LEX PORTUS VOL 11 ISS 5 2025

ISSN 2524-101X
eISSN 2617-541X

DOI 10.62821/lp11503

Next-Generation Bioenergy: Challenges for the Regulatory Environment in the Maritime Industry

Oleksiy Melnyk*, Svitlana Onyshchenko**, Vlada Zhikharieva***

**Professor, Navigation and Maritime Safety Department, Odesa National Maritime University (34, Mechnikova St., Odesa, Ukraine) https://orcid.org/0000-0001-9228-8459*

***Professor, Fleet Operation and Shipping Technology Department, Odesa National Maritime University (34, Mechnikova St., Odesa, Ukraine) https://orcid.org/0000-0002-7528-4939*

****Professor, Economics and Finance Department, Odesa National Maritime University (34, Mechnikova St., Odesa, Ukraine) https://orcid.org/0000-0002-2179-8483*

ABSTRACT

This article explores the changing landscape of next-generation bioenergy technologies and their relevance to the maritime sector amidst increasing global decarbonization efforts. It specifically highlights microalgae-based fuels, residual biomass, and hybrid biochemical-thermochemical systems, forming a varied platform for low-carbon energy. Through comparative analysis of technology, environment, and regulation, the study pinpoints key hurdles for large-scale use – such as high costs, infrastructure challenges, and regulatory inconsistencies. Attention is given to current gaps in the IMO framework, which hinder the recognition and adoption of biofuels despite their potential to significantly reduce emissions from production to use. The article emphasizes that uniform global standards, port upgrades, and support for innovative solutions like genetically optimized microalgae, bioelectrochemical systems, and blockchain tracking are crucial to advancing toward climate-neutral maritime operations.

CITATION

Melnyk, O., Onyshchenko, S, & Zhikharieva, V. (2025). Next-Generation Bioenergy: Challenges for the Regulatory Environment in the Maritime Industry. *Lex Portus*, *11*(5), 31–44. https://doi.org/10.62821/lp11503

KEYWORDS

advanced biofuels, maritime decarbonization policy, maritime transport, port energy infrastructure, hybrid bioenergy systems, cost-efficiency, IMO regulatory framework, sustainable marine fuels

Introduction

Climate change, the exhaustion of traditional energy sources, and countries' commitments to reduce greenhouse gas emissions have contributed to the global transition to renewable energy sources. Against this backdrop, the international scientific community is paying special attention to the development of a new generation of bioenergy focused on the use of microalgae and renewable biological residues as raw materials for the production of clean energy. The development of bioconversion technologies, including anaerobic digestion, thermochemical conversion, and photobioreactor systems, allows bioenergy to be integrated into modern energy chains. At the same time, the issues of cost, energy balance, and implementation on the scale of industrial generation remain relevant.

Despite their numerous advantages (high growth rate, ability to fix CO_2, the ability to grow on unsuitable land), microalgae technologies have not yet been widely commercialized due to the complexity of scaling, high cost, and instability of productivity in natural conditions. Similar challenges are observed in the use of residual biomass, in particular in the areas of collection, logistics and standardization of raw material quality. An additional problem is the poor integration of such technologies into existing energy systems, limited institutional regulation, and a lack of applied research on life cycle, economic efficiency, and ecosystem impacts. The urgency of the problem is stipulated by the need to develop a unified systemic concept for the use of innovative bioenergy technologies within the framework of a sustainable energy transition, taking into account environmental, technical, economic and political parameters.

A review of the scientific literature shows an active growth of interest in the use of new generation bioenergy technologies, in particular, those based on microalgae, biowaste, lignocellulosic biomass, and hybrid systems. This is confirmed by numerous studies in recent years. In particular, Kaur et al. (2018) proposed new solutions for the use of algae and aquatic weeds as feedstocks for bioenergy production, emphasizing their sustainable nature. A similar perspective is presented by Thanigaivel et al. (2022), who provide a detailed analysis of the potential of microalgae as a next-generation biofuel.

Global estimates of the efficiency of bioenergy in the context of reducing greenhouse gas emissions are provided by Li et al. (2025) and Raman et al. (2025). These sources indicate a significant contribution of bioenergy to achieving the Sustainable Development Goals. Studies in the context of China support their conclusions (Zhang et al., 2022; Chen et al., 2024), South America (Magne et al., 2024), and Africa (Gabisa & Gheewala, 2025). The works of Wojciechowska et al. (2024) and Zhu et al. (2024) bring new technical opportunities in bioenergy, including electrode- and nanotechnology-based systems. Kandasamy et al. (2020) also emphasized the fact that nanomaterials might be a prominent pathway to facilitate energy efficiency within bioconversion. Both microbial and genetic approaches remain of importance as brought out by Singh et al. (2024) and Uzma & Khan (2024). Ly et al. (2025) have explored from a metal-organic frameworks perspective the coupling between bioenergy and water purification.

A systematic approach to the design of bioenergy supply chains using GIS, AHP and mathematical modeling is presented in Bayani Majd et al. (2025) and Roudneshin & Sosa (2025). The obstacles to the introduction of bioenergy crops in the EU are described by Ingram et al. (2025), focusing on political and social barriers. In turn, Hoffmann et al. (2025) emphasize the socio-economic effects of bioenergy production, including changes in real estate values. Other studies (Melnyk et al., 2023–2024; Soroka et al., 2023; Mysak et al., 2024; Volyanskaya et al., 2018; Budashko et al., 2020) focus on alternative fuels in shipping, the efficiency of ship energy systems, and the climate aspects of the transition to new energy sources. Ersoy & Ugurlu (2024) and Zhao et al. (2025) discuss the role of bioenergy in national energy strategies. Chaudhary et al. (2025) and Adamu et al. (2023) provide an overview of the latest technologies and bioenergy production chains from waste, fruits, and vegetables. Finally, an analysis of CO_2 cycles and soil impacts is presented in Bordonal et al. (2024), and strategic development policies in Wang et al. (2025) and Kiehbadroudinezhad et al. (2023).

Thus, the existing scientific base demonstrates the versatility, relevance, and potential of bioenergy as a key area of energy transition to a decarbonized future. The need to find alternatives to fossil fuels is growing amid rapid climate degradation, declining oil reserves, and international commitments to decarbonize economies. At the same time, there is growing pressure on food security, water resources, and soil ecosystems, which calls into question the effectiveness of traditional biomass as a long-term solution. Against this backdrop, new-generation bioenergy, in particular, based on microalgae and renewable residues, deserves special attention. Microalgae, unlike traditional biomass, are characterized by a high density of photosynthetic conversion, rapid growth, the ability to bioaccumulate CO_2, and the possibility of growing in areas unsuitable for agriculture. In addition, the use of residual biomass (food waste, agricultural residues, wastewater) reduces the burden on ecosystems and ensures a circular economy.

The aim of the study is to comprehensively summarize current approaches to the use of microalgae and bio-waste in new generation bioenergy, with a focus on technological, environmental and strategic aspects of sustainable energy transition. The scientific novelty of the article lies in the systematization of interdisciplinary data on bioenergy innovations, identification of key barriers and prospects for the implementation of relevant technologies in the global and regional context, as well as the formation of a generalized analytical model of their evolution in the near future.

1. New Generation Bioenergy Sources: Classification, Trends and Leaders

Global demand for renewable energy sources continues to grow amid global climate goals set out in the Paris Agreement and the EU Green Deal. Bioenergy, in particular, based on microalgae and organic residues, is taking an increasing share in the structure of "green" generation, especially in countries with an agro-industrial profile and access to organic waste.

Over the past five years, large-scale pilot and commercial projects focused on closed-cycle bioenergy technologies have intensified around the world, particularly in the EU, the US, China, Japan, and Brazil. Governments fund research programs, and multinational corporations fund demonstration facilities for high energy density bioenergy. At the same time, countries in the global South (India, South Africa, Chile) are showing rapid growth in microbial and enzymatic bioenergy due to the availability of raw materials.

Table 1 summarizes the characteristics of the global bioenergy market leaders using microalgae and residual biomass as key feedstocks.

Table 1. Global leaders in algae- and biowaste-based bioenergy

Country	Main technology	Annual generation (TWh)	Key policy / flagship project
United States	Photobioreactors, gasification	≈ 40	DOE Bioenergy Technologies Office
Germany	Anaerobic digestion	≈ 30	Renewable Energy Sources Act (EEG)
China	Biomass-coal co-firing	≈ 45	National Bioenergy Development Plan
Japan	Microalgae in closed farms	≈ 12	Green Innovation Fund (NEDO)
Brazil	Sugar-cane biomass, agricultural residues	≈ 25	RenovaBio (bioenergy certificates)
India	Waste-to-bioenergy, microalgae	≈ 18	SATAT initiative (bio-CNG from agri-waste)
South Africa	Cellulosic bioethanol	≈ 6	BioEnergy Atlas & Department of Science and Technology

As Table 1 shows, countries with a developed scientific base and agricultural resources demonstrate different technological approaches: from photobioreactors (USA, Japan) to anaerobic fermentation (Germany) and agricultural processing (Brazil, India). At the same time, support from government agencies through specialized programs is a key factor in the deployment of commercial generation based on biological raw materials.

While IMO sets GHG reduction levels as targets, it also establishes regulatory-facing requirements: certification, fuel standards, and safe deployment for any alternative energy carrier made available to shipping. Strengthening IMO's governance mechanisms will be crucial to reaching a global consensus on the application of bioenergy technologies and preventing divisions in regulation.

Next-generation bioenergy covers a wide range of organic sources that do not compete with food production and have improved energy efficiency, renewability, and environmental safety. There are three key categories within these sources: microalgae, residual biomass, and biorefined wastewater/waste. Below is a classification scheme by origin, processing and final forms of energy.

The proposed scheme in Figure 1 allows for a structured presentation of the main sources of new generation bioenergy based on renewable raw materials and innovative approaches to energy conversion. The main categories are microalgae, residual biomass, and biowaste. Each of them has specific technological routes for transforming raw materials into useful energy – biofuels, heat or electricity. This classification provides the basis for further analysis of the efficiency and potential of these sources in sustainable energy supply systems.

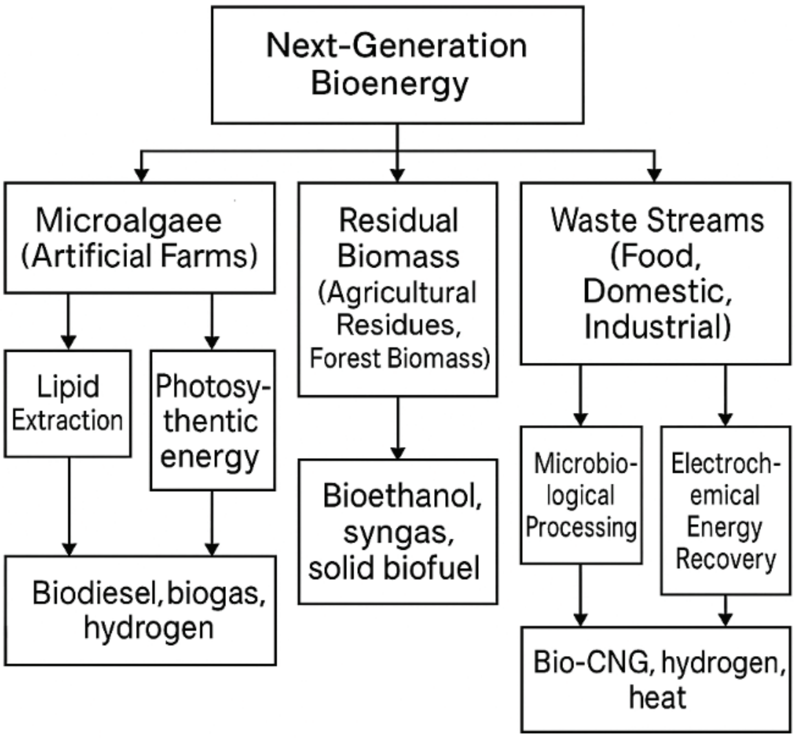

Figure 1. Classification of new generation bioenergy sources (Authors)

Figure 1 shows a classification scheme for new generation bioenergy sources. The scheme divides the sources into three main types: Microalgae-based, waste-based, and hybrid systems. Each is further subdivided based on feedstock type and conversion technology, which sheds light on the latest developments in photobioreactors, agricultural waste pyrolysis, and integrated algae and waste-based platforms. This visual structure provides a conceptual umbrella under which the article is structured, which helps to provide a comparative analysis in the following sections.

2. Comparative Analysis of Innovative Bioenergy Technologies Efficiency

At the current stage of bioenergy development, there is an active introduction of new generation technologies that ensure efficient conversion of organic raw materials into energy with minimal environmental impact. The most promising area is microalgae-based technologies, which allow for a complete closed production cycle – from cultivation to energy generation.

Figure 2 shows a typical technological algorithm for such a cycle. It begins with the cultivation of microalgae in three possible modes: photoautotrophic (on CO_2 and light), heterotrophic (using organic nutrient media) and mixotrophic (hybrid). The next stage is lipid extraction, which allows to extract the basic biomass for further energy conversion.

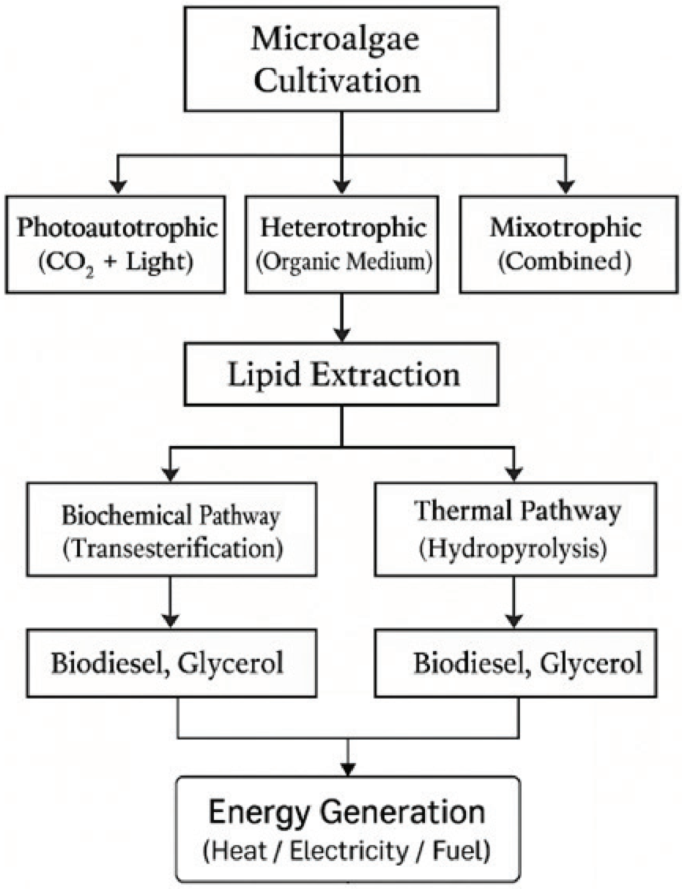

Figure 2. Technological chain of energy production from microalgae (Authors)

At the initial stage, microalgae are supposed to be cultivated in three modes: photoautotrophic (using CO_2 and light), heterotrophic (on organic medium) or mixotrophic (combined). After biomass is produced, lipids are extracted, which are the main feedstock for biodiesel.

The extracted lipids are then converted using one of two methods: biochemical transesterification or thermochemical hydrolysis. Both approaches yield similar products, biodiesel and glycerin, which are used to generate energy in the form of heat, electricity or motor fuel. In general, such systems are characterized by a high level of technological adaptability, which allows them to be integrated into both centralized and decentralized energy platforms, in particular in isolated or logistically challenging regions.

The successful implementation of new generation bioenergy directly depends on the efficiency of key technological platforms. Given the growing demand for sustainable energy sources and the need to decarbonize the energy sector, a detailed analysis of alternative approaches based on the use of renewable organic resources is becoming particularly relevant. The most promising areas today include microalgae bioconversion, residual biomass processing, and energy use of wastewater.

Each of these approaches has unique advantages: microalgae provide high energy density and do not compete with the food sector; residual biomass is an affordable raw material with minimal logistical costs; wastewater is a source of biogas that also contributes to environmental cleanup. At the same time, they also have a number of limitations related to the cost of technologies, the need for preliminary preparation of raw materials, or the availability of complex infrastructure.

A comparative analysis allows us to identify the advantages, limitations, and optimal applications for each of these approaches. Table 2 below summarizes the main criteria for such an assessment.

Table 2. Comparative Efficiency of Bioenergy Technologies

Technology	Energy Efficiency (MJ/kg)	Water Demand (L/kg biomass)	GHG Reduction Potential (%)	Commercial Readiness
Microalgae-based Systems	20–35	2000–4000	Up to 80 %	Medium
Residual Biomass	15–25	500–1000	Up to 60 %	High
Municipal & Industrial Waste	10–18	300–800	Up to 55 %	Medium
Hybrid Integrated Systems	25–40	800–1200	Up to 85 %	Low

As can be seen from the table, hybrid platforms have the highest potential for energy recovery and emissions reduction, but remain at the initial stage of commercial development. Microalgae, despite their high efficiency, require significant amounts of water, which limits their use in water-scarce environments. Residual biomass currently offers the best balance between availability, sustainability, and technical maturity.

To quickly assess the advantages and limitations of various bioenergy approaches, it will be useful to visualize key indicators for a qualitative description. In Figure 3, four main platforms of the algal biomass route are depicted, with the key features described according to four criteria: energy efficiency, greenhouse gas reduction, water consumption, and state of technological development, which include microalgae, residual biomass, municipal/industrial wastes, and hybrid systems.

It is clear that microalgae provide the highest energy yield, but have high water consumption. Residual biomass, although showing only an average level of emission reduction, has a high technological maturity and availability. Waste-based systems are advantageous in terms of low water consumption, but inferior in terms of energy conversion, and hybrid platforms have the potential for optimal balance, but their development is still in the early stages of implementation.

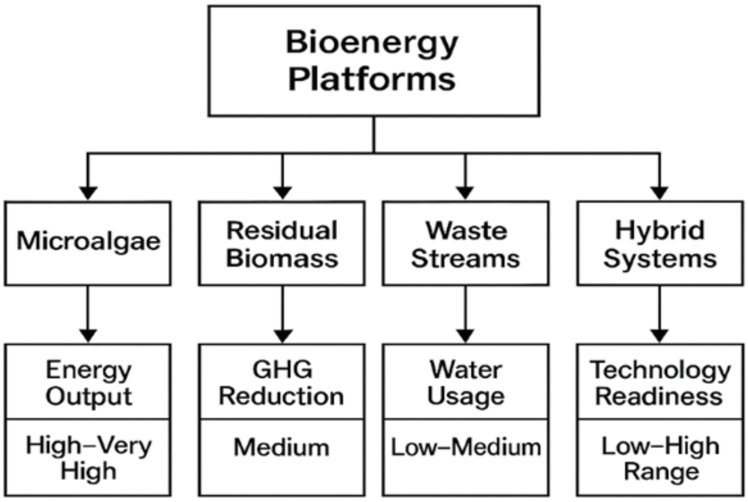

Figure 3. Comparative characteristics of bioenergy platforms (Authors)

3. Bioenergy and Transportation Challenges: Focus on the Maritime Sector

Because next-generation bioenergy is eco-friendly and can abate greenhouse gas emissions, the technologies still remain limited in full-scale deployment because of several systemic barriers. While most works in the bioenergy area are more or less concerned with production and conversion, the final use of energy, more particularly in the transport sector, is perhaps equally relevant to the bioenergy focus. This sector also is one of the major sources of CO_2 emissions into the atmosphere, accounting for about 25 percent, and is thought to be a major area to introduce biofuels. However, the adaptation of bioenergy technologies in transport has significant barriers that depend on the type of fuel, its delivery method, compatibility with existing equipment, and regulatory support.

Particular attention should be paid to maritime transport, which is both the largest in terms of cargo turnover and one of the most difficult to decarbonize. Maritime vessels traditionally use heavy fuel oil, and the transition to biofuels is accompanied by specific challenges related to operating conditions, voyage duration, fuel stability requirements, and legal compatibility with international IMO and ISO standards. With this in mind, Figure 4 below categorizes the main barriers to biofuels adoption in the maritime sector.

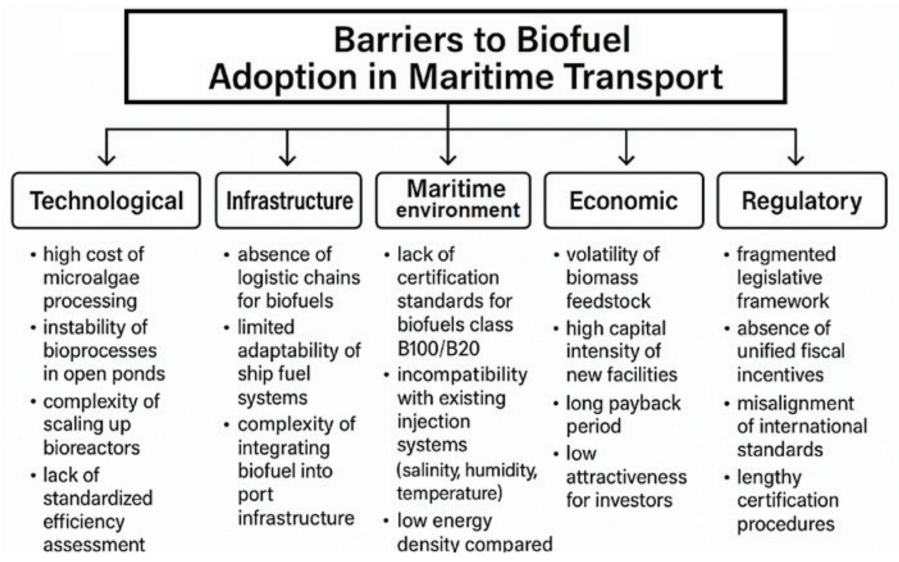

Figure 4. Barriers to Biofuel Adoption in Maritime Transport (Authors)

First of all, technological difficulties related to the high cost of biofuel production from microalgae, the instability of biological processes in open environments, and problems of bioreactor scaling are hindering development. A separate challenge is the lack of unified methods for assessing the efficiency of biomass-to-energy processes, which complicates their standardization and comparative analysis.

Barriers are particularly acute in the context of maritime transportation, where infrastructure and technical limitations become critical. Existing logistics do not provide for the storage and delivery of biofuels during long voyages, and ship fuel systems are often incompatible with B100 or even B20 biofuels. In addition, biofuels exhibit lower stability when stored in the humid and salty environment typical of marine conditions, and their energy density is inferior to traditional heavy marine fuels. The economic side of the issue also remains challenging: the high capital intensity of projects, the volatility of the biomass market, and the long payback period reduce interest from private investors. The regulatory environment adds even more uncertainty – the lack of unified certifications, insufficient coordination between national and international standards, and a weak fiscal incentive system create additional obstacles to the integration of bioenergy into the maritime transport system.

The International Maritime Organization (IMO) plays a leading role in shaping a strategic response to the challenges of climate transformation of the maritime fleet. Back in 2018, the IMO approved an initial strategy to reduce greenhouse gas emissions, which envisages a 40 % reduction in the carbon intensity of shipping by 2030 and complete decarbonization of the industry by mid-century. In 2023, these targets were revised to increase ambition, with a focus on the introduction of alternative fuels.

However, the implementation of this transformation is accompanied by significant practical challenges. One of the main problems is the lack of globally agreed standards for new fuels such as biofuels, ammonia, hydrogen, or methanol. In the technical dimension, the limited compatibility of existing marine engines with B20 or B100 biofuels is a particular challenge. The situation is further complicated by the poorly developed port infrastructure, which does not provide the ability to store and refuel new energy resources, especially in the conditions of humidity, salinity and temperature fluctuations typical of the marine environment.

Despite these difficulties, IMO is actively implementing new regulatory tools, such as the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII) Rating Scheme, which are already becoming a benchmark for assessing ships in terms of their environmental impact. In this context, high-performance bioenergy solutions with adaptive characteristics – in particular, the ability to operate in aggressive marine environments – can be a key element in achieving the goals of decarbonization and sustainable development of maritime transport.

Because next-generation bioenergy is environmentally attractive and capable of reducing greenhouse gas emissions, large-scale deployment in the maritime sector remains limited due to interlinked technological, economic, and regulatory barriers. While technological research has traditionally focused on cultivation, conversion efficiency, and feedstock logistics, the final use of biofuels – particularly in maritime transport – poses equally significant challenges. Maritime transport remains one of the hardest sectors to decarbonize due to long voyage profiles, harsh operating environments, and legacy dependence on heavy fuel oil.

A key obstacle stems from the IMO's regulatory environment, which has not yet fully adjusted to the unique features of renewable and synthetic fuels. The existing IMO framework – primarily designed around fossil fuels – causes ambiguity over how biofuels should be certified, managed, and accounted for in emission reduction goals. Although several alternative fuels like LNG, methanol, ammonia, and hydrogen are overseen by specific

IMO regulations such as the IGF and IGC Codes, there is no dedicated IMO framework for biofuels. The current conventions lack standardized definitions, blend ratios, safety guidelines, or sustainability standards for fuels derived from microalgae or waste. This regulatory gap leads to several issues:

- fragmented national certification processes;
- inconsistent bunker delivery documentation for blended fuels;
- differing regional sustainability standards, and
- uncertain carbon-reduction advantages of advanced biofuels.

These challenges are especially acute because the IMO's core climate instruments – EEDI, EEXI, and the CII Rating Scheme – primarily rely on tank-to-wake emission factors (Robalo-Cabrera et al., 2025; Lee, 2024). However, biofuels deliver most of their benefits well-to-wake, which means that vessels using sustainable biofuel blends do not currently receive full credit in their compliance calculations.

In 2024, IMO adopted the Life-Cycle GHG Assessment Guidelines (MEPC 391(81)), which provide a global well-to-wake methodology, yet the guidelines remain voluntary. Until incorporated into mandatory rules, biofuels remain disadvantaged relative to fuels that already have formal regulatory pathways.

Finally, port infrastructure represents an additional obstacle. Unlike LNG bunkering (regulated through ISO 20519 and IMO LNG bunkering guidelines (IBIA, 2023)), there are no IMO-level bunkering or storage standards for biofuels. Their known issues – oxidation, microbial growth, water absorption, instability in humid marine environments – require dedicated safety guidance not currently addressed by IMO instruments.

Thus, the maritime sector's biofuel transition is constrained by both practical conditions and regulatory uncertainty. Harmonized IMO rules addressing life-cycle emissions, bunkering practices, safety procedures, and certification would significantly accelerate adoption.

4. Policy and Regulatory Framework

The use of biofuels in the marine industry must align with the broader regulatory framework established by the IMO, especially MARPOL Annex VI, the EEDI/EEXI regulations, the Carbon Intensity Indicator (CII), and ongoing discussions about global market-based measures (MBMs). These tools collectively influence how alternative fuels, including next-generation biofuels, are integrated into maritime operations.

Currently, MARPOL Annex VI is the main regulation governing the environmental impact of fuels used at sea. While it sets standards for Sulphur and NOx emissions and incorporates efficiency metrics (EEDI/EEXI), it does not explicitly address biofuel chemistry, sustainability, or lifecycle emissions. Consequently, ships using B20–B100 blends are still subjected to default fossil fuel emission factors unless they undergo specific certification processes. This situation diminishes the true climate advantages of biofuels and hampers their adoption incentives.

The recently adopted Life-Cycle GHG Assessment Guidelines for Marine Fuels (MEPC 391(81)) mark a significant step toward a unified "well-to-wake" approach. The guidelines harmonize global carbon-intensity calculations, set verification standards for upstream emissions, and lay groundwork for future mandatory rules. Still, their impact is limited unless included in MARPOL Annex VI or linked to EEXI/CII frameworks. For biofuels to be competitive, IMO needs to incorporate LCA-based correction factors into CII ratings, develop sustainability standards similar to the EU Renewable Energy Directive (RED III), and ensure compatibility with regional systems like EU ETS, FuelEU Maritime, and California LCFS to prevent regulatory fragmentation.

Safety and Technical Standards should fill the gaps in IGF/IGC Code. Unlike methanol, LNG, ammonia, or hydrogen – which are covered under the IGF and IGC Codes – biofuels currently lack IMO-level safety and technical regulations. This gap introduces risks related to storage stability, cold-flow properties, microbial contamination, material compatibility, oxidation, and long-term degradation. Since most marine engines can only handle limited biofuel blends without modifications, IMO, in collaboration with classification societies, should develop: (i) minimum safety standards for high-blend or pure biofuels, (ii) onboard handling, filtration, and heating protocols, (iii) crew training and certification requirements.

Another aspect to consider involves port infrastructure, bunkering, and relevant quality standards. Although biofuel bunkering trials are increasing in Rotterdam, Singapore, and US ports, IMO has not developed a unified bunkering standard for biofuels, unlike the LNG-specific ISO 20519. This results in inconsistent procedures for: (i) fuel quality verification, (ii) contamination prevention, (iii) sampling and transfer operations, (iv) interaction with ISO 8217 (which still has incomplete biofuel specifications). Creating an IMO biofuel bunkering regulatory framework that aligns with ISO standards would reduce operational uncertainties and promote port readiness.

The IMO is developing a global MBM framework, such as a GHG levy, a feebate system, or a fuel standard. For biofuels to have a meaningful impact, MBMs need to incorporate recognizing LCA-verified carbon reductions, providing credit multipliers for certified advanced biofuels, and ensuring low-carbon biofuels are not disadvantaged compared to e-fuels and blue fuels. Including biofuel eligibility criteria in MBMs could immediately enhance their cost competitiveness.

The IMO could expand the Integrated Technical Cooperation Programme (ITCP) in the Black Sea region to boost pilot projects for biofuel blending (B20-B100) under different operational scenarios. Collaboration among maritime universities, classification societies, and fuel developers will help gather data efficiently through the IMO Data Collection System (DCS) and speed up the field implementation of bioenergy solutions.

Additionally, efforts should be made to prevent regulatory fragmentation worldwide. With the EU, USA, and various Asian countries introducing their own fuel standards and ETS-like systems, the risk of fragmentation rises. Only a coordinated global IMO framework can ensure that shipowners are not burdened by incompatible sustainability schemes, that fuel producers have a unified certification process, and that ports in developing economies remain competitive.

5. Future Technological Solutions for Bioenergy Development

In the context of global energy transformation and growing pressure from international climate commitments, bioenergy development can no longer be limited to traditional approaches to biomass processing. Instead, the emphasis is shifting to high-tech solutions that can overcome existing barriers and open up new horizons for sustainable energy supply, in particular in the maritime transport sector (Table 3).

Among the technologies of the future, genetically modified microalgae play a key role, demonstrating increased productivity and resistance to environmental stressors. Their use can significantly increase biofuel yields while maintaining environmental safety. In combination with new generation photobioreactors equipped with intelligent systems for monitoring growth parameters, this ensures efficient biofuel production even in unstable climatic conditions.

In parallel, bioelectrochemical systems (BES) are being developed, which are promising for implementation in port infrastructure: they simultaneously treat wastewater and generate electricity. This makes it possible to create autonomous, environmentally friendly energy sources for coastal facilities and small vessels. Innovations also include the digital

Table 3. Emerging Technological Solutions for Next-Generation Bioenergy

Technology	Functionality	Application Area	Benefit
Genetically modified microalgae	Enhanced lipid productivity and stress resistance	Biofuel cultivation	Higher biofuel yield, environmental resilience
Advanced photobioreactors	Intelligent control of CO_2, light, pH, temperature	Algae growth optimization	Stable production in variable climates
Bioelectrochemical systems (BES)	Wastewater treatment and electricity generation	Port infrastructure, small vessels	Autonomous green power and water purification
AI / IoT integration	Real-time monitoring of bioenergy systems	Whole supply chain	Operational efficiency and predictive control
Blockchain tracking	Transparency in feedstock origin and emission profiles	Supply certification	Traceability, carbon footprint accounting
Dual-fuel marine engines	Flexible adaptation to various biofuel types	Maritime propulsion	No full retrofit needed
Energy storage via BES/microgrids	Onboard or portside renewable energy storage	Coastal vessels, port terminals	Energy autonomy and hybrid resilience

transformation of bioenergy chains. AI/IoT integration allows for real-time management of the entire biofuel production and consumption ecosystem, while blockchain provides transparency in source accounting, emissions, and supply traceability. This is especially important for the maritime industry, where controlling the ecological footprint is becoming a critical factor in meeting international standards.

The opportunity of extending the Carbon Intensity Indicator (CII) with the biofuel adjustment factors could present an incentive for the shipowners. Such certified vessels that operate on verified low-carbon fuels could avail themselves of various operational incentives, for instance, reduced port dues or preferential docking at green berths, thereby rendering the use of sustainable fuels even more economically attractive.

The future of maritime transport is also associated with the use of dual-fuel engines that can adapt to different types of biofuels without a complete modernization of the power plants. New generation ships equipped with energy storage from BES or integrated microgrids in ports gain autonomy and flexibility in changing operating conditions. Thus, not only new technologies are being developed, but also entire ecosystems for bioenergy support of shipping – from genetically optimized sources to digital control models – that can ensure complete climate neutrality of maritime operations in the future.

Conclusions

Research indicates that next-generation bioenergy has significant potential to aid deep decarbonization worldwide, including in maritime sectors. Nonetheless, the study shows that technological readiness alone is not enough; widespread adoption faces economic hurdles, high resource demands, limited port infrastructure, and a lack of unified international standards. Present IMO rules mainly focus on tank-to-wake emissions, which means the full environmental benefits of sustainable biofuels are not fully captured in regulations like EEXI and CII. This discrepancy weakens incentives for shipowners and slows market growth. Overall, the research emphasizes that combining technological advances, regulatory alignment, and infrastructure upgrades is crucial for building a resilient bioenergy ecosystem that supports climate-neutral shipping. With coordinated global efforts, advanced biofuels can evolve from experimental options to a scalable element of future maritime energy systems.

REFERENCES

Adamu, H., et al. (2023). Production processes, techno-economic and policy challenges of bioenergy production from fruit and vegetable wastes. *Renewable and Sustainable Energy Reviews*, *186*, 113686. https://doi.org/10.1016/j.rser.2023.113686

Bayani Majd, A., Hajavi Seydlari, G., & Yaghoubi, S. (2025). A GIS-based food-energy-water-health-pollution nexus for sustainable food-biofuel-bioenergy supply chain network design: A case study. *Energy*, *328*, 136371. https://doi.org/10.1016/j.energy.2025.136371

Bordonal, R. D. O., et al. (2024). Carbon savings from sugarcane straw-derived bioenergy: Insights from a life cycle perspective including soil carbon changes. *Science of The Total Environment*, *947*, 174670. https://doi.org/10.1016/j.scitotenv.2024.174670

Budashko, V., et al. (2020). Main Problems of Creating Energy-efficient Positioning Systems for Multipurpose Sea Vessels. In *IEEE 6th International Conference on Methods and Systems of Navigation and Motion Control*, MSNMC 2020 - Proceedings, art. To. 9255514, 106–109. https://doi.org/10.1109/MSNMC50359.2020.9255514

Chaudhary, A., et al. (2025). Recent technological advancements in biomass conversion to biofuels and bioenergy for circular economy roadmap. *Renewable Energy*, *244*, 122714. https://doi.org/10.1016/j.renene.2025.122714

Chen, Y., et al. (2024). China's bioenergy potential will be stable and decoupling from economy and population at national level: A study based on machine regression prediction model. *Sustainable Energy Technologies and Assessments*, *69*, 103927. https://doi.org/10.1016/j.seta.2024.103927

Ersoy, A. E., & Ugurlu, A. (2024). Bioenergy's role in achieving a low-carbon electricity future: A case of Türkiye. *Applied Energy*, *372*, 123799. https://doi.org/10.1016/j.apenergy.2024.123799

European Parliament and Council. (2023, October 18). *Directive (EU) on amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652*. https://eur-lex.europa.eu/eli/dir/2023/2413/oj/eng

Gabisa, E. W., & Gheewala, S. H. (2025). Policy implications and recommendations for sustainable bioenergy development in Ethiopia. *Sustainable Futures*, *9*, 100612. https://doi.org/10.1016/j.sftr.2025.100612

Hoffmann, C., Byrukuri Gangadhar, S. S., & Müsgens, F. (2025). Smells like Green Energy: The Impact of Bioenergy Production on Residential Property Values in Germany. *Energy Economics*, *145*, 108404. https://doi.org/10.1016/j.eneco.2025.108404

IBIA. (2023, June 13). *IMO approves Interim LPG Guidelines and LNG bunkering UIs*. https://ibia.net/imo-approves-interim-lpg-guidelines-and-lng-bunkering-uis/

Ingram, J., Mills, J., & Mackley-Ward, H. (2025). "For all kinds of reasons, it hasn't happened": A novel integrative perspective for analysing the barriers to biomass crops for bioenergy in the United Kingdom. *Energy Research & Social Science*, *120*, 103936. https://doi.org/10.1016/j.erss.2025.103936

International Convention for the Prevention of Pollution from Ships, 1973/1978. https://library.arcticportal.org/1699/1/marpol.pdf

International Maritime Organization. (n.d.) *Integrated Technical Cooperation Programme (ITCP)*. https://www.imo.org/en/ourwork/technicalcooperation/pages/itcp.aspx

International Maritime Organization. (2024, March 22). *Resolution MEPC. 391(81) on Guidelines on Life Cycle GHG Intensity of Marine Fuels (2024 LCA Guidelines)*. https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MEPCDocuments/MEPC.391(81).pdf

Kandasamy, S., et al. (2020). Nanotechnology's contribution to next-generation bioenergy production. *Nanomaterials*, 511–518. https://doi.org/10.1016/B978-0-12-822401-4.00036-2

Kaur, M., et al. (2018). Aquatic weeds as the next generation feedstock for sustainable bioenergy production. *Bioresource Technology*, *251*, 390–402. https://doi.org/10.1016/j.biortech.2017.11.082

Kiehbadroudinezhad, M., Merabet, A., & Hosseinzadeh-Bandbafha, H. (2023). Bioenergy Programs in North and South America and Canada. *Encyclopedia of Renewable Energy, Sustainability and the Environment*, 871–886. https://doi.org/10.1016/B978-0-323-93940-9.00028-1

Lee, S.-S. (2024). Analysis of the effects of EEDI and EEXI implementation on CO2 emissions reduction in ships. *Ocean Engineering*, *295*, 116877. https://doi.org/10.1016/j.oceaneng.2024.116877

Li, H., et al. (2025). Bioenergy utilization and greenhouse gas emission reduction: A global impact assessment. *Renewable Energy*, *250*, 123115. https://doi.org/10.1016/j.renene.2025.123115

Ly, N. H., et al. (2025). Metal-organic frameworks avenues in microbial electrochemical systems as a sustainable approach to waste treatment and bioenergy generation. *Chemical Engineering Journal*, *505*, 158766. https://doi.org/10.1016/j.cej.2024.158766

Magne, A., Khatiwada, D., & Cardozo, E. (2024). Assessing the bioenergy potential in South America: Projections for 2050. *Energy for Sustainable Development*, *82*, 101535. https://doi.org/10.1016/j.esd.2024.101535

Melnyk, O., et al. (2024). Implementation Research of Alternative Fuels and Technologies in Maritime Transport. *Studies in Systems, Decision and Control*, *510*, 13–21. https://doi.org/10.1007/978-3-031-44351-0_2

Melnyk, O., et al. (2023). Modern Aspects of Ship Ballast Water Management and Measures to Enhance the Ecological Safety of Shipping. *Studies in Systems, Decision and Control*, *481*, 681–694. https://doi.org/10.1007/978-3-031-35088-7_39

Melnyk, O. M., et al. (2024). Enhancing shipboard technical facility performance through the utilization of low-sulfur marine fuel grades. *Journal of Chemistry and Technologies, 32*(1), 233–245. https://doi.org/10.15421/jchemtech.v32i1.297916

Mysak, S. Y., Shapoval, S. P., & Hyvliud, A.M. (2024). Analysis of the Share of Renewable Energy Sources in the Gross Final Energy Consumption of European Countries. *Energotehnologii i Resursosberezenie*, *78*(1), 59–75. https://doi.org/10.33070/etars.1.2024.05

Raman, R., et al. (2025). Analyzing the contributions of biofuels, biomass, and bioenergy to sustainable development goals. *IScience*, *28*(4), 112157. https://doi.org/10.1016/j.isci.2025.112157

Robalo-Cabrera, I., et al. (2025). Shipping Sector Decarbonisation Measures: A Review. *Sustainable Energy Technologies and Assessments*, *82*, 104549. https://doi.org/10.1016/j.seta.2025.104549

Roudneshin, M., & Sosa, A. (2025). A novel approach for optimisation of bioenergy supply chain: Integrating mathematical programming, Geographic Information System, and Analytic Hierarchy Process. *Bioresource Technology*, *418*, 131827. https://doi.org/10.1016/j.biortech.2024.131827

Singh, T. A., et al. (2024). Microbes: The next-generation bioenergy producer. *Genetic and Genome-Wide Microbial Insights: Bioenergy*, 71–80. https://doi.org/10.1016/B978-0-443-31556-5.00005-0

Soroka, B. S., Zgurskyi, V.O., & Kudryavtsev, V.S. (2023). Reducing the CO2 Atmospheric Emission by Natural Gas "Oxy-fuel Combustion", as a Means of Prevention the Greenhouse Impact. *Energotehnologii i Resursosberezenie*, *77*(4), 3–19. https://doi.org/10.33070/etars.4.2023.01

Thanigaivel, S., et al. (2022). Engineering strategies and opportunities of next generation biofuel from microalgae: A perspective review on the potential bioenergy feedstock. *Fuel*, *312*, 122827. https://doi.org/10.1016/j.fuel.2021.122827

Uzma, J., & Khan, A. A. H. (2024). Genome editing for better yield of bioenergy and biofuel. *Genetic and Genome-Wide Microbial Insights: Bioenergy*, 129-145. https://doi.org/10.1016/B978-0-443-31556-5.00009-8

Volyanskaya, Y., et al. (2018). Analysis of possibilities for improving energy indicators of induction electric motors for propulsion complexes of autonomous floating vehicles. *Eastern-European Journal of Enterprise Technologies*, *2*(8–92), 25–32. https://doi.org/10.15587/1729-4061.2018.126144

Wang, S., Yin, H., & Yin, C. (2025). "Promoting biomass co-firing in coal power plants"--The new policy will reshape the landscape of bioenergy industry in China. *Energy Strategy Reviews*, *59*, 101714. https://doi.org/10.1016/j.esr.2025.101714

Wojciechowska, E., et al. (2024). Electrode-based floating treatment wetlands: Insights into design operation factors influencing bioenergy generation and treatment performance. *Science of the Total Environment*, *949*, 175074. https://doi.org/10.1016/j.scitotenv.2024.175074

Zhang, K., Yin, K., & Yang, W. (2022). Predicting bioenergy power generation structure using a newly developed grey compositional data model: A case study in China. *Renewable Energy*, *198*, 695–711. https://doi.org/10.1016/j.renene.2022.08.050

Zhao, W., et al. (2025). Bioenergy technologies and forest resources: Pathways to a sustainable green economy. *Renewable Energy*, 123609. https://doi.org/10.1016/j.renene.2025.123609

Zhu, X., et al. (2024). Enhanced power generation by carbonized microsphere embedded with bimetallic carbides nanoparticles as efficient electrocatalyst in bioenergy harvesting systems. *Journal of Power Sources*, *624*, 235552. https://doi.org/10.1016/j.jpowsour.2024.235552

У статті розглядається зміна ландшафту біоенергетичних технологій нового покоління та їхня актуальність для морського сектору на тлі зростаючих глобальних зусиль у сфері декарбонізації. Особливу увагу приділено паливу на основі мікроводоростей, залишковій біомасі та гібридним біохімічно-термохімічним енергетичним системам, що формують різноманітну платформу для низьковуглецевої енергії. За допомогою порівняльного аналізу технологічних, екологічних та регуляторних аспектів у дослідженні визначено ключові перешкоди для їх широкомасштабного використання, такі як висока вартість, інфраструктурні проблеми та негармонізованість регуляторних підходів. Увагу також приділено прогалинам у регуляторному підході IMO, які перешкоджають визнанню та впровадженню біопалива, незважаючи на його потенціал значно скоротити викиди на всіх етапах – від виробництва до використання. У статті наголошується, що єдині глобальні стандарти, модернізація портів та підтримка інноваційних рішень, таких як генетично оптимізовані мікроводорості, біоелектрохімічні системи та блокчейн-інструменти відстеження, мають вирішальне значення для просування до кліматично нейтральних морських операцій.

Ключові слова: передові біопалива, політика морської декарбонізації, морський транспорт, портова енергетична інфраструктура, гібридні біоенергетичні системи, ефективність витрат, нормативно-правова база IMO, сталі морські палива.