ADVANCING GREEN PORT INITIATIVES: A CONCEPTUAL FRAMEWORK FOR SUSTAINABLE FUEL BUNKERING

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Abstract. The maritime shipping industry plays a vital role in global trade but continues to face environmental challenges due to its heavy reliance on fossil fuels, particularly in fuel bunkering operations. This study proposes a conceptual framework to support sustainable fuel bunkering within Green Port Initiatives (GPIs) in Malaysian ports. Using a qualitative conceptual approach based on literature and policy reviews, the framework integrates five key dimensions: technological innovation, policy and regulatory mechanisms, infrastructure development, stakeholder engagement, and inter-port bunkering substations development. The framework is guided by best practices from leading ports such as Singapore and Rotterdam and emphasizes the importance of regulatory support, infrastructure readiness, and stakeholder collaboration in achieving maritime decarbonization. It also aligns with international environmental frameworks, including the IMO GHG Strategy 2023. The study highlights that sustainable fuel bunkering is not only important for reducing greenhouse gas emissions and environmental impacts but also for improving the competitiveness, resilience, and long-term sustainability of Malaysian ports. The proposed framework provides practical guidance for policymakers, port authorities, and maritime stakeholders in supporting green port development and sustainable maritime logistics.
Keywords: *green port initiatives, bunkering, decarbonization, clean energy, international maritime organization*

Introduction

Maritime shipping is responsible for transporting about 90% of global trade by volume and plays a vital role in economic development (Verschuur et al., 2022). However, the industry still relies heavily on conventional fuels such as Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO), which contribute to greenhouse gas (GHG) emissions, air pollution, water pollution, and environmental degradation (Aaserud, 2024). Fuel bunkering activities at ports are among the contributors to these environmental impacts if not managed sustainably (Hoang et al., 2022). To address these challenges, Green Port Initiatives (GPIs) have been introduced to promote cleaner fuels, energy efficiency, and environmentally sustainable port operations. These initiatives support the United Nations Sustainable Development Goals (SDGs), particularly SDG 7, SDG 13, and SDG 14, and are aligned with international standards such as ISO 14001 and ISO 50001 (Lee et al., 2025). Leading ports such as Singapore, Rotterdam, and Los Angeles have adopted sustainable bunkering practices through investments in alternative fuels, infrastructure, and environmental regulations (Ismail, 2023; Hendrik et al., 2023).

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Despite these developments, Malaysian ports such as Northport, Penang Port, and Johor Port continue to face challenges in implementing sustainable bunkering practices. Key issues include limited alternative fuel infrastructure (Alenazi, 2021), high investment costs (Klopott et al., 2023), operational risks such as fuel spills and limited monitoring systems (Zhang et al., 2021), technical capability gaps, and regulatory uncertainties related to the IMO 2020 Sulphur Cap and IMO GHG Strategy 2023 (Ismail, 2023). In addition, many ports still depend on conventional bunkering systems with limited adoption of digital technologies and cleaner fuel facilities (Jeevan et al., 2023). Therefore, this study examines the challenges of fuel bunkering and proposes a conceptual framework based on technological innovation, policy and regulatory mechanisms, infrastructure development, stakeholder engagement, and inter-port bunkering substations development. The framework aims to support sustainable fuel bunkering, maritime decarbonization, and green port development in Malaysia.

Literature review

Green port initiatives

GPIs have emerged as an important approach to reducing the environmental and social impacts of port operations through cleaner technologies, energy efficiency, and compliance with environmental regulations (Sogut et al., 2022). Key GPI areas include emissions reduction, waste management, sustainable fuel use, water conservation, and community well-being, with fuel bunkering receiving increasing attention due to its environmental impact. Several leading ports have successfully implemented GPIs. For example, the Port of Los Angeles and the Port of Long Beach introduced shore-to-ship power systems and stricter emissions monitoring under the Clean Air Action Plan to reduce vessel emissions at berth (Densberger et al., 2022). Similarly, the Port of Gothenburg provides incentives and port fee reductions for vessels using low-emission fuels and energy-efficient technologies (Florez et al., 2021). The Port of Singapore has also become a leader in sustainable bunkering through its Green Ship Programme, digital bunkering systems, and the promotion of LNG and bio-LNG fuels (Yap et al., 2024).

Despite these developments, the implementation of GPIs in Malaysia and many Southeast Asian ports remains challenging due to limited funding, technological gaps, regulatory issues, and insufficient green infrastructure (Bahri et al., 2025; Idris, 2022). Malaysian ports such as Northport, Penang Port, and Johor Port have adopted green initiatives under national frameworks including the Low Carbon Mobility Blueprint 2021–2030, supported by measures such as ISO 14001:2015 Environmental Management Systems, Vessel Traffic Services (VTS), and energy-efficient equipment (Mustaffa et al., 2023; ESCAP, 2023). However, challenges remain in developing alternative fuel bunkering infrastructure, upgrading fuel storage facilities, and strengthening environmental enforcement. Researchers have emphasized the need for stronger policy coordination, technical investments, and stakeholder collaboration to support sustainable fuel bunkering and port decarbonization (Mahmud et al., 2024). Aligning Malaysian port strategies with international frameworks such as the IMO 2023 GHG Strategy and integrating sustainable bunkering into broader port sustainability systems can enhance environmental performance, operational sustainability, and global competitiveness (Klopott et al., 2023).

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Global fuel bunkering practices, environmental impacts, and fuel transition challenges

Fuel bunkering is a critical activity in maritime logistics, traditionally relying on conventional fuels such as Heavy Fuel Oil (HFO) and Marine Diesel Oil (MDO), which contribute significantly to greenhouse gas emissions and environmental pollution (Vedachalam et al., 2022). In response to stricter environmental regulations and global decarbonization goals, the maritime industry is increasingly adopting cleaner fuels such as LNG, biofuels, green ammonia, methanol, and hydrogen (Salminen, 2024; Ramsay et al., 2023). International initiatives, including the IMO 2020 Sulphur Cap and IMO GHG Strategy 2023, have accelerated this transition. Consequently, major ports such as Rotterdam, Singapore, and Yokohama have invested in LNG infrastructure, alternative fuel projects, and digital fuel monitoring systems to support sustainable bunkering practices (Klopott et al., 2023; Hendriksen, 2023). Policy support, incentives, and technical standards have also been identified as important factors in encouraging cleaner fuel adoption (Wang et al., 2024). Despite these developments, fuel bunkering continues to pose environmental risks if not properly managed. Bunkering activities can release pollutants such as volatile organic compounds (VOCs), particulate matter (PM), nitrogen oxides (NOx), and sulphur oxides (SOx), which affect air quality and public health (Duong et al., 2023). Fuel spills and improper bunkering practices can also damage marine ecosystems through water contamination and waste generation (Kamal et al., 2021). Lee et al. (2020) reported that bunkering emissions may account for up to 30% of total emissions in busy port areas. The 2021 bunker spill at the Port of Fujairah further demonstrated the environmental consequences of poor bunkering management and highlighted the need for stronger monitoring and emergency response systems (Khalili, 2021).

These challenges are often more significant in developing countries where environmental monitoring and enforcement systems are less effective. In Southeast Asia, including Malaysia, many ports are located near residential and coastal communities, increasing environmental and public health concerns (Zain et al., 2024). Poor bunkering management can negatively affect local fisheries and surrounding communities (Mohd Zaideen et al., 2026). To address these issues, ports such as Los Angeles and Gothenburg have implemented Green Port Initiatives (GPIs), including zero-emission targets, low-sulphur fuel incentives, and shore power systems (Alamoush et al., 2022; Densberger et al., 2022; Florez et al., 2021). International platforms such as the APEC Green Port Conference also promote advanced monitoring technologies, regional cooperation, and sustainable bunkering systems to improve environmental performance (Idris, 2022). However, the transition to cleaner fuels remains challenging due to high investment costs, infrastructure limitations, and regulatory uncertainties. Alternative fuel technologies often require vessel retrofitting, specialized storage facilities, safety systems, and trained personnel (Lebedevas et al., 2024; Klopott et al., 2023). Many ports in Southeast Asia, including Malaysia, face constraints related to funding, space, fuel availability, and inter-agency coordination, which slow the development of alternative fuel infrastructure. In addition, differences in fuel standards, emissions monitoring requirements, and certification systems create compliance challenges for industry stakeholders (Rebelo, 2021). Although fuels such as green ammonia and hydrogen are viewed as promising long-term solutions, their commercial availability remains limited (Notteboom et al., 2023). Therefore, stronger policy support, infrastructure investment, stakeholder collaboration, and workforce development are required to accelerate sustainable fuel adoption and support green maritime development in Malaysia and other developing maritime nations (Alamoush et al., 2024; Saxena, 2024).

Materials and Methods

This study adopts a qualitative conceptual research design based on an extensive review of secondary sources, including academic journal articles, sustainability reports, IMO frameworks, maritime policies, and industry publications related to GPIs and sustainable fuel bunkering. A conceptual approach is used because the study aims to develop a strategic framework rather than conduct empirical or statistical analysis. Through conceptual and thematic synthesis, the literature was analysed to identify key challenges, opportunities, and sustainability factors influencing fuel bunkering practices. The proposed framework focuses on five main dimensions: technological innovation, policy and regulatory mechanisms, infrastructure development, stakeholder engagement, and interport bunkering substation development. In addition, best practices from leading ports such as Singapore, Rotterdam, and Los Angeles were reviewed to strengthen the framework and support sustainable maritime governance, decarbonization, and green port development in Malaysia.

Proposed conceptual framework for sustainable fuel bunkering

To address the challenges of fuel bunkering and support GPIs in Malaysia, this study proposes a conceptual framework for sustainable fuel bunkering. As shown in Figure 1, the framework consists of five key components: Technological Innovations, Policy and Regulatory Mechanisms, Infrastructure Development, Stakeholder Engagement, and Interport Bunkering Substation Development. These components work together to support cleaner and more efficient bunkering operations. The framework can assist policymakers, port authorities, and industry stakeholders in developing practical strategies to reduce emissions, improve sustainability, and strengthen Malaysia's green shipping and decarbonization efforts.

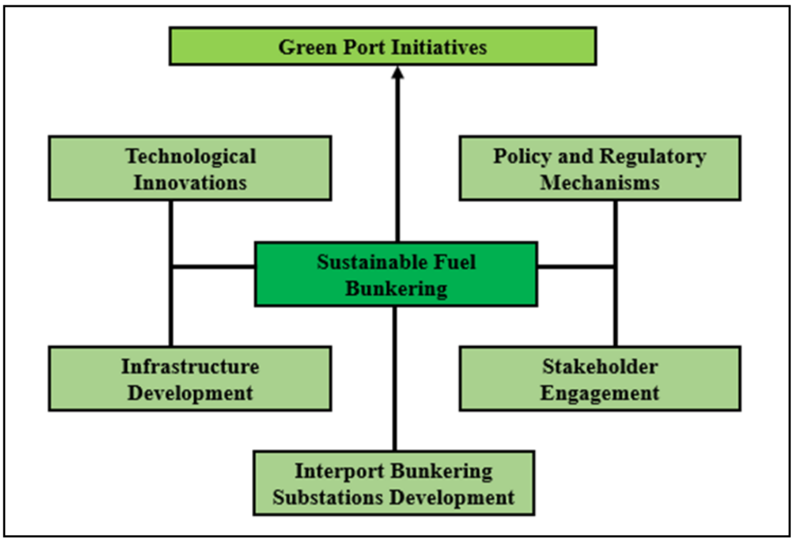

Figure 1. *Conceptual framework for sustainable fuel bunkering.*

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Technological innovations

Technological innovation plays an important role in improving the sustainability of fuel bunkering operations and supporting GPIs. Leading ports such as Rotterdam and Los Angeles have adopted shore-to-ship power systems, electric cargo-handling equipment, and digital fuel monitoring technologies to reduce greenhouse gas (GHG) emissions and improve operational efficiency (Hendrik et al., 2023). A notable example is the Yara Birkeland, the world's first fully electric and autonomous container vessel, which is estimated to reduce approximately 678 tonnes of CO_2 emissions annually by eliminating diesel fuel use (Knaving et al., 2022). Similarly, Singapore has promoted LNG bunkering, electric tugboats, and digital emissions monitoring systems, while the Port of Yokohama has implemented cold ironing systems to reduce NOx and SOx emissions from berthed vessels (Ismail, 2023; Bakar et al., 2023). These technologies support international environmental targets such as the IMO 2020 Sulphur Cap and the IMO GHG Strategy 2023. In Malaysia, technological innovation is increasingly being integrated into port sustainability initiatives. Northport (Malaysia) Bhd has introduced electric Rubber-Tyred Gantry (e-RTG) cranes, fuel-efficient terminal vehicles, and power management systems to reduce energy consumption and emissions (Sadiq et al., 2021). In addition, ports such as Port Klang and Port of Tanjung Pelepas are exploring digital twin technologies and automation systems to improve operational efficiency and data-driven decision-making. These initiatives are aligned with the ASEAN Green Shipping Strategy and the Twelfth Malaysia Plan (2021–2025) (Lee et al., 2025). Overall, technological innovation is essential for reducing emissions, improving port performance, strengthening environmental sustainability, and enhancing the competitiveness of Malaysian ports in the green maritime industry.

Policy and regulations

Policies and regulations are important for supporting cleaner fuels and sustainable maritime operations. The International Maritime Organization (IMO) has introduced several measures to reduce GHG emissions, including the Energy Efficiency Design Index (EEDI) for new ships and the Carbon Intensity Indicator (CII) for existing vessels (Baumler et al., 2021). The IMO also aims to reduce total shipping emissions by at least 50% by 2050 compared to 2008 levels (Joung et al., 2020). These regulations encourage the use of cleaner fuels such as LNG and biofuels, as well as more energy-efficient technologies. In Asia, countries such as Singapore and China have introduced green shipping programmes, alternative fuel bunkering facilities, emission control areas, and shore power systems to reduce maritime emissions (Tang, 2024). Regional initiatives such as the ASEAN Green Shipping Strategy and APEC maritime programmes also support sustainable shipping development (Jin et al., 2024). In Malaysia, policy support is helping ports improve environmental sustainability. The Port Klang Authority and Northport (Malaysia) Bhd have implemented initiatives such as ISO 14001 Environmental Management Systems (EMS), air quality monitoring, and sustainable bunkering guidelines (Jeevan et al., 2023). However, stronger regulations and better cooperation among authorities are still needed to support cleaner fuel adoption and sustainable port operations. These efforts will help Malaysian ports achieve environmental goals and remain competitive in the green maritime industry.

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Infrastructure development

Infrastructure development is essential for supporting sustainable fuel bunkering and green port operations. Many leading ports have invested in facilities for alternative fuels such as LNG, hydrogen, and biofuels to support maritime decarbonization. For example, several European ports have developed dedicated LNG bunkering infrastructure and ship to ship LNG bunkering services to become major LNG hubs (Grosso et al., 2025). These investments improve fuel accessibility, support cleaner shipping operations, and contribute to the long-term decarbonization goals of the IMO. In Asia, ports such as Singapore, Busan, Yokohama, and Shanghai have developed LNG bunkering facilities, explored future fuels such as methanol and ammonia, installed solar energy systems, and expanded cold ironing facilities to reduce emissions from berthed vessels (Roh et al., 2023). In Malaysia, infrastructure for alternative fuel bunkering is still developing. Government agencies and port authorities are conducting feasibility studies on LNG and hydrogen bunkering at major ports such as Port Klang and Port of Tanjung Pelepas (Yahya, 2024). In addition, several ports have installed solar panels on warehouse rooftops to increase the use of renewable energy and reduce dependence on conventional electricity. These initiatives can support sustainable fuel adoption, reduce emissions, and strengthen Malaysia’s position as a green maritime and logistics hub.

Stakeholder engagement

Stakeholder engagement is important for supporting sustainable fuel bunkering and green port operations (Alamoush et al., 2024). At the global level, initiatives such as the Sustainable Shipping Initiative (SSI) and the Getting to Zero Coalition bring together shipowners, ports, fuel suppliers, and regulators to promote cleaner fuels such as hydrogen, ammonia, and biofuels. These collaborations encourage knowledge sharing, technology development, and investment in sustainable maritime solutions. According to Kornowski (2023), cooperation, transparency, and long-term partnerships are key factors in achieving shipping sustainability goals. In Asia, countries such as Singapore, Japan, and China work closely with shipping companies, research institutions, and technology providers to support low-carbon maritime development. For example, Singapore’s Maritime Green Future Fund supports research and pilot projects related to clean fuels and sustainable port operations (Ismail, 2023). Regional platforms such as ASEAN and the APEC Port Services Network (APSN) also facilitate knowledge sharing on green bunkering and sustainable port practices. In Malaysia, stakeholder engagement is becoming increasingly important in supporting GPIs. Ports such as Northport (Malaysia) Bhd collaborate with government agencies, fuel suppliers, terminal operators, and regulators to explore clean fuel bunkering and port electrification opportunities. Workshops, training programmes, and stakeholder discussions are regularly conducted to improve awareness of alternative fuel safety and environmental regulations (Jeevan et al., 2023). In addition, partnerships between ports, universities, and industry players support environmental research and workforce development. These collaborative efforts help strengthen skills, improve sustainability awareness, and support the long-term development of green ports in Malaysia.

Inter port bunkering substations development

The development of inter-port bunkering substations is important for ensuring a reliable supply of cleaner marine fuels across shipping routes (Klopott et al., 2023). These substations act as additional refuelling points between major ports, allowing vessels to access alternative fuels such as LNG, biofuels, hydrogen, and ammonia more easily. This reduces dependence on major ports, minimizes route deviations for refuelling, and supports more efficient and lower-carbon maritime operations. The system is particularly beneficial for feeder vessels and short-sea shipping services that require frequent refuelling and quick turnaround times. In Europe, the TEN-T (Trans-European Transport Network) initiative has established interconnected LNG bunkering networks across ports such as Zeebrugge, Gothenburg, and Klaipeda, improving fuel accessibility and supporting low-emission shipping activities (Jensen, 2020). In Malaysia, interport bunkering substations could improve fuel accessibility and support sustainable maritime operations along the Straits of Malacca. Collaboration among major ports such as Port Klang, Port of Tanjung Pelepas (PTP), and Penang Port could facilitate the distribution of cleaner fuels and encourage sustainable bunkering practices. For example, LNG or hydrogen bunkering substations located near Lumut or Langkawi could support vessels travelling between northern and southern Malaysia while reducing congestion at major ports. These facilities could also be integrated with Floating Bunkering Units (FBUs) to improve operational flexibility and reduce infrastructure costs. Overall, the development of inter-port bunkering substations can strengthen Malaysia’s position as a sustainable and competitive maritime hub in the Asia-Pacific region.

Results and Discussion

The proposed conceptual framework provides a comprehensive approach to support sustainable fuel bunkering and GPIs in Malaysia. The framework integrates five key dimensions: technological innovation, policy and regulatory mechanisms, infrastructure development, stakeholder engagement, and inter-port bunkering substations development. Together, these dimensions can help reduce carbon emissions, improve energy efficiency, strengthen operational sustainability, and support environmentally responsible port operations (Sadiq et al., 2021). The framework is also aligned with the IMO decarbonization agenda and the ASEAN Green Shipping Strategy 2030, highlighting the importance of sustainable fuel bunkering in achieving long-term maritime sustainability and strengthening Malaysia’s position as a regional maritime hub. The successful implementation of this framework requires strong institutional support and collaboration among government agencies, port authorities, shipping companies, fuel suppliers, and research institutions. Organizations such as the Maritime Institute of Malaysia (MIMA), Malaysian Green Technology and Climate Change Corporation (MGTC), Marine Department Malaysia, Port Klang Authority, Penang Port Commission, and Johor Port Authority play important roles in supporting policy development, green technology adoption, infrastructure development, and environmental governance (Lee et al., 2021; Karimpour, 2022). In addition, training programmes, research collaborations, and industry engagement initiatives can improve knowledge sharing and stakeholder participation. Therefore, the framework offers a practical and scalable approach to improve cleaner fuel accessibility, strengthen environmental management, and enhance Malaysia’s competitiveness as a sustainable maritime hub in the Asia-Pacific region.

Conclusion

Fuel bunkering remains a vital component of maritime logistics, but its environmental impacts have increased the need for more sustainable practices under GPIs. This study proposes a conceptual framework that integrates technological innovation, policy and regulatory mechanisms, infrastructure development, stakeholder engagement, and inter-port bunkering substations development to support sustainable fuel bunkering and maritime decarbonization. The framework highlights the importance of cleaner fuels, supportive regulations, adequate infrastructure, and strong collaboration among stakeholders in achieving sustainable port operations. Experiences from leading ports such as Singapore demonstrate that economic growth and environmental sustainability can be achieved simultaneously through investments in alternative fuels, technology adoption, and effective partnerships. Ultimately, sustainable fuel bunkering is not only a strategy for reducing greenhouse gas emissions and improving environmental performance but also an opportunity for Malaysia to strengthen its competitiveness, attract green investments, and position itself as a leading sustainable maritime hub in the Asia-Pacific region.

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Conflict of interest

The authors confirm that there is no conflict of interest involve with any parties in this research study.

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