweed production. This underscores the need for sustainable and scalable seaweed cultivation methods to meet such substantial demands. The potential advantages of reduced methane emissions and enhanced feed efficiency must be weighed against real-world implementation and economic considerations to ascertain the actual economic viability of seaweed-based ruminant diets [56].

Seaweed-derived bioactive compounds have been found to modulate rumen microbial populations and exhibit prebiotic effects in humans, positively influencing the composition and function of the gastrointestinal microbial community, commonly known as the gut microbiome [57, 58]. Given the nascent stage of our understanding of the microbiome and its implications for animal health, metagenomic studies are essential for unravelling the impact of specific seaweeds on the rumen microbiome and exploring the potential manipulation of these effects to benefit animal health, productivity, and the environment [54, 59].

The incorporation of seaweed-based ruminant diets not only holds promise in mitigating methane emissions from cattle but also aligns with the objectives of the blue carbon economy. This alignment with the blue carbon economy is a significant stride toward realizing the sustainable development goals (SDGs), particularly those pertaining to climate action, marine life preservation, and sustainable consumption and production.

The reduction of methane emissions through seaweed-based cattle diets directly contributes to SDG 13, which centers on combating climate change. By harnessing seaweed's carbon sequestration potential while curbing methane emissions, this approach addresses both environmental and climate-related challenges. Furthermore, it supports SDG 14, which emphasizes life below water, as seaweed cultivation and its role in carbon sequestration and marine ecosystem restoration contribute to the conservation of underwater biodiversity[4].

By reducing methane emissions, this systematic approach contributes to GHG reduction while leveraging the carbon-sequestering capabilities of marine resources, ultimately advancing global efforts to combat climate change and foster sustainable development. The incorporation of red seaweed, specifically *Asparagopsis taxiformis*, into cattle diets has demonstrated remarkable methane reduction results. Studies have shown that the supplementation of red seaweed can lead to an impressive reduction in enteric methane emissions, often exceeding 80% in beef steers [55]

This substantial reduction in methane emissions is a testament to the effectiveness of red seaweed as a dietary additive for methane mitigation in cattle. While specific quantitative estimates may vary based on factors like diet composition and seaweed dosage, the overarching evidence underscores the significant potential of red seaweed in substantially curbing methane emissions from cattle.

In summary, the incorporation of seaweed-based ruminant diets presents a multifaceted solution that not only addresses methane emissions and aligns with the blue carbon economy's objectives but also resonates with the broader aspirations of the SDGs. This positions it as a promising pathway toward a more sustainable and environmentally conscious future.

[4]The United Nations Statistics Division. (2023). The sustainable development goals report. Retrieved from: https://unstats.un.org/sdgs/report/2023/The-Sustainable-Development-Goals-Report-2023.pd

5. Conclusion

The successful integration of seaweed farming as a climate solution necessitates government support to manage market demand and address various challenges, including policy limitations, planning restrictions, market constraints, and financial hurdles. In Indonesia, the Gorontalo Utara regency has witnessed the success of female-led seaweed farming, supported by the local government's "fisher's community empowerment" initiative. Collaboration among various societal components, including village counselors and youth community leaders, has fostered an environment conducive to knowledge and experience exchange, enhancing women's participation in the industry. In Tanzania, seaweed cultivation has not only yielded economic benefits but has also empowered women and improved family food security, significantly enhancing the well-being of coastal communities. Similarly, in countries such as India, Indonesia, Malaysia, the Philippines, and Sri Lanka, coastal women have actively embraced seaweed farming, contributing to their economic empowerment and family earnings. The seaweed sector has created opportunities for women to engage in economic activities, emphasizing its potential to empower coastal women [60].

To ensure the sustainable adoption of seaweed as a climate-resilient crop, it is imperative to develop robust accounting methods that accurately evaluate the carbon sequestration capabilities of seaweed habitats while considering the overall carbon emissions associated with the entire seaweed production lifecycle. Both governments and businesses play crucial roles in advancing research and studies in various fields related to climate change and seaweed cultivation.

Seaweed possesses significant potential as a blue carbon sink and a sustainable, renewable energy source. Its capacity to sequester carbon, contribute to the bioeconomy, and offer diverse applications positions it as a valuable solution for addressing long-term climate change and decarbonization efforts. Moreover, seaweed cultivation presents opportunities for economic development and sustainable livelihoods, making it a versatile response to pressing environmental and socioeconomic challenges. Continued research and investment in seaweed-based initiatives are not only essential but also represent a powerful tool for paving the way toward a more sustainable and resilient future. These initiatives hold the potential to significantly contribute to our efforts in building a more environmentally sustainable and economically resilient world.

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Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data available on request from the corresponding author upon reasonable request.

Author Contribution Statement

Prakash Saravanan: Conceptualization, Methodology, Resources, Data curation, Writing – original draft, Visualization. **Antara Chatterjee:** Conceptualization, Methodology, Resources, Data curation, Writing – review & editing, Visualization. **Gourav Dhar Bhowmick:** Conceptualization, Data curation, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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