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Mini-Review

Sustainable biomethane production from marine algae: challenges and process strategies

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Abstract

Marine algae have gained increasing attention as sustainable substrates for biomethane production due to their rapid growth, high photosynthetic efficiency, and adaptability to saline cultivation conditions. This study evaluates recent advances in anaerobic digestion of marine micro- and macroalgae, focusing on the main technological challenges and process strategies to improve methane production. Methane yields from marine algal biomass vary widely depending on species and operating conditions, ranging from approximately 0.05–0.58 m^3 CH_4 kg^{-1} VS. Key limitations include salinity-induced inhibition of methanogenic microorganisms, resistant algal cell walls that limit hydrolysis, and free ammonia toxicity (above 1500–3000 mg NH_3/L) associated with the breakdown of high protein content. Several strategies have been proposed to address these challenges, including pretreatment technologies, co-digestion with other organic substrates, microbial acclimation to saline environments, and integration of anaerobic digestion within algal biorefinery systems (e.g., lipid extraction). This mini review demonstrated that marine algae can serve as a viable feedstock for biomethane production in coastal bioenergy systems, although further research is needed to improve process efficiency and enable large-scale implementation.

Key words: Anaerobic digestion, biomethane, marine algae, pretreatment, scale-up

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Introduction

Global energy demand and the urgent need to reduce greenhouse gas emissions have intensified the need for renewable and sustainable energy sources (Candra et al. 2023). Among bioenergy pathways, anaerobic digestion (AD) has emerged as an effective technology for converting organic biomass into biogas, a renewable energy carrier primarily composed of methane (CH_4) and carbon dioxide (CO_2) (Qian et al. 2025).

AD is a complex biological process involving four main stages: hydrolysis, during which complex organic polymers are converted into soluble compounds; acidogenesis, where these intermediates are transformed into volatile fatty acids; acetogenesis, which converts these products into acetate, hydrogen, and CO_2; and finally methanogenesis, where methanogens produce CH_4 as the final energy-rich product (Atelge et al. 2021).

Methanogenic archaea mediate biomethane production during AD via distinct metabolic pathways, i.e., acetoclastic methanogenesis, in which acetate is converted to CH_4 and CO_2, and hydrogenotrophic methanogenesis, in which H_2 and CO_2 are converted to CH_4. In addition, homoacetogenic bacteria can indirectly influence methane production by converting H_2 and CO_2 into acetate, which acetoclastic methanogens can subsequently utilize for methanation. The balance between these microbial pathways plays a crucial role in determining process stability and biomethane yield.

Conventional biomethane production through AD is mostly based on well-known substrates such as wastewater sludge, animal manure, and the organic fraction of municipal solid waste (Li et al. 2011; Shen et al. 2015; Njuguna Matheri et al. 2018). These systems are typically characterized by relatively stable operating conditions (e.g., hydraulic retention time (HRT) of 15–30 d) and consolidated process configurations (e.g., single- or two-stage AD), enabling efficient, predictable methane production under continuous operation (e.g., 0.9–1.1 m^3 CH_4 m^{-3} d^{-1} with CH_4 content of 50–70%) (Shen et al. 2015).

In this context, marine feedstock, particularly micro- and macroalgae, has attracted increasing attention as an alternative substrate for biomethane production due to its rapid growth rates, high photosynthetic efficiency, and ability to grow in seawater without competing for arable land or freshwater resources (Qian et al. 2025). Marine algae contain significant fractions of proteins, carbohydrates, and lipids, making them a promising substrate for AD-based bioenergy systems (Saranya et al. 2025).

Despite these advantages, the AD of marine algae presents several technical challenges. High salinity conditions can inhibit methanogenic microbial activity, while the low carbon-to-nitrogen ratio (C/N) and high protein content of microalgal biomass may lead to ammonia accumulation during AD (Kwietniewska and Tys 2014). In addition, the rigid cell wall structure of many algal species limits biomass biodegradability and methane recovery (Prokop et al. 2015).

These limitations have led to improved research on the efficiency of AD processes applied to marine algal biomass, resulting in the development of various technological and operating strategies. Recent studies have explored microbial acclimation to saline environments, pretreatment technologies to enhance biomass solubilization, and integration with algal biorefinery systems (Eusébio et al. 2022; Pardilhó et al. 2022a).

To further support the need for a more integrated understanding of process challenges and optimization strategies, a bibliometric keyword co-occurrence analysis was conducted using VOSviewer to systematically explore the current research landscape. The bibliometric analysis was performed using the Scopus database, applying the following search string: (“microalgae” AND “biomethane”). The analysis included publications from 2000 to 2026, resulting in a dataset of 330 documents. Keywords were extracted and analyzed using VOSviewer, applying a minimum occurrence threshold of 5 to identify the most relevant terms and generate the co-occurrence network. The resulting network map (Fig. 1) highlights the main research clusters related to marine algae-based bioenergy systems. Central keywords such as biomethane, microalgae, and AD appear as dominant nodes, reflecting

the growing interest in converting algal biomass into renewable gaseous fuels. Distinct thematic clusters can be identified, including methane production and AD processes, wastewater treatment and resource recovery, and algal biofuel production pathways such as biodiesel and bioethanol. The strong interconnection between these clusters indicates that marine algae research is increasingly framed within integrated bioenergy and circular bioeconomy concepts.

Although an increasing body of literature has been identified in the bibliometric analysis (Fig. 1), current research remains insufficiently integrated in linking process-related challenges with optimization strategies. Specifically, a critical review that systematically links operating limitations to technological solutions remains lacking.

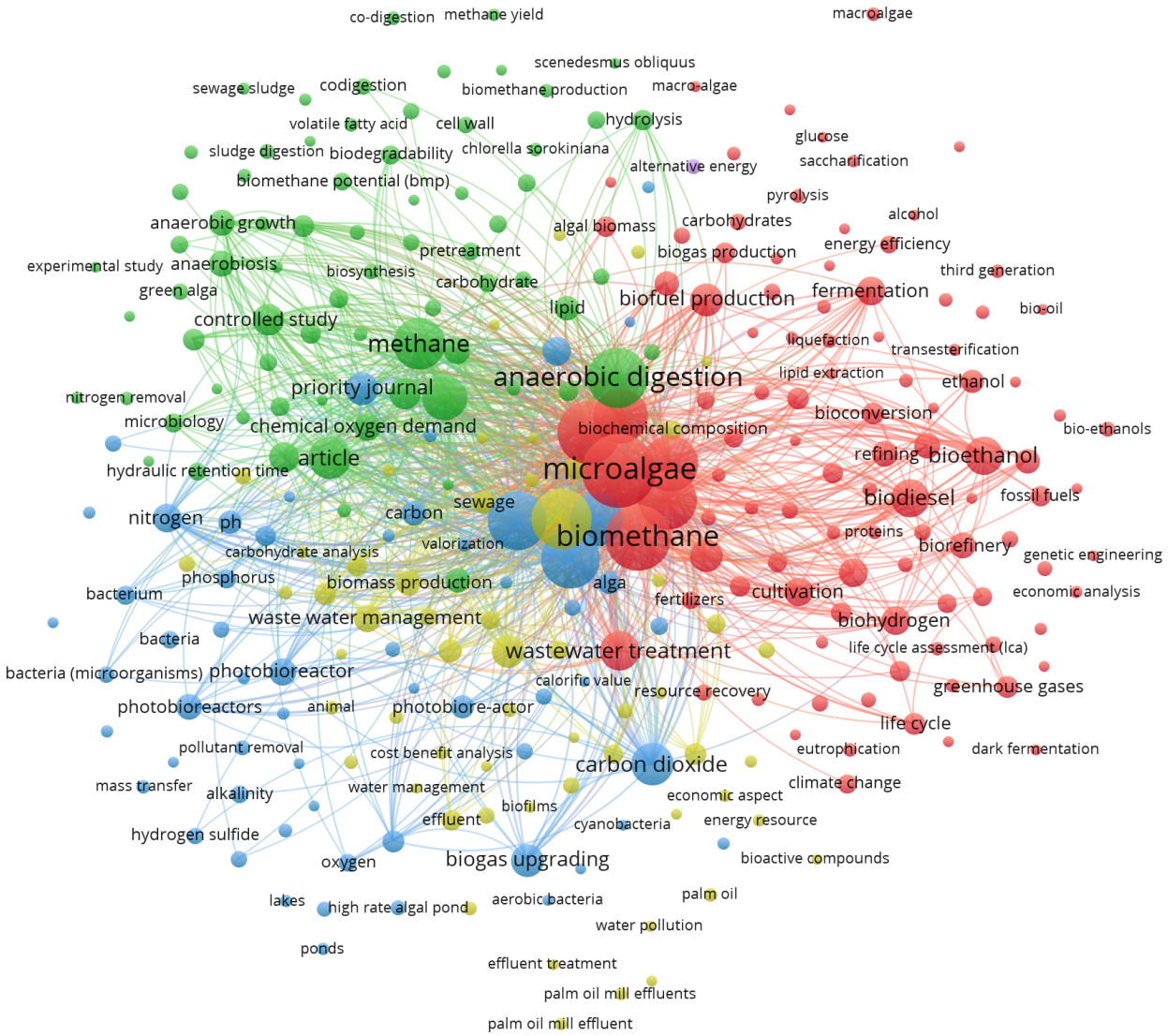

Figure 1. Keyword co-occurrence network related to marine algae-based bioenergy and biomethane production generated using VOSviewer. Node size represents keyword frequency, while colors indicate thematic clusters. The analysis highlights the main research directions in the field, including anaerobic digestion (AD) processes, biomethane production, wastewater treatment, and algal biofuel pathways. It also reveals limited integration between process-related challenges and optimization strategies, highlighting the need for a comprehensive, integrated review of marine algae-based AD.

Recent review literature has provided a general overview of marine algae as renewable feedstocks for biofuel production, primarily focusing on their biochemical composition, conversion pathways, and overall sustainability issues (Narayanan 2024). Also, Saranya et al. (2025) has delved into integrated concepts, including the integration of biomethane generation with a desalination system and circular bioeconomy models, as well as the promise of marine microalgae in multifunctional energy systems. At the same time, Hasan et al. (2024) highlighted issues at the process level, such as limitations in hydrolysis, inhibitory effects, and the need to optimize pretreatment and co-digestion strategies. However, none of these reviews provided a comprehensive and integrated analysis that simultaneously linked process challenges, optimization strategies, and scale-up perspectives.

Therefore, this study is aimed at critically reviewing the current state of biomethane production from marine micro- and macroalgae, focusing on the main operating issues and process optimization. Specific focus is placed on pretreatment technologies, co-digestion methods, acclimation of microorganisms to saline conditions, and AD integration into algal biorefinery systems (Fig. 2). The recent progress in the scale-up perspectives is also presented in this work, and the key research gaps that need to be addressed in order to allow large-scale implementation are identified.

Figure 2. Conceptual overview of the main challenges and technological strategies involved in biomethane production from marine algal biomass through anaerobic digestion.

Marine algae as feedstock for biomethane production

Marine algae have emerged as a promising substrate for biomethane production due to their high growth rates, efficient photosynthetic activity, and ability to grow in saline environments without competing with freshwater resources or arable land. Compared with terrestrial biomass, microalgae and macroalgae exhibit higher areal productivities and can be cultivated in coastal or offshore systems, making them attractive substrates for sustainable bioenergy production (Narayanan 2024).

From a biochemical perspective, marine microalgal biomass typically contains substantial amounts of proteins, carbohydrates, and lipids, which can be converted into methane via AD. Reported biochemical compositions of marine microalgae typically include 30–60% proteins, 10–30% carbohydrates, and 5–20% lipids, depending on species and cultivation conditions (Narayanan 2024). However, the biochemical composition varies widely across species and cultivation conditions, thereby influencing the final methane yield. For example, methane potentials reported for different microalgal strains can reach values of approximately 0.24–0.36 m^3 CH_4 kg^{-1} volatile solids (VS), whereas screening studies have identified strains capable of producing up to about 0.41 m^3 CH_4 kg^{-1} VS under optimized AD conditions (Zamalloa et al. 2012a; Frigon et al. 2013).

Marine macroalgae also represent a valuable substrate for biomethane production, particularly when biomass accumulates naturally along coastal regions and can be recovered as waste. For instance, AD of the brown macroalgae *Saccorhiza polyschides* resulted in methane yields of approximately 0.15 m^3 CH_4 kg^{-1} VS, demonstrating the potential of marine algal residues as feedstocks for bioenergy recovery (Pardilhó et al. 2022a).

Although these advantages exist, the effective conversion of algal biomass into methane is strongly influenced by several physical-chemical and biological factors, including biomass composition, salinity levels, and hydrolysis limitations during AD (Fig. 2).

Key challenges in anaerobic digestion of marine algae

The AD of marine algae copes with several technical challenges that can limit methane production yields. One of the most critical constraints is salinity, which can inhibit methanogenic microorganism activity through osmotic stress and ionic imbalance. High concentrations of sodium and sulfate, commonly present in marine biomass, may reduce methanogenic activity and slow overall digestion. Experimental studies reported that methane production may be significantly affected at salinity levels above 10–15 g L^{-1}, although acclimated microbial communities can maintain stable digestion performance at salinities close to 27–35 g L^{-1} (Parsy et al. 2024). For example, AD experiments with the marine microalgae *Isochrysis galbana* indicated that sodium inhibition significantly affected methane yields, although pretreatment strategies such as biomass washing were able to partially mitigate this limitation (Santos et al. 2014). Therefore, acclimated microbial consortia can tolerate elevated salinity levels, enabling methane production even under saline conditions typical of marine environments (Mottet et al. 2014).

Another major limitation is associated with the recalcitrant structure of microalgal cell walls, which often contain resistant biopolymers that hinder microbial hydrolysis. Because hydrolysis is typically the rate-limiting step in AD, the structural resistance of algal cells can significantly reduce substrate accessibility and methane yield. Experimental studies on marine microalgae, such as *Phaeodactylum tricornutum*, have shown that incomplete hydrolysis may result in partial conversion of organic matter during digestion (Zamalloa et al. 2012a).

These limitations highlight the need for optimized process strategies, including pretreatment technologies, microbial adaptation, and integrated digestion systems, to improve the conversion efficiency of marine algal biomass into biomethane (Fig. 2).

Strategies to enhance biomethane production from marine algae

To overcome the limitations of AD of marine algal biomass, several strategies have been investigated to improve methane yields and overall process stability. Among these approaches, pretreatment technologies, co-digestion strategies, microbial acclimation, and biorefinery integration have shown promising results. Experimental studies investigating biomethane production from marine algal biomass and strategies to improve AD performance are summarized in Table 1.

Pretreatment methods are frequently applied to enhance the hydrolysis of algal biomass and increase substrate accessibility for microbial communities. Mechanical, thermal, and chemical pretreatments have been widely investigated to disrupt the resistant cell wall structures of microalgae. For example, ultrasound-based pretreatment (i.e., at 150 W for 20 min) applied to marine microalgae such as *Tetraselmis suecica* and *Nannochloropsis oceanica* has demonstrated methane yields of approximately 0.10–0.17 m^3 CH_4 kg^{-1} VS, highlighting the influence of biomass structure and pretreatment intensity on digestion performance (Paul et al. 2023). These results highlight the strong influence of pretreatment intensity on methane production kinetics and substrate biodegradability.

Another widely investigated strategy is co-digestion, where algal biomass is combined with other organic substrates to improve nutrient balance (i.e., C/N) and microbial activity. Co-digestion of marine microalgae with sewage sludge (i.e., 20:80, w/w) has been shown to enhance process stability and maintain high biogas yields under mesophilic conditions. In such systems, biogas production values of approximately 0.44 m^3 kg^{-1} VS have been reported, demonstrating the potential of integrating algal biomass with existing AD infrastructures (Caporgno et al. 2015).

In saline systems, microbial acclimation represents an effective strategy to mitigate the inhibitory effects of salt. Experimental studies have demonstrated that gradual adaptation of methanogenic communities can significantly improve tolerance to salinity. For instance, acclimated microbial consortia have been shown to maintain stable methane production at salinity levels up to 27 $g{\cdot}L^{-1}$, indicating the feasibility of AD processes using saline algal biomass (Parsy et al. 2024).

Finally, integrating AD into algal biorefinery systems can significantly improve the overall sustainability and energy efficiency of marine biomass valorization. In such integrated systems, residual biomass generated after lipid extraction or other processing steps can be further converted into biomethane.

Table 1. Experimental studies on biomethane production from marine algal biomass and strategies to enhance anaerobic digestion performance.

Algal substrate	Process/strategy	Key findings	Methane yield	Refs.
Phaeodactylum tricornutum (microalgae)	Anaerobic membrane bioreactor (AnMBR)	Demonstrated feasibility of biomethane production from industrial microalgal biomass with partial COD conversion	~52% COD recovered as biogas	(Zamalloa et al. 2012b)
Isochrysis galbana (microalgae)	Mechanical and chemical pretreatment	Pretreatment increased soluble COD and improved methane production; sodium inhibition was observed	0.009 m^3 CH_4 kg^{-1} VS after hydrolysis optimization	(Santos et al. 2014)
Tetraselmis suecica, *Nannochloropsis oceanica*	Ultrasound pretreatment	BMP tests showed species-dependent methane potential after cavitation pretreatment	0.10–0.17 m^3 CH_4 kg^{-1} VS	(Paul et al. 2023)
Marine microalgae + sewage sludge	Anaerobic co-digestion	Salt-acclimated microbial consortia maintained methane production under saline conditions	0.20 m^3 CH_4 kg^{-1} VS	(Parsy et al. 2024)
Crypthecodinium cohnii residues	Biorefinery integration (lipid extraction residues)	AD integrated with lipid production improved energy recovery	Up to 0.58 m^3 CH_4 kg^{-1} VS	(Eusébio et al. 2022)
Marine microbial community + microalgae	Marine inoculum for AD	Demonstrated feasibility of marine microbial inocula for methane production	0.30 m^3 CH_4 kg^{-1} VS	(Fistarol et al. 2016)
Marine microalgae residues	Salinity acclimation of microbial consortia	Methane production is maintained at a salinity close to seawater concentration	Stable CH_4 production at ~35 g L^{-1} salinity	(Mottet et al. 2014)

Experimental results have shown methane yields of up to 0.58 m^3 CH_4 kg^{-1} VS when residual microalgal biomass was digested together with fermentation by-products, highlighting the potential of circular bioenergy approaches based on marine algae (Eusébio et al. 2022).

From a techno-economic perspective, many process optimization strategies have been proposed, though their large-scale applicability is limited by cost and energy constraints. Indeed, the use of energy-intensive pretreatment methods can limit overall process applicability unless optimized (Zieliński et al. 2019), whereas co-digestion and microbial acclimation tend to have more favorable cost-benefit ratios (Wehner et al. 2021). These strategies demonstrate that process optimization and system integration are essential to fully exploit the bioenergy potential of marine algal biomass.

Scale-up and techno-economic perspective

From a scale-up perspective, microalgal biomass production offers significant advantages over conventional terrestrial bioenergy crops. With high productivities > 90 t dry matter ha^{-1} $year^{-1}$, high conversion efficiencies (i.e., above 70%), and by using high-rate anaerobic digesters, microalgae cultivation systems can be used as high-yield feedstocks for renewable biomethane production (Zamalloa et al. 2012b). Methane production kinetics obtained during AD of marine algal biomass are frequently described using modified Gompertz models (Parsy et al. 2024), as follows:

$$M(t) = M_0 \cdot \exp\{-\exp[(R_m \cdot e/M_0)(\lambda - t) + 1]\} \quad \text{(Eq. 1)}$$

Kinetic parameters reported for marine macroalgae digestion include methane potentials (M_0) between approximately 0.05 and 0.10 m^3 CH_4 kg^{-1} VS, maximum methane production rates (Rm) of 0.0072 m^3 CH_4 kg^{-1} VS d^{-1}, and lag phases (λ) ranging from 6 to 16 days, depending on substrate concentration and operational conditions (Pardilhó et al. 2022b).

To illustrate the potential for methane production from marine algal biomass, a scale-up simulation (Table 2) was performed, as reported by Şenol et al. (2026). The model used kinetic parameters derived from previous AD experiments on marine macroalgae (i.e., M_0 = 0.082 m^3 CH_4 kg^{-1} VS, Rm = 0.0072 m^3 CH_4 kg^{-1} VS d^{-1}, λ = 9.8 d) (Table 2), assuming average operating conditions. Biomass availability was estimated assuming a microalgal productivity of approximately 90 tons of total solids (TS) ha^{-1} yr^{-1}, corresponding to a slurry input of about 250 t d^{-1} at 10% TS. It should be noted that the assumed biomass productivity was used only to define the feedstock availability scenario. Variations in areal productivity (e.g., 50–100 t TS ha^{-1} yr^{-1}) would primarily affect the cultivation area required to sustain the selected input flow, whereas AD performance is governed by the kinetic parameters and operating conditions used in the model. The simulation did not explicitly model a freshwater dilution step. Rather, the AD performance was estimated from literature-based kinetic parameters, which were assumed to reflect operating conditions representative of marine algal biomass.

The results suggested that marine algae-based AD could be performed at an HRT of 25 d (Fig. 3) with four reactors, each with a volume of approximately 1719 m^3, and an organic loading rate (OLR) of 2.46 kg VS m^{-3} d^{-1}. Under these conditions, methane production was estimated at about 1287 m^3 CH_4 d^{-1} (Fig. 3), corresponding to nearly 93% of the ultimate methane potential predicted by the kinetic model (Eq. 1).

Table 2. Scale-up simulation for biomethane production from marine algal feedstock based on modified Gompertz kinetics for anaerobic digestion (AD) process. Diameter-to-height ratio (D:H) of 1:1.

Parameter	Value	Unit
Slurry input flow	250	t d^{-1}
Volumetric inflow	250	m^3 d^{-1}
Total solids (TS)	10	%
Volatile solids (VS) input	16875	kg VS d^{-1}
Initial substrate concentration (S_0)	67.5	kg VS m^{-3}
Methane potential (M_0)	0.082	m^3 CH_4 kg^{-1} VS
Maximum methane production rate (Rm)	0.0072	m^3 CH_4 kg^{-1} VS d^{-1}
Lag phase (λ)	9.8	d
Design hydraulic retention time (HRT)	25	d
Total AD volume	6875	m^3
Organic loading rate (OLR)	2.46	kg VS m^{-3} d^{-1}
Specific methane yield at HRT	0.076	m^3 CH_4 kg^{-1} VS
Methane production	1287	m^3 CH_4 d^{-1}
Biogas production	2219	m^3 d^{-1}
Electricity potential	4490	kWh d^{-1}
Number of digesters	4	–
Volume per digester	1719	m^3
Digester diameter (D)	13	m
Digester height (H)	13	m

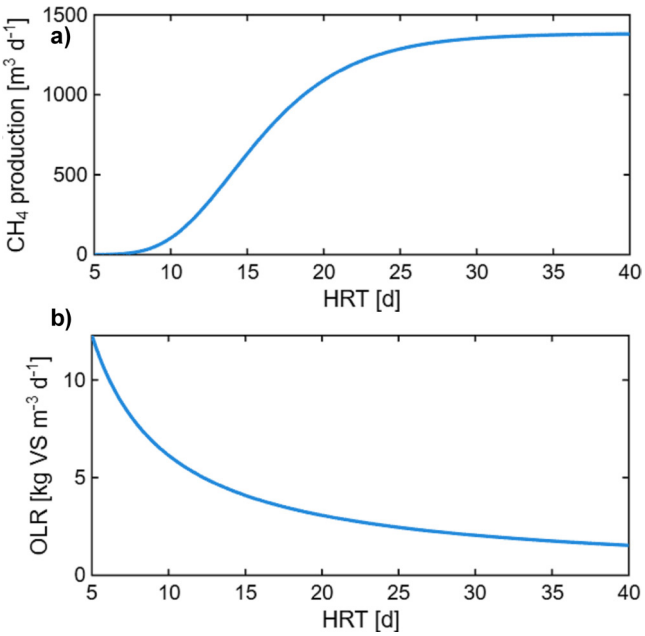

Figure 3. a. Predicted methane production as a function of hydraulic retention time (HRT), showing the progressive increase in methane yield and the approach to the asymptotic methane potential; **b.** Relationship between hydraulic retention time (HRT) and organic loading rate (OLR) for the considered system.

In addition, a techno-economic review further highlights the potential of marine algae-based biomethane systems. Experimental studies showed that the AD of microalgal biomass can generate significant energy recovery, with reported values reaching up to approximately 5.8 kWh kg^{-1} VS when residual biomass from lipid extraction is valorized through integrated biorefinery approaches (Eusébio et al. 2022). In addition to energy recovery, algal digestion processes may provide economic benefits through nutrient recovery and digestate valorization. For instance, previous analyses estimated that the conversion of microalgal biomass through AD could generate an overall value of approximately €2.13 per kg of algal TS, considering both biogas production and nutrient recycling (Zamalloa et al. 2012b). However, these benefits should be balanced against the additional energy inputs and process complexity required for efficient conversion of marine algal biomass. Indeed, taking into account the biomethane yield reported in Table 1, the estimated electricity generation of the marine algae-based system is 0.27 kWh kg^{-1} VS, which corresponds to approximately 1.6 GWh $year^{-1}$ assuming a CH_4 energy content of 9.97 kWh m^{-3} and a combined heat and power (CHP) electrical efficiency of 35% (Atelge et al. 2021).

In comparison, full-scale AD in wastewater treatment plants showed comparable positive energy and economic balances. Electricity production can reach approximately 700,000–860,000 kWh yr^{-1}, with supplementary thermal energy recovery exceeding 1.0 GWh yr^{-1}. From an economic perspective, terrestrial systems can reach benefit-to-cost ratios of 1.08–1.14, indicating that energy recovery is sufficient to offset operating costs, although margins remain relatively limited and are strongly influenced by sludge management costs, which can account for more than 50% of total expenses (Wehner et al. 2021). These findings suggest that integrating biomethane production with algal biorefineries and wastewater treatment systems could improve the economic viability of marine algae-based bioenergy technologies.

Conclusions

Marine algae represent a promising and sustainable feedstock for biomethane production through AD, offering advantages such as rapid growth rates, high productivity, and the ability to be cultivated without competing with agricultural land or freshwater resources. However, several challenges still limit their full exploitation in large-scale bioenergy systems, including the recalcitrant structure of algal cell walls, the high protein content, which leads to ammonia inhibition, and the presence of salts that may affect microbial activity during AD. These constraints remain key bottlenecks for large-scale implementation, as they directly affect process stability and methane productivity under real operating conditions.

Various process strategies have been proposed to overcome these limitations, including mechanical, thermal, chemical, and biological pretreatments to improve biomass biodegradability and methane yields. In addition, co-digestion with complementary substrates such as sewage sludge or organic wastes has demonstrated significant potential to enhance process stability, optimize nutrient balance, and mitigate inhibitory effects. However, their effectiveness depends strongly on process integration and operating conditions, and no single strategy is sufficient to overcome all limitations.

A kinetics-driven scale-up based on modified Gompertz parameters reported in the literature further illustrated the potential for marine algae-based AD systems. Under representative conditions, assuming a slurry input of approximately 250 t d^{-1} at 10% TS, the process could be performed at an HRT of about 25 d, corresponding to an OLR of approximately 2.46 kg VS m^{-3} d^{-1}. In this scenario, methane production was estimated at approximately 1287 m^3 CH_4 d^{-1}, with a reactor configuration consisting of four digesters of about 1719 m^3 each, highlighting the technical feasibility of modular digestion systems for marine algal biomass.

Integrating marine algae cultivation with AD and appropriate process optimization strategies could support the development of scalable and sustainable biomethane production systems in coastal and marine environments. These findings indicate that the large-scale feasibility of marine algae-based biomethane systems will depend on the development of integrated and energy-efficient process configurations. In particular, combining AD with algal biorefinery concepts and optimized co-digestion strategies appears essential to improve both economic viability and process stability under real operating conditions.

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Additional information

Conflict of interest

The author has declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Artificial Intelligence (AI) use

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Data availability

All of the data that support the findings of this study are available in the main text.