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Original Research Article

Sustainable Ship Design for the Red Sea and Arabian Gulf

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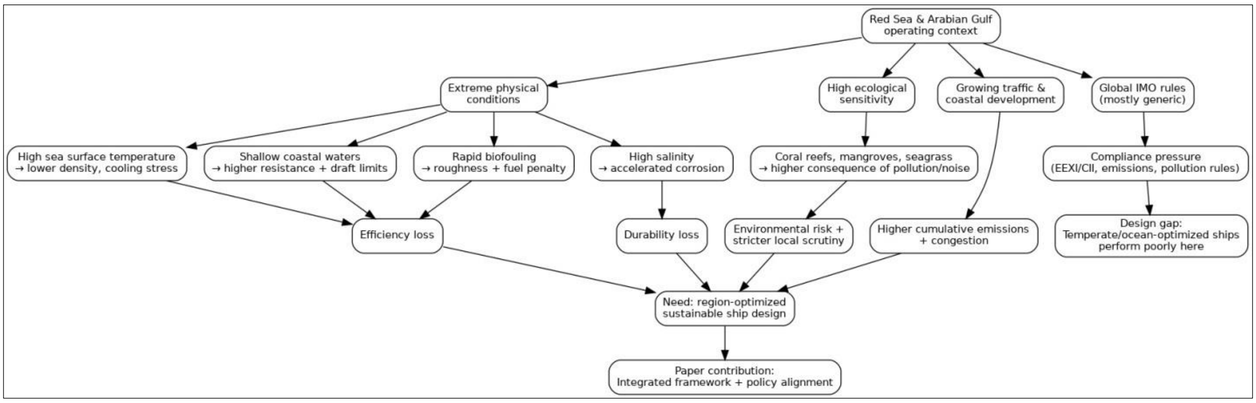
Abstract: Two of the most environmentally critical and operationally challenging maritime environments anywhere in the world are the Red Sea and the Arabian Gulf. The shallow waters and high salinity levels, along with unprecedented sea surface temperatures and growing traffic from commercial vessels, are presenting major challenges to conventional design concepts that are highly unlikely to overcome the challenges for ship designs. In addition, there are global environmental statutes and regional sustainability agendas, especially within the Middle East, which put a greater focus on greener and more efficient maritime practices. This paper presents an examination of sustainable ship design concepts, focusing specifically on the environment of the Red Sea and the Arabian Gulf. The present paper critically reviews major dimensions of ship design, such as ship optimization, propulsion systems, energy-efficient technologies, alternative fuels, and environmentally adaptable materials, through a comprehensive review of recent developments in naval architecture with an analytical synthesis of advances made in marine engineering and sustainable technologies. Furthermore, this research also identifies the applicability of new concepts of sustainable ship design regarding international maritime legislation and regional policy, considering sustainability factors involved with regional economic and environmental growth. The research shows that fuel efficiency, emission reduction, and consequently environmental protection could be substantially achieved with regionally tailored design approaches, along with improved ships' operational performance and reliability. A conceptual framework for sustainable ship design, incorporating environmental constraints, adopting technological advancement, and adhering to regulations, has been presented in the paper.

Keywords: Red Sea, Arabian Gulf, Green Shipping, Decarbonization, Fuel Efficiency.

INTRODUCTION

With more than 80 % of international cargo being transported by maritime transport, it forms the backbone of international trade. ((UNCTAD), n.d.) It is a very crucial form of transport in ensuring the development of the economy and regions in terms of connectivity. However, the shipping sector has equally been a source of environmental challenges with greenhouse gases, pollution, and degradation of ecosystems. This problem has proven even greater in areas such as the Red Sea and the Arabian Gulf because of the environmental conditions of the region. Such prevailing conditions call for great measures during the design of vessels for the region. The salinity levels are also high in the Red Sea and Arabian Gulf, but with correspondingly high surface temperature levels, low rates of circulation, and large areas of shallow coastal waters. These conditions mean a high degree of hydrodynamic resistance, material degradation, and biofoulant growth, leading to poor vessel performance and higher operating costs. (Analysis of the spatio-temporal variability of seawater quality in the southeastern Arabian Gulf, 2016, pp. 127-138) However, the environmental sensitivity of coral, mangrove, and seagrass marine ecosystems also accentuates the environment-related risk associated with conventional forms of shipborne transportation. (Almahasheer *et al*., 2025) Therefore, environmentally favorable ship design has greater local relevance with ongoing increases in freight traffic generated by expanding energy trade, containerized commerce, tourism, and large-scale coastal development projects. The global concerns about the environment have prompted the global maritime community to introduce a number of regulatory instruments with the aim of minimizing the impact of marine activities on the environment. There are very strict regulations by the International Maritime Organization on issues such as maritime energy efficiency, emissions control, and prevention of marine pollution. The regulations have therefore forced maritime designers and operators to adopt very eco-friendly technologies as well as design strategies for more efficient ship designs. However, the regulations have not considered maritime regions individually, such that ships originally designed for temperate waters in open oceans will operate inefficiently in the Red Sea and Arabian Gulf. In this perspective, therefore, sustainable ship design applies as a holistic solution. The sustainable ship design approach ensures that environmental considerations are taken into account in all phases throughout a ship's life. What distinguishes this methodology from all other design methodologies is its emphasis on energy efficiency, low emissions, durability, and virtually no impact on the surrounding environments.



To this end, there is a need to further optimize ship shapes, ship drives, ship cooling systems, and coatings in order to be able to continue working effectively in hot and saline waters without building up maintenance problems. From all these perspectives, it is evident that the high strategic importance of the Red Sea and Arabian Gulf waterways further proves that sustainable design for ships is relevant and significant for this particular area. These waterways have high potential for international trade exchange between Europe, Asia, and Africa; at the same time, they have an important part in regional moves towards the diversification of economies within these regions. (Choramo *et al*., 2024) In recent times, countries within the Middle East have shown a much higher inclination towards sustainability as a means of long-term development. Massive investments towards green infrastructure development and sustainable energy have shown promising moves towards the sustainability of economies within these regions. (Rowe, 2025) The maritime sector would notably contribute to these economies on the road to sustainability. However, despite the increasing interest in green shipping and energy-efficient vessels, the existing literature pursued a general approach, and shipping trends were emphasized as opposed to region-specific requirements for designing and developing such vessels. In addition, literature surveys have been conducted about the viability of particular technologies, including alternative fuels and/or energy-efficient devices, which did not take regional environmental factors into account. (Environmental regulation on the energy-intensive container ship sector: A restraint or opportunity?, 2021) The gap that intrinsically exists within the realm of existing literature is, therefore, concerning an integrated approach toward designing and developing vessels, keeping in view regional complexities relative to the Red Sea and the Arabian Gulf. This paper seeks to fill this gap by considering the elements of sustainable ship design for which conditions in the Red Sea and Arabian Gulf are relevant. Based on a synthesis of naval architecture, marine engineering, and maritime policy studies, the paper addresses how sustainable ship designs can be implemented for optimal energy efficiency, emissions, and environmental impact, besides reliability, and discusses also the level of compatibility between sustainable ship design and the changing policy, regulation, and dynamic innovation. The rest of the paper is organized as follows: After this introductory section, an overview of existing literature with respect to sustainable ship design and green technologies for ships, especially with reference to ship operations in high-temperature and high-salinity environments, is presented. Then, the analysis of the Red Sea environment as well as Arabian Gulf environment, and suggestions for a framework of sustainable ship designs are presented along with overall policy and regulation issues. The paper concludes with suggestions based on the findings, especially for ship designers, operators, and how sustainability can improve operations within this region of geopolitical importance.

LITERATURE REVIEW

The incorporation of sustainable ship design appears to be a major aspect of maritime engineering and environmental science studies. This can be mainly attributed to factors such as the pressures from maritime regulators, fuel costs, and environmental factors surrounding shipping activities. Studies based on the literature have shown that sustainable ship design involves a comprehensive package of factors such as energy efficiency, reduction of emissions, life cycle assessments, and environmental concerns, but with strict emphasis on ship safety. Although based on literature, an indication of sustainable ship design from a theoretical framework appears possible, its applicability to region-specific maritime conditions in the Red Sea and Arabian Gulf may be dubious. Under this discipline, much literature can be tracked on ship energy efficiency as well as emission mitigation. The researchers studied hull optimization, propeller-hull relationships, and other measures of energy efficiency like ducts, fins, air lubrication, etc. The studies reveal that fuel savings can be obtained with a reduction of 5-15 percent under optimal conditions. (Decarbonising Maritime, n.d.) During these experiments/simulations, the temperature and salinity were moderate, whereas these conditions in the Red Sea as well as the Arabian Gulf are more severe. Water temperature as well as salinity increases under more drastic temperature-salinity conditions, which represent a very high level of hydrodynamic resistance. (Escobar *et al*., 2016, pp. 325-336)Another field of research is alternative fuels and clean propulsion systems. Among such alternative fuels, as mentioned earlier, liquefied gases, methanol, biofuels, hydrogen, and ammonia have drawn significant attention towards their potential as alternative fuels for reducing the emissions of GHGs from the marine transportation sector. Some of the publications mainly emphasize the reduction potential of the mentioned fuels, particularly towards the emissions of sulfur oxides, nitrogen oxides, and particulate matter. (Alternative fuels to reduce greenhouse gas emissions from marine transport and promote UN sustainable development goals, 2023) At the same time, significant challenges associated with the efficient use of alternative fuels have also been noted and discussed in the published literature. (Lin, 2024, pp. 1-9) Apart from this, keeping the weather conditions, such as temperature, prevailing in the specific region of the Red Sea and Arabian Gulf in mind, significant challenges have also been noted for alternative fuels, such as their stability and storage systems along with cooling requirements; however, a relatively lower number of such published literature is available on a specific region. (Alternative Fuels in the Maritime Industry: Emissions Evaluation of Bulk Carrier Ships, 2025)Material selection and coating is another important attribute of sustainable ship design. It can be ascertained that selection of appropriate materials for reducing corrosion resistance, as well as coatings that reduce biofouling, can reduce maintenance costs considerably because they control hull roughness. (Steffen, 2025, pp. 1-7) It is extremely important in such environments because the rate of corrosion is high, especially in such environments due to high salinity, which is usually higher than that of the average values of the global environment. (Chohan *et al.,* 2024) A study done on coatings such as silicone-based coating and other biocides-free coating products has shown promising results for conserving the environment, but there is little observed effect of such coatings in Red Sea and Arabian Gulf environments. (Sustainable Marine Coatings: Comparing the Costs, Benefits, and Impacts of Biocidal and Biocide-Free Paints, 2025) In most cases, assumptions are made during ship designing. Added importance has been laid upon environmental impact studies and lifecycle analysis in maritime as well. The methods discussed above are based on lifecycle analysis. Thus, sustainability can only be achieved in reference to emissions, materials used in building the ships, and recycling. It can be observed that most of the lifecycle analysis of the phenomena is being carried out on a global scale, but there seems to be no reference made in any of the studies about regional ecological elements such as the presence of reefs and water current trends, which are characteristics of the Red Sea and Arabian Gulf. (Sengupta *et al*., 2023) From a regulatory point of view, there is existing literature on regulations regarding the maritime environment, but there is also research on the impact of such regulations, especially regarding the maritime environment, in encouraging technological developments in ship designs. (Effects of regulation-driven green innovations on short sea shipping's environmental and economic performance, 2020) There is also a concern as shown by the literature, indicating that these regulations handle problems inflexibly, failing to consider regional differences in environmental threats. Adaptation of the design is also indicated as a gap in existing knowledge, especially regarding semi-enclosed seas. Overall, it is very evident that the current literature promotes a common trend with a clearer understanding of the benefits of sustainable design, yet there is a notable lack of a common framework concerning extreme conditions within respective regions, particularly with regard to the Red Sea and Arabian Gulf, taking into account the economic significance of those regions. With regard to the above, there is a notable lack of a systems approach within respective issues, with most relevant works being based on individual subjects rather than a generalized approach, as follows.

Table 1: Summary of Key Literature Themes in Sustainable Ship Design

Research Theme	Key Focus Areas	Limitations Identified
Energy-efficient hull and propulsion design	Hull optimization, propeller efficiency, energy-saving devices	Limited validation under high-temperature and high-salinity conditions
Alternative fuels and propulsion systems	LNG, methanol, hydrogen, ammonia	Infrastructure and thermal stability challenges in hot climates
Materials and coatings	Corrosion resistance, anti-fouling technologies	Lack of long-term regional performance data
Lifecycle and environmental assessment	Emissions, resource use, end-of-life impacts	Insufficient consideration of regional ecological sensitivity
Regulatory and policy analysis	IMO standards, compliance strategies	Limited regional adaptation of global regulations

Environmental and Operational Challenges of Red Sea and Arabian Gulf

The environmental and operational condition of the Red Sea and the Arabian Gulf is such that it makes them peculiar in coping with the challenges that have direct implications on the ship's efficiency, durability, and environmental friendliness. In contrast with the hydrodynamical conditions of the other navigation routes, where the hydrodynamical characteristics can be described only by an average temperature, the Red Sea and the Arabian Gulf possess extreme climatic, chemical, and ecological properties. This work thus proves the necessity of developing ship designs pertinent to the region's operative requirements. Probably the most distinguishing environmental factor of these regions is their high level of sea surface temperatures. For instance, on an average, the temperatures of the water in these regions are higher compared to other regions across the world, especially during long summer seasons. For example, such high levels of water temperature will result in low densities of water, which affects propulsor and buoyancy levels, among other factors. In addition, such temperatures will affect cooling systems, where such systems as engines might perform worse. The salinity of water in the Red Sea and Arabian Gulf still remains one of the highest recorded anywhere in the world due to extremely high rates of evaporation and scarce availability of fresh water. (The Physical and Biogeochemical Parameters along the Coastal Waters of Saudi Arabia during Field Surveys in Summer, 2021, 2024) The increased average rate of salinity hastens all corrosion processes in metallic structures, pipe systems, and components of machinery equipment. Regular operational issues could include severe damage to hull surfaces, increased rates of corrosion of ballast tank surfaces, and a shortened lifespan of power equipment components. These factors heighten the need for superior operational resource strategies in guaranteeing a long and safe lifespan at sea. The complexity is further added by the maritime operation in the shallow coastal water areas and restricted zones. A great deal of the Arabian Gulf is characterized by a shallow seabed area, which raises the dangers of grounding deep draft vessels. Shallow water effects increase hydrodynamic resistance, which, in turn, increases the fuel costs by virtue of decreased propulsion efficiency, especially when taking into account those vessels that are not specialized in maritime operations. The next important operational challenge in that region is biofouling. Warm waters provide optimal conditions that help marine organisms grow significantly on the hull surface, propellers, and sea chests. Marine growths can enhance the roughness in ship travels due to biofouling. Reports have proven that biofouling can cause fuel consumption levels to increase by over 20 percent during a vessel's normal operations. (IMO Study Shows Higher-Than-Expected Fuel Cost From Fouling, 2021) However, in sensitive environments, the current anti-fouling paint application poses problems in terms of toxic releases into the marine environment and its effects on marine wildlife, particularly in coral reefs and sensitive ecosystems. Besides, both of the aforementioned marine bodies can also be regarded as an environment sensitive zone. One of the strongest coral reef structures in the world has also been located in the Red Sea, and in addition, important ecological mangroves, seagrass, and fish nurseries are located in the Arabian Gulf. (Coral Reefs of the Gulf of Aqaba and the Red Sea in the Kingdom of Saudi Arabia, n.d.) Such sensitive marine structures are at a very high risk of accruing various types of pollution, temperature discharge, and physical impacts resulting from shipping. Oil spills, untreated ballast waters, and noise pollution in the sea pose a serious threat to environmental security, and as a result, the pressure on regulations and public complaints against shipping operations is bound to rise. The operational situation here is that shipping activities within this particular region are increasing at a very rapid pace, especially in terms of the exports related to energy, container vessels, cruising activities related to tourism, along with aspects related to coastal development schemes. (Container port competitiveness amid disruptions: Insights from the European maritime network during the Red Sea crisis, 2025) The density of shipping activities here requires that the vessels engaging in such activities should not only perform well but should also be able to match the increasing standards related to responsible activities for the environment and other regulatory controls. These environmental and operational constraints highlight, collectively, a truth that conventional ships, whose design has traditionally been predicated on what is effectively the normal world, may be considered to have limited use in one or other of the areas under consideration. Ships that are well-suited to effective use on the open waters of, say, the Pacific Ocean may be expected to suffer diminished efficiency, higher operational costs, and greater environmental impact when applied to one or other of the regions under consideration: the Red Sea, or the Arabian Gulf.

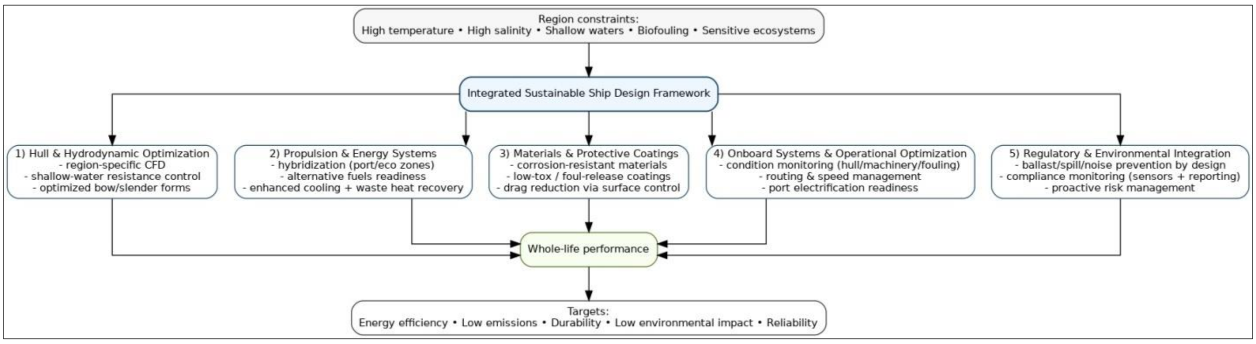
Table 2: Key Environmental and Operational Challenges Affecting Ship Design in the Red Sea and Arabian Gulf

Challenge	Operational Impact	Design Implications
High sea surface temperature	Reduced propulsion and cooling efficiency	Enhanced cooling systems, thermal-resilient machinery
High salinity	Accelerated corrosion and material degradation	Corrosion-resistant materials and advanced coatings
Shallow coastal waters	Increased resistance, draft limitations	Optimized hull forms and reduced draft designs
Rapid biofouling	Higher fuel consumption and emissions	Environmentally friendly anti-fouling technologies
Ecological sensitivity	Increased environmental risk and regulation	Pollution prevention and low-impact operational systems
Dense maritime traffic	Congestion and cumulative emissions	Energy-efficient operation and emission control systems

Sustainable Ship Design Framework for the Red Sea and Arabian Gulf

Thus, for developing a sustainable ship design for the Red Sea region, as well as for the Arabian Gulf, a holistic approach has to be considered wherein all the environmental conditions, needs, as well as design regulations, are integrated into a single concept of design philosophy. Generally, the traditional process of ship design aims for optimizing a ship for worldwide operating conditions; however, there is a lack of consideration of the cumulative effect of high temperatures, high salinity, small waters, and sensitive ecological conditions of these regions. (The Marine Environmental Impacts of, 2024)The proposed framework is designed to take a systems-based approach in its design, with a full comprehension that the performance and sustainability of a ship depend on a number of its design elements rather than technology. It is composed of five integrated ship design pillars: hull and hydrodynamic optimization, propulsion and energy, materials and coatings, onboard operation, and finally, regulatory and environmental integration.

Hull and Hydrodynamic Optimization



The design of the hull is an important aspect that relates to vessel resistance, fuel efficiency, and emissions. Additionally, resistance levels for a vessel are particularly high when moving in warm and shallow water due to low water density and shallow water effects. (Samuvel & Vijayakumar, 2025, pp. 345-356) Therefore, an important aspect with regard to sustainable ship design located within the relevant area is that low-speed optimizing hull forms with less wave resistance are significant for vessel resistance levels. Slender hull forms and bulbous bow forms, especially regarding vessel speeds within this area, have potential advantages for vessels. (T., 2023) With the advancement in technology, vessels can be simulated using computational fluid dynamics technology based on the region-specific temperature and salinity levels. While accurately measuring the performance of vessels in real seawater conditions, the efficiency of the vessel's resistance can be predicted with greater accuracy, which can play a crucial role in saving fuel and thus reducing greenhouse gases during its period of usage.

Propulsion and Energy Systems

The choice of the type of the propulsion system is an important criterion because it affects the sustainability performance significantly. In the case of the vessels moving in the Red Sea and the Arabian Gulf, for instance, a propulsion system needs to take into consideration factors such as energy efficiency, thermal resistance, and fuel compatibility, particularly because the vessels move at high speeds and are exposed to high ambient temperatures, which calls for high cooling capacity for the engines and the power electronics. Hybrid systems, consisting of combinations of traditional systems coupled with battery-based power assist systems, have been found to possess tremendous potential as an alternate solution, especially as regards harbor activities and speed transits to environmentally sensitive areas. (Hybrid Propulsion Systems: Marrying Diesel, Batteries, and Fuel Cells, 2026) New fuel sources like liquefied natural gas have been found to possess tremendous potential as regards emission control with appropriate handling systems onboard. (Research on the performance and emission characteristics of the LNG-diesel marine engine, 2015, pp. 945-954) Waste recovery systems also need to be brought into play to enhance efficiency due to excessive wastes generated during high-temperature conditions.

Materials and Protective Coatings

The importance of using the best material can also be realized in areas with higher rates of salinity compared to the average rate of corrosion. (Materials Selection in Seawater Systems, n.d.) The sustainable design of ships usually focuses on using materials that can resist corrosion, composite materials, and module materials in designing ships that are durable. Lightweight materials can also be important in terms of fuel conservation owing to the reduction in vessel displacement. Protective coatings constitute an integral part of the interface between the ship structures and their marine surroundings. Environmentally friendly anti-fouling coatings, with applications having minimum discharge of toxic waste, are very important near areas of coral reefs. Silicone-based coatings have good potential to reduce hydrodynamic drag, and these coatings are eco-friendly, while foul release coatings have such promising potential. (Hu *et al*., 2020)

Onboard Systems and Operational Optimization

In short, the sustainability of a ship, to a great extent, depends upon its systems and processes. For instance, more energy-efficient systems for auxiliary machines, such as smart power systems and monitors, may improve fuel and emissions optimization in real-time. Apart from that, current sensors may monitor conditions such as hull and machine condition, and even biofouling, thereby avoiding down-time instead of unplanned down-time. Other operational strategies, like routing optimization, speed management, and port-side electrification, may contribute to added sustainability performance as well. (Managing port disruption through sailing speed optimization for sustainable maritime transportation, 2024) With regard to congested corridors of navigation, speed management may prevent not only the pollution of GHGs but also underwater noise pollution as a consequence.

Regulatory and Environmental Integration

Included in the development of sustainable ship design is also regulatory compliance. This also forms a framework in which ship design and international regulations concerning the marine environment can be integrated, while at the same time providing local regulations with needed flexibility. Designing ship systems, such as systems promoting emission prevention, prevention of ballast water, and prevention of spillage, is integrated in the very beginning of the design process rather than at the end of ship production at extra costs. (IMO Guidelines for Ballast Water Management, 1997) Environmental integration can also include, in particular, responsive and, better still, proactive risk management, especially in the sensitive areas of the environment. Design features that minimize ship discharge, noise, and disturbance are crucial in ship protection and building public trust in shipping. (Noise Exposure and Mitigation on High-Speed Craft: Assessing Acoustic Environment and Regulatory Compliance, 2026)

Table 3: Key Design Pillars and Sustainability Contributions

Design Pillar	Primary Focus	Sustainability Contribution
Hull optimization	Reduced resistance, shallow-draft design	Lower fuel consumption and emissions
Propulsion & energy systems	Hybrid systems, alternative fuels	Reduced air pollutants and thermal impact
Materials & coatings	Corrosion resistance, low-fouling surfaces	Extended lifespan and reduced maintenance
Onboard systems & operations	Smart monitoring, energy management	Improved operational efficiency
Regulatory & environmental integration	Compliance and ecosystem protection	Reduced ecological risk and improved governance

Regulatory and Policy Alignments for Sustainable Ship Design

Thus, the issue of regulatory compliance is an important element that, in turn, affects sustainable design, especially considering the sensitivity of a region like the Red Sea, as well as the Gulf, owing to its strategic position. Modern regulations have not ceased to deal with the various challenges, thus affecting the manner in which designers and users of oceanic vessels are dealing with issues like emissions, fuel, protection of the ecosystems of their regimes all over the world, a specific region like the one mentioned included. At the international level, there are already regulations laid out by the International Maritime Organization, which are elaborately designed to ensure that the impacts of shipping activities on the environment are minimized. (IMO Sustainability Targets — Sustainable Ships, 2025) Regulations regarding requirements for energy efficiency are designed to ensure that hull design, propulsion systems, and energy efficiency are maximized. Similarly, regulations on emission control aim to reduce sulfur dioxide emissions, nitrogen oxide emissions, and greenhouse emissions. (IMO 2020 – cutting sulphur oxide emissions, 2020) These regulations and requirements have led to the adoption of efficient energy technologies and cleaner fuels, and they are applicable all over the world without any specific considerations being made. (IMO Net-Zero Framework, 2025) In the case of semi-enclosed seas such as the Red Sea, or the Arabian Gulf, even the environmental impacts may be perceived as enhanced due to the sensitive ecosystem with low water exchange. (IMPACT OF TWO SEMI-ENCLOSED SEAS ON NEIGHBORING SEA, 2023) At present, a sustainable design solution at an international level should take into consideration the incorporation of levels with regards to any probable impacts from pollution. (IMO Sustainability Targets — Sustainable Ships, 2025) The implementation of a sustainable design with enhanced levels regarding treatment and prevention with regards to ballast water and reduction in underwater noise will contribute to a better level of environmental protection, as defined on an international level. (Ballast Water Management Convention, 2017) The regional policies have also underscored the importance of sustainability in the larger maritime development context. (Regional policy framework, Red Sea and Gulf of Aden Special Areas effective from 2025, 2023) The countries of the Red Sea and the Arabian Gulf have begun to underscore the importance of sustainability as a dimension of their larger strategy and long-term planning process. (Saudi Arabia's Sustainability Commitment in the Red Sea, n.d.) Sustainable shipping solutions are no longer a necessity, but nor are they not considered a viable strategy which can enhance (Saudi maritime push strengthens global trade links, 2025)e general competitiveness, not only of regional maritime trade but also tourism. Ship designs which underscore the importance of sustainability are thus more likely to receive the sanction and support of regulatory authorities. (Tadros *et al.*, 2024) The strategies for national development emphasize diversification, innovation, and responsibility towards the environment. These strategies are meant to be supplemented by those of the maritime industry, which should be clean-tech and environmentally driven. (National Strategy for a Sustainable Ocean Economy, n.d.) This implies that sustainable ship designs act as a bridge between compliance with international regulations and the implementation of national strategies for development. (Strategic environmental assessment for sustainable coastal zone management in Saudi Arabia, aligning with vision 2030, 2024) The integration of regulatory issues into ship design matters at an early stage can reduce costs, increase flexibility, and optimize value from the ships. Another area that is actively being utilized in enforcing any regulation is that of port state control and regional sea authorities, especially in terms of enforcing environmental protection regulations. (PERSGA Highlights MARPOL Compliance and Port State Control Efforts in the Red Sea and Gulf of Aden at IMO MEPC 83, 2025) Even more strict measures are being implemented in terms of reporting and monitoring, especially in terms of digital regulation and enforcement. (Quigley *et al.*, 2025) Especially with the vessel designing and monitoring occurring, navigation can become even more effective in terms of adhering to the changes in terms of regulations.

(Quigley *et al*., 2025) From the vessel design itself, digital tools are required in terms of compliance and monitoring, especially in terms of regulation. (Real-Time IMO Regulation Updates through AI Document System, 2025) Note, however, that this should by no means be regarded as a disincentive to innovativeness but as a call to offer momentum to the optimization of sustainable design. This is in consideration of the fact that by predicting regulations to be put in place in the near future, which will certainly be stringent, it will be possible to have vessels that will remain aligned to these regulations for much longer periods. This, in turn, will propel the way to greener shipping modalities. As a foregoing statement implies, therefore, it becomes necessary to adopt a forward-looking, holistic, or integrated design philosophy to ensure appropriate regulatory and policy alignment by accommodating compliance, environmental, as well as efficiency issues in ship design at the earliest possible time to ensure that sustainable ship design is able to contribute to regional sustainability in economic terms as well.

Table 4: Regulatory and Policy Drivers Influencing Sustainable Ship Design

Regulatory Level	Key Focus Areas	Design Implications
International	Energy efficiency, emission reduction, pollution prevention	Optimized hulls, cleaner propulsion, emission control systems
Regional	Ecosystem protection, maritime safety	Enhanced ballast water treatment, spill prevention, low-noise design
National	Sustainability and economic diversification	Adoption of green technologies and future-ready designs
Port-state control	Compliance monitoring and reporting	Integrated sensors and digital compliance systems

DISCUSSION

The results of this research reiterate the need to talk about a regional approach for ship design in sustainable ways, specifically in consideration of the region of the Red Sea and Arabian Gulf. Unlike the general vague approach to "green shipping," as presented in the literature and considered appropriate worldwide, the method presented in this research has verified that, in consideration of the region of the Red Sea and Arabian Gulf, there are dimensions dealing with sustainability in a special way. To begin with, we have the realization that factors such as sea temperature and salinity levels have an incredibly large influence on the effectiveness of traditional approaches towards the achievement of adequate levels of energy efficiency, which can presumably be considered known and accepted variables within the framework of the overall equation of reduced fuel costs as a result of the implementation of the approach as indicated in the levels of loss where such have not been explicitly considered. As is again indicated, the notion of an effective approach towards sustainability is again pertinent. The debate also implies that there is a wide range of co-benefits to sustainable ship design, apart from greenhouse emissions reduction. For instance, the reduction in corrosion resistance and biofouling directly impacts the maintenance costs of a vessel. For a region with high levels of salinity, ship design will add positive value to assets and values. Where ship management is concerned, monitoring and predicting will optimize ship performance trends in a manner that optimizes ship management to environmental stress factors before they happen. It goes without saying that this will most certainly add positive value to the positive debating points in favor of adopting sustainable design in that region. One other factor of importance, although not to the same extent, is that of the environment itself and their public trust duties. The Red Sea and Arabian Gulf are noted in the literature as sensitive in terms of ecological risks, and, as discussed, shipping does leave its mark in these environments. Certainly, in terms of pollution control, low-noise impact, and discharges, shipping operations are adopting a precautionary role with regard to their environmental public trust duties. In this regard, shipping operations, by considering this element, are ensuring that they not only minimize their risks to their environment but also point to their approach to their duties regarding social demands, and this factor is clearly an element that will become even more relevant as its sustainability is brought into further de facto question. This creates a key enabling factor as opposed to limiting, what with the consideration of the concept of regulatory alignment as opposed to limiting factor alignment. Thereafter, there is also the element of the factor that considers international regulations as drawn up by the IMO and implemented within the context of maritime performance in terms of environmental issues, with a need emphasized to perform better than a minimum standard within a specified region. With shipbuilding, the consideration of a need to regulate in the future creates a smooth path as opposed to a need to modernize in accordance with regulation. Moreover, there is also a reference within the text to particular issues that might be of interest for policymakers or for people who care for the marine environment. For example, regionally differentiated ship design concepts could assist policymakers in dealing with general sustainability issues by mitigating the overall impact of ships on the environment, particularly along frequented sea routes. Once again, policymakers can take into consideration these ship design concepts as a way of developing incentive models or even access/green corridor models for boats with good performances regarding the environment. Ship design within a green environment is, therefore, also part of a broader governance of the sea. Nevertheless, in spite of the conceptual nature of such ideas, relevant contributions are made to the field in relation to such research. With regard to the research, there was a lack of available empirical data concerning any vessels undertaking such work. In addition, with regard to future research, it is of interest to note that such research could be undertaken based upon the findings determined through conducting such a venture, with regard to the Red Sea and Gulf. In conclusion, as can be clearly understood from the above discussion, it is evident that the affirmation made above has been made with a view to reach a conclusion and a determination regarding the fact that the notion of sustainable ship design in the region of the Red Sea and the Arabian Gulf in particular should necessarily and essentially be conceptualized from the system level with reference to notions and concepts of environment science, engineering creativity, and forward thinking in terms of regulation.

CONCLUSION AND POLICY IMPLICATIONS

This study has provided an investigation of the sustainable ship design strategies that have been developed with particular reference to the environmental conditions and circumstances that have been prevalent in the Red Sea/Arabian Gulf areas. These areas have created a particular maritime environment characterized particularly with reference to very high sea surface temperatures, salinity levels, shallowness of waters in the coastal regions, and very high levels of sensitivity from an ecology point of view. (Council, 1995) This analysis has proved that the ship designs that have been developed for addressing global circumstances have proved to be inadequate in addressing the sustainability issues in this particular environment. (Strategic Environmental Assessment for Sustainable Coastal Zone Management in Saudi Arabia, aligning with Vision 2030, 2024) In accordance with a synthesis of efficient knowledge in the fields of Naval Architecture, Marine Engineering, Environmental Science, and Maritime Policy, the present paper proposed a holistic framework for sustainable design based on the "five pillars": the best possible design of the "hull and its hydro dynamic performances," the best possible "propulsion and energy efficiency," the best possible "use of materials and coating systems," the best possible "use of onboard systems," and lastly "regulation and integration with the environment." (Review of current regulations, available technologies, and future trends towards green shipbuilding industry, 2026) Sustainability is maximized when there is a "consideration of environmental constraints at the early design stage instead of refitting and/or operation itself." (Review of methods for sustainability appraisals in ship acquisition, 2015) This finding also shows the relevance and importance of "regionally optimized design forms," "thermally optimized propulsion systems," "corrosion resistance," and "EAF anti-fouling systems that help reduce fuel costs and emissions and improve maintenance conditions," through which fuel savings, cost reductions for emissions, and maintenance costs can be realized and fulfilled. (Keyes, 2025) Moreover, it is further encouraged that a "holistic approach to sustainable ship design should include consideration of both environmental aspects and economic justification, i.e., Red Sea and Gulf region." There is further policy support for the need for innovation and its link and alignment with "various policy issues at an international and regional scale regarding the environment." (Strategic environmental assessment for sustainable coastal zone management in Saudi Arabia, aligning with vision 2030, 2024) This is because there can be an "adoption of regional-specific design guidelines for shipping operations," as well as "incentivization of environmental performance standards for shipping operations and address the regional environmental impacts—enhancing global competitiveness for regional shipping operations." (Marina Planning and Design Code, 2025) In addition, there are some implications presented by this paper that may affect and impact the "ship design and industry authorities' ability to meet changing regulations and reduce risks," "improve cost estimation," "address the rising needs and requirements imposed by industry authorities and people over time." In a country where there is an increasing trend in land use, especially along coastal and marine areas, a sustainable design of a ship may play a vital role in ensuring a secure future for a country and stimulating diversity. (A Review on Navigating Sustainable Naval Design: LCA and Innovations in Energy and Fuel Choices, 2026) However, even as this present study may have served as conceptual study on how best to ensure a sustainable ship design in governing bodies such as those in the Red Sea or the Arabian Gulf, it is propose that in the future, considerations will be made to also have empirical study on ship designs through numerical or actual ship operations.

REFERENCES

- Bower, A. S., Johns, W. E., Fratantoni, D. M., & Peters, H. (2005). Equilibration and circulation of Red Sea outflow water in the western Gulf of Aden. *Journal of Physical Oceanography, 35*(11).

- Carlton, J. (2019). *Marine propellers and propulsion* (4th ed.). Butterworth-Heinemann.
- Chillemi, M., et al. (2024). A review of advanced air lubrication strategies for ship drag reduction and energy efficiency. *Applied Sciences, 14*(13), 5888.
- Corbett, J. J., & Koehler, H. W. (2003). Updated emissions from ocean shipping. *Journal of Geophysical Research: Atmospheres, 108*(D20).
- DNV. (2024). *Energy Transition Outlook 2024: Maritime forecast to 2050*. DNV.
- Flack, K. A., & Schultz, M. P. (2019). Review of hydraulic roughness effects on turbulence and drag. *Applied Mechanics Reviews, 71*(6).
- Hellio, C., &Yebra, D. (Eds.). (2009). *Advances in marine antifouling coatings and technologies*. Woodhead Publishing.
- Hjellbak, S., & others. (2023). Potential energy savings of air lubrication technology on ships: A global assessment model. *International Journal of Naval Architecture and Ocean Engineering, 15*, 100510.
- International Maritime Organization. (2008). *International Convention on the Control of Harmful Anti-fouling Systems on Ships (AFS Convention): Entry into force 17 September 2008*. IMO.
- International Maritime Organization. (2017). Implementing the Ballast Water Management (BWM) Convention (entered into force 8 September 2017). IMO.
- International Maritime Organization. (2017). Safety for gas-fuelled ships—new mandatory IGF Code enters into force (Press briefing). IMO.
- International Maritime Organization. (2018). *Initial IMO strategy on reduction of GHG emissions from ships* (adopted by MEPC 72). IMO.
- International Maritime Organization. (2023). *2023 guidelines for the control and management of ships' biofouling to minimize the transfer of invasive aquatic species* (Resolution MEPC.378(80)). IMO.
- International Maritime Organization. (2023). *2023 IMO strategy on reduction of GHG emissions from ships* (Resolution MEPC.377(80)). IMO.
- International Maritime Organization. (2023). EEXI and CII—ship carbon intensity and rating system (FAQ). IMO.
- ISO. (2016). *ISO 19030-1: Ships and marine technology—Measurement of changes in hull and propeller performance—Part 1: General principles*. International Organization for Standardization.
- ISO. (2016). *ISO 19030-2: Ships and marine technology—Measurement of changes in hull and propeller performance—Part 2: Default method*. International Organization for Standardization.
- Kim, Y. R., et al. (2023). Potential energy savings of air lubrication technology on ships: Model development and fleet-scale implications. *International Journal of Naval Architecture and Ocean Engineering*.
- Lackenby, H. (1963). The effect of shallow water on ship resistance. *Shipbuilding and Shipping Record*.
- MAN Energy Solutions. (2021). *Two-stroke engine operating and performance guidance for alternative fuels*. MAN Energy Solutions.
- Methanol Institute. (2023). *Marine methanol: Future-proof shipping fuel*. Methanol Institute.
- Molland, A. F., Turnock, S. R., & Hudson, D. A. (2017). *Ship resistance and propulsion: Practical estimation of ship propulsive power* (2nd ed.). Cambridge University Press.
- Neumann, A. C. (1961). Circulation of the Red Sea in early summer. *Deep-Sea Research, 8*(3–4), 223–235.
- Papadimitriou, S., & others. (2023). Assessment of the economic, environmental and safety impact of biofouling development on ship operation. *Ocean Engineering, 279*, 114509.
- Pawar, V., & others. (2020). A review of alternative fuels for maritime transportation: Pathways to decarbonization. *Renewable and Sustainable Energy Reviews, 124*, 109782.