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The Role of AI and Autonomous Systems in Navigating China's Future Maritime Sustainability and Blue Economy Governance

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Abstract

This study emphasizes the need to integrate digital technologies to create sustainable sea use and contribute to the blue economy in the maritime sector. The paper examines the potential of Artificial Intelligence, Blockchain, and the Internet of Things to enhance operational efficiency and reduce environmental footprint. It also addresses evolving governance and law, including how existing systems address new issues such as cross-border data transfer and autonomous shipping. This paper aims to raise awareness of policy, technology, and sustainability, and to offer a way forward for the future of marine energy and environmental protection in China. The study contributes to the international law literature in the Atlantic, and to the offshore industry, particularly regarding the use of digital technology. It offers policy recommendations on cooperation and on supporting legal access governance of technological advances. Therefore, this paper emphasizes the importance of national law to keep pace with the rapid development of marine technologies and international cooperation to manage marine resources sustainably.

Keywords: Maritime Sustainability, Blue Economy, Autonomous Shipping, Maritime Governance

Introduction

The marine economy includes industries that rely on marine and sea resources, including fisheries, shipping, coastal tourism, and offshore renewables. These industries play an important role in economic development and are also unique in that sustainability issues are especially relevant (Khaskheli et al., 2025). However, rising temperatures, overused marine resources, and increasing pollution mean the offshore energy sector urgently needs innovation that balances the economy and the environment (Van Kuik et al., 2016). Pressures on the blue economy's growth are becoming more frequent and are directly related to resource depletion, climate change, and fractured governance. New digital technologies like artificial intelligence, blockchain, and IoT can significantly transform operational efficiency and eco-sustainability (Jin et al., 2025; Talha, Sardar, et al., 2024). However, the international legal framework regulating these technologies in marine fisheries has not always kept pace with these innovations. The maritime domain is one of the most critical for decarbonization, and the offshore domain and international shipping continue to contribute significantly to anthropogenic greenhouse gas emissions. Low-emission maritime technologies can help achieve international climate targets (Alweqyan, 2024). Nuclear propulsion and nuclear heat generation in the marine environment are emerging technologies that may transform the marine energy transition (Androjna et al., 2020). China has well-developed

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nuclear technology at sea. China has made significant advances in the development of nuclear applications at sea. China's government is exploring nuclear energy as a potential means for onboard applications, floating nuclear power plants, onshore power generation, and high-level sea monitoring (Q. Wang, 2025). These initiatives are part of a strategic thrust to understand different low-carbon solutions to address future challenges in ocean governance.

International law treaties such as the UN Convention on the Law of the Sea (UNCLOS) establish the general framework for activities at sea. UNCLOS came into force in 1982, but it is obviously limited in its capacity to address new technologies that could emerge in the digital seas, such as deep-sea data aquaculture or AUVs (autonomous underwater vehicles). In practice, however, international treaties such as the Paris Agreement or the International Maritime Organization (IMO) 2020 Sulphur regulations aren't relevant to the shipping industry. Nevertheless, they indirectly affect a country via digital technologies such as route optimization, fuel checking, and emission control. (Talha, 2023b), (Talha, Mukhtar, et al., 2023). At the same time, the build-up of CBD and 2023 agreement obligations on Biodiversity beyond National Jurisdiction is highlighting the need for greater engagement in marine protection. But the capacity building of systems of monitoring and predictive modeling from which enforcement technologies are derived may be outpacing the technologies. Commercial ship navigation also faces operational risks that autonomous navigation can further reduce and may even improve efficiency. But fundamental elements of the system, including perception, planning, and control, have started to create liability problems. Maritime laws lag behind technology, with liability questions around maritime remote control and who’s at fault, including the ship proprietor, software provider, and data provider. (Adv. Ahmad Talha, 2022). In addition, regional regulations, such as the European Union's General Data Protection Regulation and Digital Services Act, make an already difficult situation with cross-border data flows even more complex, and cross-border data flows play a key role in ensuring progress in maritime digitalization. (Earsom, 2025).

This study was intended to investigate the possible link between digitisation practices for sustainability and the flexibility of shipping regulations. A lack of understanding of UNCLOS provisions, especially for laying subsea cables, continues to affect the governance situation, and no specific ISBA guideline covers the use of AI in deep-sea mining. The analysis uses concrete cases of digitisation in the offshore wind and seafood industries with blockchain. It proposes measures that make such technologies economically successful and explains how they will help secure the ocean and the United Nations Sustainable Development Goals (Mingfei et al., 2026; Talha, Tayyab, et al., 2023). As the world's second-largest economy, China should be a key player in the global market, with tremendous dynamism. The marine economy is rapidly expanding and fulfils essential human needs such as recreation, transport, food and energy production. With over three million square kilometers of sea area and the world's fourth-longest coastline, China has laid a solid foundation for developing the ocean industry. Sea-related GDP in China reached 9.4628 trillion yuan in 2022, and its share of GDP rose to 7.8%, growing by 1.9% each year (Fang et al., 2024). The marine economy has developed well, leaving behind the backward and polluting economic activities of the past, especially in important economic zones such as the Bohai Rim, Yangtze River Delta, and Pearl River Delta. However, the domestic marine engineering equipment industry has focused on lower-value-added (LVA) and externalised value chains, manufacturing only a small share of high-value-added (HVA) equipment and packages (Li et al., 2024), (Talha, Noor, & MA, 2024). European and American companies strongly influence the design of innovative marine products, and they subcontract production to Asian partners, making it difficult to develop the domestic marine product industry. Therefore, Chinese companies are mostly oriented toward the low end of the global value chain in marine equipment production. In this area, strategic opportunities include digital technologies and market access, which can be improved to support the sector (X. He et al., 2022).

Literature Review and Analysis Framework

A considerable amount of literature has been published on the development of nuclear propulsion systems for maritime applications, including technology history, technological improvements, operational advantages, economics, safety, and environmental protection (Q. He et al., 2025; Noor et al., 2024). It is argued that using nuclear power to power ships in marine operations is a possible solution for decarbonizing the industry. What we really need to reduce are ship emissions, which may make nuclear energy more than a disruptive energy supply in shipping, a topic still under discussion in academia (Talha et al., 2026). There has been a lot of discussion about what is meant by ‘digital trade’. The United States International Trade Commission (ITC), after much study, found three basic dimensions: trade supported by internet infrastructure; cross-border transfers of digital content; and trade in goods and services. The framework focuses on data mobility and digital platforms and their relevance to international trade (T. Sardar et al., 2025). Companies increasingly need to move products and services digitally, with information sharing and robust Internet infrastructure no longer just "nice to have" in their operations. Digitalization thus offers immense opportunities for economies seeking greater digitization, not only in developing economies but also for those interested in providing more services to the rest of the world. However, to gain those benefits, effective governance is needed, and some academics have proposed a coordinated international regulatory regime.

The interaction between policy, regulation, and law, particularly as it affects sea energy transitions, has also grown in importance and requires specialists who can interpret and engage with this interplay in a shipping context. Maritime innovation has long been subject to legal scrutiny, and maritime trade law in many countries fails to keep pace with these ongoing changes (Talha, 2022). All stakeholders need to proactively prepare for evolving climate mitigation and sustainability (environmental, social, and governance) and renewable energy deployment needs and challenges to remain relevant (Bai et al., 2024). Maritime industry professionals will increasingly need specific skills and information on new areas, such as technology for China's rapidly expanding hydrogen industry (Zhang & Yang, 2022) .

Digital Technology Application to Maritime Sectors

Digital technologies are growing more important in the transformation of maritime operation processes and creating a host of opportunities, but they are also raising governance issues (Ahmad Talha et al., 2025). Traffic continues to develop slowly but steadily despite digital technologies, which enhance shipping safety, efficiency, and sustainability, and shipping is the backbone of sea transport and supports trade (Chae et al., 2025). This review discusses a range of empirical studies that reflect current trends in development and technology use. One of the central themes that appeared in the literature is cultural dislike of the digital tools coupled with a resistance to full adoption of the tools (Mustafa et al., 2023). Attitudes within the organization need to change a lot more in this way, it has been proposed (De Hert et al., 2018; Talha, 2023a).

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The benefits of digitalization are great; yet key institutional and practical issues remain unresolved. This is why adoption rates vary across shipping markets.

Policy, Legal and Regulatory Issues of Unmanned Marine Systems

Marine system autonomy creates complex legal challenges, including surveillance, territoriality, data rights, and legal compliance. Uncertainty remains in case law regarding the use and extension of international agreements, including the United Nations Convention on the Law of the Sea (UNCLOS), in the exclusive economic zone (EEZ) and in relation to marine scientific research activities (Yüksel et al., 2025). In addition, tagging raises concerns about national sovereignty over data and ethical issues, and stronger international standards are needed. The rules need to encourage technological development and innovation, safeguard the marine environment, and offer legal security and certainty for good governance in a maritime area that's rapidly changing with new technologies (Mazzuto et al., 2024). The rules of the game regarding the manning system and the Collision at Sea Doctrine are also concerns. Conventional vessels' SOLAS and COLREGs were not necessarily designed for the autonomous-vessel world and may therefore not apply to all situations, potentially causing concerns. Under UNCLOS, the primary responsibility lies with a state through the registration of the ship (Chae, 2025).

Economy Business Models Transformations

Sustainable solutions are integrated into newly developed business models, and they even affect the global economy. A paradigm shift from linear to circular resource extraction, production, and disposal models has been initiated to maximize resource efficiency and minimize waste generation (Bertram & Van Coppenolle, 2024). Meanwhile, innovation in the maritime sector is transforming the way things are done with digital tools like blockchain traceability, smart logistics and simulation by digital twins.

Social Equity Dimensions

Social equity is an integral part of environmental and economic development; it must be achieved through inclusive and equitable access to opportunities and resources. Numerous examples worldwide show high levels of social exclusion, particularly economic, geographic, and racial. Employment, income, household registration, and more affect perceptions of social justice (Nguyen et al., 2023; Zhao et al., 2024). Thus, the adoption of policy and legislation that seek to achieve both environmental and social benefits ought to guarantee the right of marginalized groups, defined here as rural communities, low-income families and ethnic minorities, to access the benefits of sustainability policies (X. Wang & Liu, 2022). This digital divide, especially between rich and poor countries, has made it even harder to achieve social equality. For instance, in the maritime industry, developing countries lack the facilities needed to establish automated shipping systems with fail-safe mechanisms that comply with COLREGs and maritime laws (Xia et al., 2024). Smart ports and autonomous fleets in advanced economies may exclude developing countries, while advanced economies may be reluctant to venture beyond their existing networks of ports and providers (Akpan et al., 2022). Furthermore, seagoing jobs, a key source of employment in the Global South, are at risk from the automation of maritime operations, and questions remain about whether the protection offered by the ILO Maritime Labor Convention is sufficient. Multiple scholars have urged a comprehensive approach to technology transfer, as in the case of the UN Framework Convention on Climate

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Change, to make productive involvement in the new blue economy more inclusive (Exarchopoulos et al., 2018).

Figure 1. Accountability in Autonomous Shipping Failures

Belligerent Pollution and Environmental Sustainability

Traditional Western understandings of industrialization have been more oriented toward economic issues and have resulted in significant environmental harm (Bilawal Khaskheli et al., 2025). In contrast, the Chinese model is pragmatic in both governmental and economic terms and is anchored in a philosophy of sustainable development. It builds on and is underpinned by established cultural principles and values, recognizes the harmony between human action and nature, and moulds public and decision-makers' perceptions of resource management (Elhaw, 2023). China's recent reform focuses more on pollution prevention and control and on monitoring environmental effects. The outcome framework seeks to integrate development needs with conservation issues. It is expected to shift from a traditional emphasis on extractive development to an emphasis on ecologically balanced and sustainable development and conservation. One important aspect of this change is to do it up front and at a whole-of-system level, rather than 'end-of-pipe' and reactive (Y. Wang et al., 2022). Yet direct emissions from infrastructure offset some of the pros, including the extraction of rare earth elements and energy-consuming data centers (Z. Wang et al., 2025). This discrepancy is thought to stem from the lack of compulsory rules to pursue RE in digital systems, and whether and how digital systems can contribute to RE has not been fully revealed (Gkatsikos, 2025; Talha, Noor, Mingfei, et al., 2024). Although the Paris Agreement of 2015 prescribes clear limits on GHG emissions, maritime activities continue to add to overall environmental pressure that must be reduced to achieve sustainable outcomes (Rajamani, 2024).

Circular Economy Principal Integration

The social justice dimension of ecology and economic development must be inclusive; that is, it should involve access to resources and opportunities. Sustainability policies should not disadvantage social actors already excluded, such as low-income people, ethnic minorities, and rural inhabitants, nor should they neglect the societal need for an equal distribution of services if

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the goal is a more equal and just society (Geissdoerfer et al., 2017). This way of thinking will help foster the good of the community and its environment, thereby creating inclusive opportunities for development. The digital divide further worsens this inequality, as investment in independent shipping technology and intelligent ports grows unevenly across the richest countries. But less developed countries have not yet become part of the world trading network because they still lack infrastructure (Korhonen et al., 2018). This gap restricts economic participation and also threatens compliance with decent work standards under the International Labour Organization (ILO) Maritime Labour Convention (MLC) (Talha et al., 2026; Weissbrod & Bocken, 2017). Furthermore, the transition to automation is affecting seafarers' livelihoods, as the maritime industry is a key contributor to the national economies of the Global South (Rodrigues et al., 2025).

Identified Literature Gap

The latest research on the sustainable governance of the maritime industry shows that digital transformation, environmental sustainability, and legal reforms are areas of growing interest. However, our literature review shows that these topics remain fragmented, and research across these theme areas is uneven, as shown in *Table 1*. We have compiled the most significant research needs systematically under five broad categories: legal and regulatory frameworks, technological innovations, environmental governance, socio-economic and equity issues, and interdisciplinary approaches. These categories highlight areas that need further exploration and integration to develop a coherent understanding of sustainable maritime governance.

Table 1. **Key Gaps and Suggestions in Advancing Sustainable Maritime Digitalization**

Gap	Explanation	Suggestions
Legal and Regulatory Gaps	Existing legal frameworks (UNCLOS, BBNJ, national laws) don't fully adapt to digital technologies in shipping.	Adopt and harmonize regulatory frameworks on a cross-jurisdictional level in order to create standards for autonomous vessels, data governance and real time monitoring.
Technological Gaps	Limited integration of digital tools for risk management and environmental protection.	Develop solutions that work at both small and large scales, such as AI prediction and ecosystem monitoring for sustainable operations.
Environmental Governance Gaps	Lack of coordination between digital technology use and environmental protection frameworks.	Create interdisciplinary efforts in environmental law, technology, and governance to implement integrated environmental pollution monitoring and environmental law enforcement.
Socio-economic and Equity Gaps	Developing countries are underrepresented in digital maritime initiatives.	Encourage inclusive governance processes and build local capacity in developing countries, so that digital maritime technologies are used equitably.

Interdisciplinary Research Gaps	Few studies systematically link legal, technological, economic, and environmental perspectives.	Maintain more powerful interdisciplinary arrangements to tackle complex shipping and governance issues with holistic solutions.

Research Methodology

The research uses primary research from reliable, credible sources, including the World Database and lessons learnt from the Global Environmental Protection Agency (GEPA) and other international agencies, as well as secondary data from academic sources. The study examines digital approaches to promote sustainable management of dietary governance, the marine economy, and environmental compliance, and to reduce shipping risks. The paper reviews key international acts and agreements applicable to maritime activities, such as International Maritime Organization (IMO) Regulations, United Nations Sustainable Development Goal (SDG) 14, the Paris Agreement, and the United Nations Convention on the Law of the Sea (UNCLOS). Other sources of information include the activities of organisations involved in international marine conventions, such as the United Nations Environment Programme (UNEP), the European Commission (EC), and the Helsinki Commission.

The study also reviewed literature and academic claims related to the environment to obtain secondary data for the results and discussion sections. To support this understanding of the interactions between technology, law, and the environment, the proposed work combines legal, technological, and environmental aspects. It pinpoints stakeholder responsibilities, including those related to legislation on autonomous systems. This involves enhancing risk management, maritime law enforcement, and governance, with the potential to support shipping companies risk management and contribute to the sustainability and responsibility of the marine environment and the digital maritime economy.

Results and Findings

Key developments in economic and business models for sustainability, digitalisation, and Business Model Innovation will be analyzed. Case studies are provided, including success stories on green technologies; international businesses adopting green technologies for Sustainability (International Business Machines Corporation (IBM) applying green technologies for Sustainability case study); and environmental technologies (Food Trust (IBM) case study). Furthermore, tools and concepts now allow the considered integration of sustainability into business practice, including the EU AI Act, the Circular Economy Action Plan, etc. (Cancela-Outeda, 2024). These cases reflect the industry's future and profitability, focusing on technology, regulations, and green finance. Meanwhile, they continue to promote green protection.

Shipping is Stumbling All Over the World

Today's shipping world faces pressure, with challenges ranging from low growth rates and higher shipping costs to uncertainty in a fast-changing environment of hot spots and shifting trade routes and configurations. Maritime traffic is expected to rise slowly in 2025, with at least a 0.5% increase, following a solid 2.2% increase in 2024, in line with the United Nations Conference on Trade and Development (UNCTAD) Review of Maritime Transport 2025, released on September 24th (Xu & Chen, 2025). These developments are turning the picture of world shipping upside down, and, as Figure 2 shows, new and changing trade routes are also reshaping the geography of global commercial activity. In the past, it used to take days to travel from one place to the next across the Red Sea; today, it takes weeks. As a result, shifting costs, rising and unpredictable shipping costs, supply chain tensions, and the closure of several ports across the nation have created a longer, more meandering shipping route (Gu et al., 2023). This has led to a rise in ton-miles, a measure of distance travelled per ton of cargo, of 6%, almost twice as much as the increase in actual trade volume. At the same time, cargo traffic via the Suez Canal has dipped significantly as security worries in the Red Sea persist. In 2024, disruptions were highest in the first quarter, and over half of the transits were lost compared to the pre-crisis period. There were signs of recovery in much of the latter half of 2024; however, traffic was much depressed in much of 2025 (Tsao et al., 2025). In some months, container shipments did not fall compared with the pre-peak period, with about 75 vessels crossing daily (Shen et al., 2025). By the end of 2025, the government reported less improvement in the number of ships or tonnage than in July. However, some container companies remained reluctant and decided to sail around the Cape. The shipping industry has also expressed significant concern about possible disruptions at other critical maritime choke points, including the Strait of Hormuz (Mycoo & Roopnarine, 2024). Approximately 20% of the world's petroleum liquids and over 25% of the world's seaborne oil trade pass through this narrow waterway, and these figures remained static through 2024 and into 2025 (L. Wang et al., 2025). These vulnerabilities highlight the fragility of sea lines used by the international shipping industry, the role of geopolitics in driving large, lasting logistical impacts, and unprecedented increases in operating costs for international shipping.

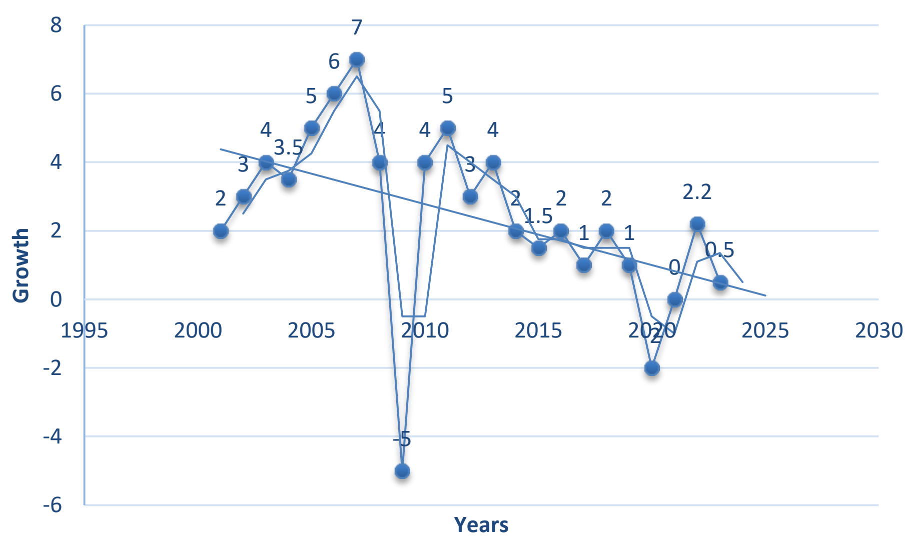

Figure 2. Maritime Trade Growth

Maritime Cargo Rerouted

Converging developments increasingly influence maritime trade trends. With tariffs and port fees on Chinese-built or -run ships higher for container or trans-Pacific shipping, shipping costs in the United States will rise, and shipping uncertainty will increase as these tariffs and fees are implemented (Yang et al., 2020). These measures can also distort the movement of goods and put upward pressure on import prices, as illustrated in Figure 3. However, the future of retail sales of commodity energy products is less clear. Decarbonization efforts have created a long-term downward trend, but peaks have occurred due to high demand in Asia and changes in sourcing strategies (De et al., 2021). Overall, oil volumes have not changed much, although shorter routes are increasingly being avoided to slow supply chains through reduced transit options and rerouting around conflict zones and sanctions (De et al., 2021). Meanwhile, LNG trade has boomed, with alternative sources meeting energy needs in Europe and Asia and with newly emerging export capacity.

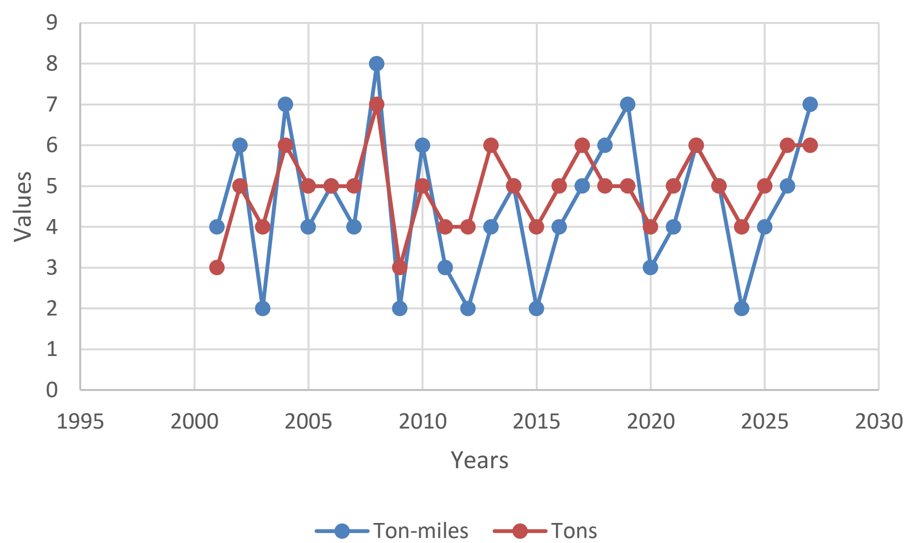

Figure 3. Rerouting of Voyages with Volumes of Energy

The Period of Persistent Volatility of Freight Rates

Container shipping is now characterized by higher rates at times and lower rates at other times. Because of supply-demand imbalances, changes in trade policy, and rapid shifts in the geopolitical landscape, the market outlook is unclear. These factors have contributed to unprecedented volatility in the container business, particularly in dry bulk and tankers (Liu & Wahab, 2025). After the dislocations in the Red Sea, spot and time charter rates soared early in 2024, and more normal levels began to reemerge (Kavussanos et al., 2026). Despite the partial adjustment, rates were still quite high, even as pandemic COVID-19 adjustments were made. Other factors, such as growth normalization and demand characteristics that failed to materialize, also weighed on rates. It remains plagued by supply-chain friction and fuel price volatility (Tarkun, 2025). The new conflict on the international stage relates to critical minerals vital for digital technologies and renewable energy infrastructure, as illustrated in Figure 4. This increases stress on maritime logistics by congesting it, driving investment in international stocks of the products and processing facilities in those countries, and heightening geopolitical considerations (Sun et al., 2025). These pressures are compounded by greater structural turmoil and complexity in building supply chains for key commodities, with the potential impact of disruption greatly outweighing the shipping costs (Yeassin et al., 2025).

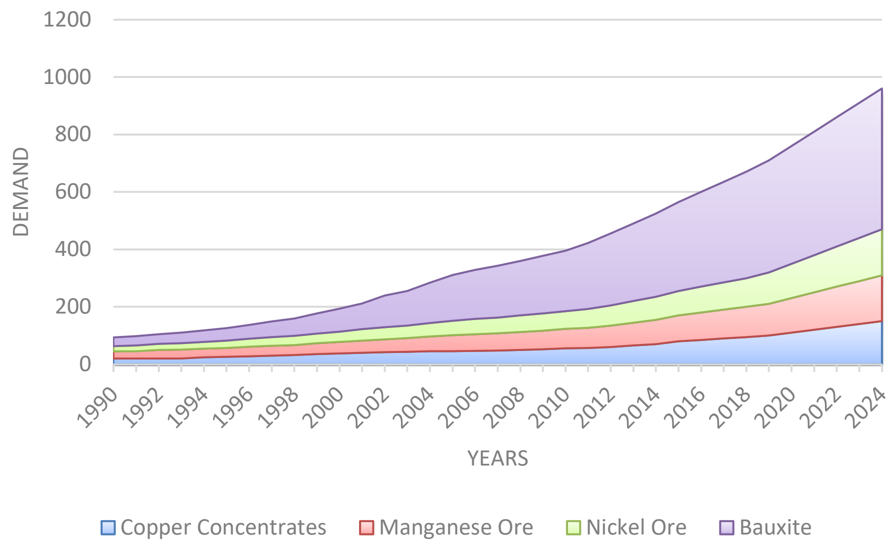

Figure 4. Rising Demands Boost Critical Minerals

Transformation of the Maritime Energy Trade

Energy markets have been completely redesigned in the maritime sector. The price of crude oil, the most traded energy commodity, slowly decreases (red line) from just above 8,500 thousand to around 6,500 thousand. Oil consumption still remains one of the energy sources that the world heavily depends on, and currently the reduction would only be up to 2016 (A. Sardar et al., 2025).

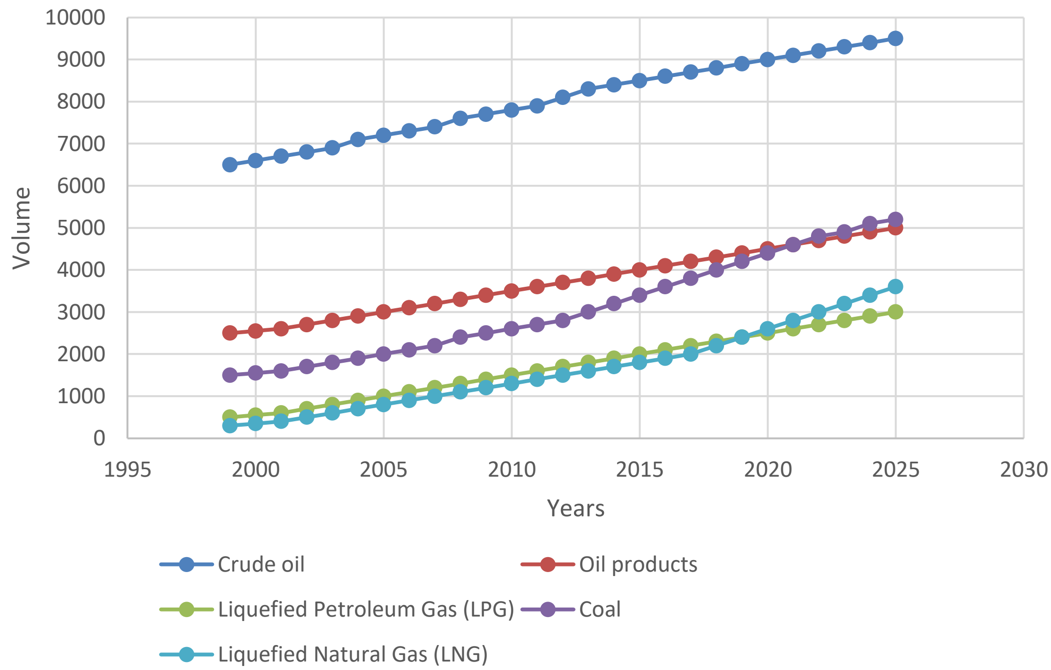

Figure 5. Maritime Energy Trade

Meanwhile, the use of oil products has grown from some 2,500 thousand in 1999 to 5,000 thousand in 2025 (Q. Wang, 2024). This growth indicates rising global demand for refined petroleum products. The development of terminal facilities to receive LNG expanded most quickly, having increased from approximately 300 thousand tons to over 4,000 thousand tons in 1999. This will be a significant improvement and will make LNG a far more environmentally friendly fuel than coal or oil (Galimova et al., 2025). LPG (Liquefied Petroleum Gas) consumption also grew to almost 3100 thousand units in 2006, up from 500 thousand in 1999 (Vaca-Cabrero et al., 2026). As shown in Figure 5, total energy consumption from coal fluctuated only a few times and reached its highest level at around 5,200 thousand units, indicating declining energy consumption due to substitution with cleaner fuels.

Analysis and Discussion

The marine economy is wide-ranging, encompassing shipping, fisheries and aquaculture, tourism, offshore energy and marine biotechnology. Although pressure to exploit these resources has increased markedly globally, there is a trend toward sustainable exploitation. In turn, Marine industries are increasingly leaning towards Digital technologies such as Artificial Intelligence (AI), Internet of Things (IoT), Big Data Analytics, Remote Sensing, and Blockchain (Gavalas et al., 2022). These technologies ensure optimal use, minimize pollution, and simplify compliance. Machine learning and AI can optimize shipping and fishing routes and fuel consumption by predicting the likelihood of certain cargo or fish appearing at particular locations. If IoT sensors can collect water quality and marine biodiversity data and automatically control the water environment, then regulation of the water environment will be possible (Miller et al., 2025). Further, blockchain-powered tracking and tracing of seafood is significant in combating illegal, unreported, and unregulated (IUU) fishing. They complement each other and are crucial components of a blue economy solution for sustainable management of marine resources.

However, several problems must be addressed before digital technologies can be applied in the marine industry. Non-uniformity of technologies across regions is one challenge. Many developing countries lack access to information and digital tools because of limited resources or know-how to use the latest digital technology (Baghizadeh et al., 2025). Pace remains a challenge, as do information security and the standardization of vast improvements in marine information. The lack of consistent data formats and protocols for classifying and sharing information makes it harder to integrate and share data and stunts collaborative efforts in marine research and management (Sahu et al., 2025). But environmental problems are also associated with digital technologies, such as energy requirements and e-waste. Although digital processes can improve efficiency, they require careful consideration and can contribute to renewed environmental degradation.

The United Nations Convention on the Law of the Sea (UNCLOS) is the key international legal agreement both governing and protecting ocean resources. UNCLOS provides recommendations for the "sustainable" utilization of the resources of the sea, as well as recommendations on protecting the marine environment (Dong et al., 2024; Franckx, 2023). UNCLOS Article 13 of Part XIV and Chapter 13 of the Convention also address the development and transfer of marine knowledge and technology, including equitable access to marine technology for developing countries to support the conservation and sustainable utilization of marine resources. Article 266 of UNCLOS places particular emphasis on promoting marine scientific research and technology transfer to developing States to build their capacity to manage marine resources (Franckx, 2023; Humphries et al., 2020). Furthermore, the commitment to "marine environmental protection in connection with marine scientific and technological research" is found in Article 145 of the UN Law of the Sea Convention, and this should be done "principally in the interests of the protection of the marine environment" with special attention being paid to "precautionary and environmental protection measures about marine technology" (UN, 1982).

However, other international documents and activities have also supported sustainable practices in the Marine environment, in addition to UNCLOS. Adopting the UNCLOS treaty on the conservation and sustainable exploitation of the marine living resources of the high seas is an important step in this regard. This was concluded in 2023 and is known as the High Seas Treaty or BBNJ agreement (UN, 2023; Zhou, 2026). The treaty outlines principles and directions for countries to apply when biodiversity is being exploited in areas that belong to other countries as well, such as through creating marine protected areas and carrying out environmental impact assessments before undertaking activities that might affect the environment. It especially emphasizes the growing need for international scientific cooperation and capacity building. It aims to build on the wording of UNCLOS to provide developing countries, in particular, equal access to marine technologies (Friedman, 2024). For the treaty to succeed, it must be signed on a large scale and properly implemented, and the international community will play a role in ensuring compliance.

Adopting digital technologies can significantly change how ocean activities are conducted and offers a potentially transformative way to improve the efficiency and sustainability of ocean economic activities. But realizing this requires a combination of technological advancement, adaptive legislation, and robust governance, among other (Janmethakulwat & Thanasopon, 2025). UNCLOS remains the framework and sets the overall principles for sustainable resource use, while technology transfer and capacity building remain important parts of the equitable process of using resources. To address these challenges, three key aspects will need to be considered: capacity development and the equitable sharing of benefits arising from sustainable international cooperation; biodiversity and sustainable development; the digital challenge in relation to the necessary blue economy transition; and a sustainable moratorium focused on resilient and sustainable pathways of development. Ultimately, this innovation and evolution of legal and institutional systems will shape the extent to which the legal sector can deliver on its higher potential.

Conclusions and Recommendations

In the marine market, the progress of digitization for smart fishing and for integrating digital technologies that potentially support smart monitoring systems like artificial intelligence or emission tracking systems based on blockchain technology, as well as autonomous underwater drones, has made a huge step in line with global sustainability objectives. These innovations could transform the industry by improving efficiency and sustainability across many marine businesses. This development is, however, severely limited by the lack of international marine law, particularly regarding jurisdiction over international deep-sea data collection and the transfer of marine data between states. These issues are still being addressed in conventional treaties such as the United Nations Convention on the Law of the Sea (UNCLOS), which was not framed with fast-changing maritime technology in mind. The UN High Seas Treaty, also known as the BBNJ Agreement, represents a landmark effort to address salient gaps in protecting marine biodiversity and in the equitable and fair distribution of benefits from the use of the High Seas. Despite this, the treaty's implementation mechanisms are less than ideal and cannot match the power of the technologies it seeks to regulate.

In this regard, China has proved itself a pioneer, with legal innovation and global reach. China is the second-largest economy globally, and its legislation, including the “Anti-Unfair Competition Law” (2025) and reporting obligations for rare earth production, has been adapted to implement digital market legislation and environmentally sustainable practices. Furthermore, the Hainan Free Trade Port showcases China's commitment to marine conservation, such as coral reef protection and the use of digital tracking technologies. These regional efforts reinforce cooperation with the Association of Southeast Asian Nations (ASEAN) to share information and collaborate through research. Moreover, China's leadership in international ocean science and technology cooperation, including the UN Decade of Ocean Science and the Digital Twin Oceans program, promotes the sharing of ocean information and skills, particularly in the Global South. Yet obstacles remain. However, regionally divergent legislation strongly affects cross-border maritime logistics and data management, with stringent data-control laws such as the European Union's General Data Protection Regulation and the Digital Services Act. While these tools can, and should, enable privacy and accountability on the platform, they can also hamper the free flow of information, an essential feature in integrated supply chains.

However, there are multiple ways to improve ocean governance. Besides improving multilateral mechanisms, including the Clearing-House Mechanism of the Agreement on Marine Biodiversity of Areas Beyond National Jurisdiction, modernizing existing core international tools to capture digitalization is a priority. Expanding PPPs can also help equitably spread technology and capacity-building activities across jurisdictions. China is a regulator and technological leader, suggesting a strong future role in building a united global framework for the blue economy. These contributions illustrate that, from an environmental perspective, economic growth does not necessarily conflict with strong economic performance, but can be compatible and complementary in meeting shared sustainability objectives.

Recommendation

More research is needed on the role of digital technologies in marine sustainability, including new opportunities and challenges. This research should include life cycle estimates of the environmental impacts of digital technology, social and economic impact assessments, and ongoing assessments of policy interventions to ensure policy meets sustainability objectives. All actions must ensure digitalization is possible across sectors, with particular attention to whether this is possible in the developing world, especially for small-scale operators. This encompasses physical facilities and technology transfer programmes, as well as ongoing learning mechanisms and digital education programmes. International cooperation programmes, such as the United Nations Decade of Ocean Science for Sustainable Development, should prioritise capacity building for sustainable digitalization. Governance structures are needed to ensure coherence in addressing the challenges digital technologies may bring to the marine sector. Such mechanisms should not only permit data use through clear, transparent data-management arrangements, but also safeguard IP rights over marine data and implement other measures to ensure effective, sustainable operations, such as the various measures being developed under the IMO's carbon

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intensity indicators. Innovation ecosystems could be built through collaboration among technology providers, operators, researchers, and regulators to bridge the gap between technology and sustainability. Beyond national and international efforts, broader socio-technical change requires concerted local action. Digital tools can improve human welfare and conserve ocean ecosystems through the Blue Economy.

Limitations of Study

This study has several limitations. First, information on the long-term ecological impacts of marine digital technology is limited, especially in deep-sea habitats. Second, the outgoing and reverse currents of international norms and uniform enforcement systems across jurisdictions make global governance difficult. Many laws are defined by treaties that are publicly accessible and may not align with a country's more recent policies. An innovation may outgrow a regulatory system's capacity to keep pace, and feasibility studies are usually written for developed nations and may not address issues facing resource-poor areas. Third, a lack of interdisciplinary communication among technological progress, marine environmental sciences, and law makes comprehensive sustainability analysis difficult. These limits indicate the need for big-data-sharing systems and cross-border governance. Furthermore, this work does not adequately account for the legal, policy, and technical requirements for digital and autonomous maritime systems, including the application of frameworks like the Maritime Autonomous Surface Ships (MASS) Code, the legal interpretation of COLREGs, IACS Unified Requirements (UR E26/E27), and IEC 62443 cyber-physical security certification.

Future Research Directions

Several new fields have been identified for exploring and enhancing the positioning of digital technologies for sustainable marine management, and these are recommended for future research. Future studies are also needed to develop smart systems to predict and optimize marine resource exploitation, and to use blockchain as a communication platform to improve transparency in the marine resource value chain. The present research addresses this need by examining digital systems in detail from a sustainable maritime regulation perspective. Future activities will focus on integrating operational observation and validation activities to enhance operational management and shipping operations to meet the needs of our marine environment. This year, research trends include quantum computing and its application to maritime systems, Cyber-Physical Security for Underwater IoT (UwIoT), and Climate modeling for Coastal Ecosystems. Further studies are recommended to explore the socio-economic impacts of autonomous fishing technology in coastal communities and enhance understanding of ethical considerations for using AI in fisheries management. Next steps will involve research to develop biomimetic sensors inspired by marine organisms and to produce interoperable "digital twins" across various marine research disciplines. New research areas are opened up with the potential of mixed reality technology, for instance in the field of digitalization in Arctic shipping and marine space planning. Indigenous Environmental knowledge could be integrated with existing digital systems through a cross-cultural approach. This could offer clues on how traditional and modern science might be merged in the future to protect and promote marine resources.

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