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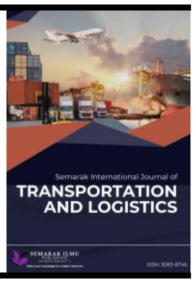

Smart GIS Applications for Enhancing Green Port Practices in Malaysian Seaports: A Proposed Conceptual Framework

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ABSTRACT

Ports are vital to global trade but face significant environmental challenges, including emissions, pollution, and resource inefficiencies. Green port practices (GPPs) aim to address these issues by promoting sustainable operations. This study explores integrating smart Geographic Information Systems (GIS) applications into green port practices, highlighting its potential to enhance environmental management and operational efficiency. Smart or innovative GIS combines real-time data from sensors, artificial intelligence, and advanced analytics to monitor, analyse, and predict environmental impacts. Key applications include emission tracking, waste management optimization, renewable energy planning, and biodiversity conservation. Case studies from leading ports demonstrate the effectiveness of smart GIS in reducing emissions, improving resource allocation, and aligning with global sustainability goals. Despite these successes, the adoption of smart GIS in Malaysian ports remains limited, constrained by high implementation costs, data integration challenges, and a lack of technical expertise. This research addresses these gaps by proposing a conceptual framework for integrating smart GIS into green port practices, tailored to the Malaysian context. The framework emphasizes data integration, spatial analysis, decision support, stakeholder collaboration, and real-time monitoring. The findings illustrate how smart GIS can drive sustainable port development by reducing environmental impacts, enhancing decision-making, and fostering stakeholder collaboration. By adopting these technologies, Malaysian ports can align with international sustainability standards and strengthen their competitiveness. This study contributes to advancing green port practices by providing actionable insights and a roadmap for integrating smart GIS into port operations in Malaysia.

1. Introduction

Ports are integral components of global trade, facilitating the movement of more than 80% of the world's goods, according to the United Nations Conference on Trade and Development [6]. However, their operations often result in adverse environmental impacts, including greenhouse gas (GHG)

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emissions, water pollution, and solid waste generation [4,8]. The shipping industry, for instance, accounts for approximately 2.89% of global CO2 emissions [7], a statistic that underscores its contribution to climate change. As global awareness of sustainability issues grows, ports are increasingly held accountable for their environmental footprints. Major international frameworks, such as the International Maritime Organization's (IMO) greenhouse gas reduction strategies and the United Nations Sustainable Development Goals (SDGs), have set ambitious targets for sustainable development.

Malaysian ports, including Port Klang, Johor Port, and Penang Port, play a critical role in the country's economic growth and connectivity but face mounting pressure to align with these global sustainability benchmarks. Environmental challenges such as marine pollution, excessive fuel consumption, and inefficient waste management systems present significant hurdles. To address these issues, GPPs have been introduced as a transformative framework to reduce environmental degradation while enhancing operational efficiency. Mishra *et al.,* [12] state that these practices encompass initiatives like adopting cleaner energy technologies, real-time emissions monitoring systems, and integrated waste management strategies.

A critical enabler of GPPs is smart GIS, a technology that integrates GIS with emerging innovations like the Internet of Things (IoT), Artificial Intelligence (AI), and Big Data analytics. Smart GIS allows ports to collect, analyse, and visualise environmental and operational data in real-time, enabling predictive analytics and data-driven decision-making. Meanwhile, Van der Kroft *et al.,* [20] discovered that the Port of Singapore has successfully implemented GIS-enabled predictive models to optimise vessel traffic management, resulting in a 20% reduction in operational emissions. Similarly, European ports have leveraged Smart GIS to track energy consumption and manage marine pollution more effectively [24]. Despite these global advancements, the adoption of Smart GIS in Malaysian ports is still nascent, with limited applications and a need for comprehensive frameworks for integrating such technologies into port operations [9].

Although global ports have demonstrated the potential of Smart GIS in achieving sustainable port management, Malaysian ports need to catch up in its adoption and implementation. Existing studies have priority focused on technical evaluations or isolated case studies but have yet to explore a holistic framework for applying Smart GIS to Green Port Practices within the Malaysian ports. For example, regarding on Supardi *et al.,* [17], The integration of spatial within a GIS database provides a powerful framework for managing marine water pollution in Port Klang. This method enables the simultaneous consideration of diverse datasets, including pollution sources, water quality metrics, coastal features, and land-use patterns, to better understand the interactions between human activities and marine environments.

By identifying patterns and assessing the impact of management strategies, GIS analysis forms the foundation for evidence-based decision-making in marine water quality management. The findings highlight the importance of ongoing monitoring, pollution control measures, regulatory enforcement, and responsible waste management [17].

There is also a need for more research examining the operational, environmental, and economic benefits of Smart GIS for Malaysian ports. Moreover, current practices in Malaysian ports often rely on traditional methods that need more real-time monitoring and predictive capabilities, limiting their ability to address sustainability challenges proactively [25].

This study addresses a critical gap by proposing a comprehensive framework for integrating Smart GIS into Green Port Practices, specifically tailored to the Malaysian port ecosystem. While existing research has explored green port practices and the implementation of GIS in port management, there is a limited focus on integrating Smart GIS technologies specifically tailored to enhancing sustainability efforts within Malaysian seaports. Moreover, previous studies may not have comprehensively addressed how Smart GIS can support key green port initiatives such as energy efficiency, waste management, pollution control, and real-time monitoring of environmental parameters. This study aims to bridge these gaps by proposing a conceptual framework that links Smart GIS capabilities with green port practices, emphasizing the unique challenges and opportunities in the Malaysian context. By doing so, the research contributes to a deeper understanding of how advanced GIS applications can optimize port operations while supporting global sustainability goals. This focus on the underexplored intersection of Smart GIS and green port practices underscores the novelty and relevance of the study.

The research holds significant value in advancing the country's sustainability agenda by demonstrating how Smart GIS can optimise resource usage, reduce environmental impacts, and align with international sustainability standards. Additionally, the findings of this study can serve as a model for other developing countries facing similar challenges in achieving sustainable port operations.The primary objective of this research is to evaluate the potential of Smart GIS in enhancing the sustainability of Green Port Practices in Malaysian ports. It seeks to develop an integrated framework that combines Smart GIS with environmental and operational parameters, enabling data-driven solutions for mitigating environmental impacts and improving efficiency.

2. Literature Review

2.1 Evolution of Green Port Practices (GPPs)

Over the years, GPPs have evolved from reactive environmental measures to proactive, integrated strategies for long-term sustainability in port operations. Wang *et al.,* [21] found that early implementations of GPPs centred around compliance-driven initiatives such as reducing air pollution through the adoption of low-sulphur fuels and implementing waste management systems. However, as the shipping industry faced increasing scrutiny for its environmental footprint, particularly its greenhouse gas (GHG) emissions, ports worldwide began adopting more comprehensive and innovative practices. Today, GPPs encompass renewable energy integration, emissions monitoring, waste reduction, biodiversity conservation, and digital transformation through emerging technologies such as GIS and AI. These practices align closely with global frameworks like the International Maritime Organization's (IMO) sustainability goals and the United Nations Sustainable Development Goals (SDGs) [27]

Globally, ports have leveraged diverse strategies to address unique environmental challenges. For example, the Port of Rotterdam has pioneered emissions monitoring and control by implementing shore-to-ship power systems, which allow docked vessels to switch off their engines and use onshore electricity instead. This reduces carbon emissions and mitigates noise and air pollution in the surrounding areas. The port further utilises GIS to monitor real-time emissions, identifying high-pollution zones and enabling targeted interventions. Over five years, this approach has led to a 25% reduction in nitrogen oxide (NOx) emissions, demonstrating the potential of data-driven solutions to achieve significant environmental outcomes [22].

Similarly, the Port of Los Angeles has embraced renewable energy integration by installing extensive solar panel systems. Vagen *et al.,* [18] agreed that GIS played a critical role in determining optimal installation sites to maximise energy generation while minimising costs. This initiative has resulted in a 15% reduction in reliance on non-renewable energy sources, making the port a global leader in renewable energy adoption. In the realm of biodiversity conservation, Johor Port in Malaysia conducted a GIS-based Environmental Impact Assessment (EIA) to assess the ecological effects of dredging activities on nearby mangrove ecosystems. Research by Kaur *et al.,* [10] stated that by mapping and analysing habitat data, the port implemented conservation measures that preserved critical ecosystems, highlighting the role of GIS in balancing economic development with environmental protection.

2.2 Smart GIS: Definition and Capabilities

GIS represents a revolutionary advancement in spatial technology by integrating traditional GIS capabilities with cutting-edge technologies such as IoT, AI, and Big Data analytics. Unlike traditional GIS, which primarily focuses on static spatial data, Smart GIS enables dynamic, real-time analysis and decision-making. It achieves this by incorporating live data streams from IoT sensors and applying predictive analytics powered by AI algorithms. For instance, IoT sensors installed on port equipment, such as cranes and cargo-handling machinery, can transmit real-time data on fuel consumption and emissions. When analysed using GIS, this data helps identify inefficiencies and recommends optimisation strategies to enhance operational sustainability [5].

The capabilities of Smart GIS are transformative for port management. Real-time monitoring allows ports to track critical environmental parameters such as emissions, energy usage, and waste generation. For example, IoT-enabled GIS systems can monitor air quality across port terminals, enabling immediate corrective actions in high-pollution areas. Powered by AI, predictive analysis uses historical and real-time data to forecast future trends, such as peak emission periods or energy demand surges, allowing ports to implement pre-emptive measures. Additionally, GIS dashboards provide intuitive data visualisations, simplifying the interpretation of complex datasets and aiding decision-makers in communicating insights to stakeholders effectively. These capabilities position Smart GIS as a cornerstone technology for advancing green port initiatives [13].

2.3 Applications of Smart GIS in GPPs

Smart GIS has become a cornerstone technology in advancing the effectiveness of GPPs by integrating advanced data collection, analysis, and visualisation to address critical environmental challenges in port operations.

One notable application is emission monitoring and reduction, where ports such as Rotterdam and Los Angeles have leveraged GIS-enabled systems to track emissions from vessels, trucks, and cargo-handling equipment. The Port of Rotterdam employs GIS to pinpoint high-pollution zones, enabling strategic investments in cleaner technologies, such as electric cranes, hybrid vehicles, and shore power systems. These technologies allow docked ships to rely on onshore electricity rather than burning fuel, resulting in a marked reduction in carbon emissions and improved air quality in the surrounding region. Over the past five years, such efforts have led to a 25% reduction in nitrogen oxide (NOx) emissions and have positioned Rotterdam as a leader in sustainable port practices [3]. Similarly, the Port of Los Angeles has adopted GIS-integrated emission tracking tools to measure and manage carbon footprints, ensuring compliance with California’s stringent air quality standards.

In the domain of waste management, GIS plays a pivotal role in identifying waste generation hotspots within port terminals. This capability enables ports to optimise the placement of recycling and disposal facilities, reducing operational inefficiencies and environmental impacts. For instance, Port Klang in Malaysia could adopt similar systems to enhance its waste segregation efforts, aligning with Malaysia's national waste management strategies. By integrating GIS data with waste management plans, ports can improve recycling rates and minimise the disposal of hazardous materials, contributing to cleaner port environments [1].

Renewable energy optimisation represents another critical application of Smart GIS in green port initiatives. The Port of Singapore, for example, uses GIS to determine the most suitable locations for solar panel installations, factoring in parameters such as sunlight exposure, shading, and land use. This data-driven approach has enabled the port to reduce energy costs by 20% while significantly increasing its reliance on renewable energy sources. Additionally, GIS models assist in predicting energy production levels under varying weather conditions, ensuring that renewable energy systems meet operational demands without interruption [24].

Smart GIS also plays a vital role in marine biodiversity conservation, particularly in ports where dredging and construction activities pose a risk to ecosystems. At Johor Port, GIS-based habitat mapping was used during an Environmental Impact Assessment (EIA) to analyse the ecological implications of dredging activities on sensitive mangrove habitats. The port implemented targeted conservation strategies by identifying high-risk areas, such as creating buffer zones and restoring damaged ecosystems. These measures have preserved critical biodiversity while allowing the port to proceed with necessary development projects, demonstrating how GIS can balance ecological sustainability with economic growth [6].

Integrating Smart GIS into these diverse applications showcases its transformative potential in addressing environmental challenges in the maritime industry. By enabling real-time data monitoring, predictive analytics, and informed decision-making, Smart GIS empowers ports to enhance their sustainability efforts, reduce operational costs, and achieve compliance with global environmental standards. These advancements not only strengthen ports' environmental performance but also position them as key players in achieving global sustainability objectives.

2.4 The Challenges and Limitations Encountered in Implementing Smart GIS Technologies

One of the fundamental challenges in implementing Smart GIS is the need for robust infrastructure, including digital networks, modernized GIS hardware, and cutting-edge software. For example, studies on Chinese ports, such as Shanghai and Guangzhou, reveal that transitioning from traditional port management systems to Smart GIS requires significant investments in upgrading legacy systems [23]. These ports had to enhance their internet connectivity, deploy IoT-enabled sensors, and establish data processing centres to handle the high volume of geospatial data. However, such infrastructure upgrades are often financially prohibitive for ports in developing countries. Similarly, in African seaports, a lack of reliable electricity and internet access further hampers Smart GIS implementation, highlighting the disparity between well-resourced and less-resourced regions [13]. These examples emphasize the critical need for assessing and addressing infrastructure gaps before deploying Smart GIS solutions.

Data integration poses another significant challenge. Smart GIS relies on data from multiple sources, such as satellite imagery, sensors, shipping databases, and environmental monitoring systems. These data streams often come in varying formats and standards, making it difficult to achieve interoperability. For instance, at the Port of Rotterdam—one of the most technologically advanced ports—early attempts to integrate Smart GIS faced delays due to incompatible legacy systems. The port overcame this challenge by developing a centralized data platform that harmonized diverse data inputs, but this required years of collaboration among technology providers and port authorities [27]. On the other hand, smaller ports often lack the resources to undertake such extensive integration efforts, which can limit the functionality and scalability of Smart GIS applications.

In the Malaysian context, studies could explore whether existing port systems are ready for such integration or whether additional frameworks and protocols are needed to standardize data collection and sharing. A lack of standardized data can reduce the effectiveness of GIS analytics, especially in real-time applications such as pollution tracking or vessel scheduling [17]. Successful

Smart GIS implementation depends heavily on the involvement and collaboration of all stakeholders, including port operators, government agencies, private companies, and local communities. Resistance to change among stakeholders is a common issue, especially when there is limited understanding of Smart GIS's benefits. For example, a study on Indian ports found that many port operators were hesitant to adopt Smart GIS due to a lack of training and concerns about job displacement caused by automation. Additionally, government agencies were slow to align regulatory frameworks with new technologies, delaying progress [15].

In developed ports such as Singapore, stakeholder engagement has been managed more effectively through awareness campaigns, training programs, and incentives. For instance, the Maritime and Port Authority of Singapore provided grants for companies adopting GIS-enabled solutions and organized workshops to demonstrate the value of these systems in achieving sustainability and operational efficiency [16]. This proactive approach highlights the importance of stakeholder buy-in, particularly in building trust and ensuring smooth transitions.

The literature review highlights the significant advancements in GPPs and the transformative role of Smart GIS in addressing environmental challenges in port operations. Despite these developments, several gaps must be addressed through the proposed conceptual framework. While ports like Rotterdam, Los Angeles, and Singapore have effectively employed GIS for emissions monitoring, waste management, and renewable energy optimisation, integrating these practices often needs a unified and dynamic system to manage real-time data across multiple dimensions.

Current GIS applications focus on specific areas, such as emissions or energy use, and need to fully leverage their potential for holistic decision-making and stakeholder engagement. Furthermore, the absence of a standardised approach to incorporating biodiversity conservation into port operations suggests an opportunity for more comprehensive environmental assessments using GIS.

The proposed conceptual framework for smart GIS in GPPs effectively addresses the gaps identified in the literature review. While the literature demonstrates significant progress in leveraging GIS for emissions monitoring, waste management, renewable energy integration, and biodiversity conservation, these applications are often fragmented and need a cohesive system for real-time data integration, analysis, and decision-making. Additionally, these environmental initiatives need to be more aligned with effective stakeholder engagement and comprehensive decision-support mechanisms.

The proposed conceptual framework resolves these issues by integrating a Data Integration Layer to consolidate diverse datasets, Spatial Analysis to provide in-depth environmental insights, and Interactive Dashboards to facilitate real-time monitoring and visualisation. Moreover, including a Decision Support System enables predictive and data-driven decision-making, while the Stakeholder Engagement Platform fosters stakeholder collaboration and transparency. Together, these components create a unified and dynamic system that addresses the limitations of current practices, enabling ports to adopt a holistic, technology-driven approach to sustainability and achieve greater alignment with global sustainability goals.

3. Conceptual Framework for Smart GIS in GPPs

Integrating Smart GIS into GPPs requires a robust conceptual framework incorporating advanced technologies, real-time data analytics, and stakeholder collaboration. This framework can be broken into five essential components, each critical to achieving environmental sustainability while maintaining operational efficiency.

Figure 1 presents a Conceptual Framework for Smart GIS in GPPs, highlighting the integration of critical components to enhance sustainability and operational efficiency. At its core is the Data

Integration Layer, which consolidates and harmonises data from various sources, serving as the foundation for other elements. The framework incorporates Interactive Dashboards to visually present data, enabling intuitive analysis and real-time monitoring. It also features a Decision Support System that aids in strategic planning and informed decision-making. Additionally, Spatial Analysis leverages geospatial data to provide in-depth insights into environmental and operational aspects. Lastly, the Stakeholder Engagement Platform fosters stakeholder collaboration and communication, ensuring inclusive participation in green port initiatives. This holistic approach aims to optimise green port practices through technology-driven solutions.

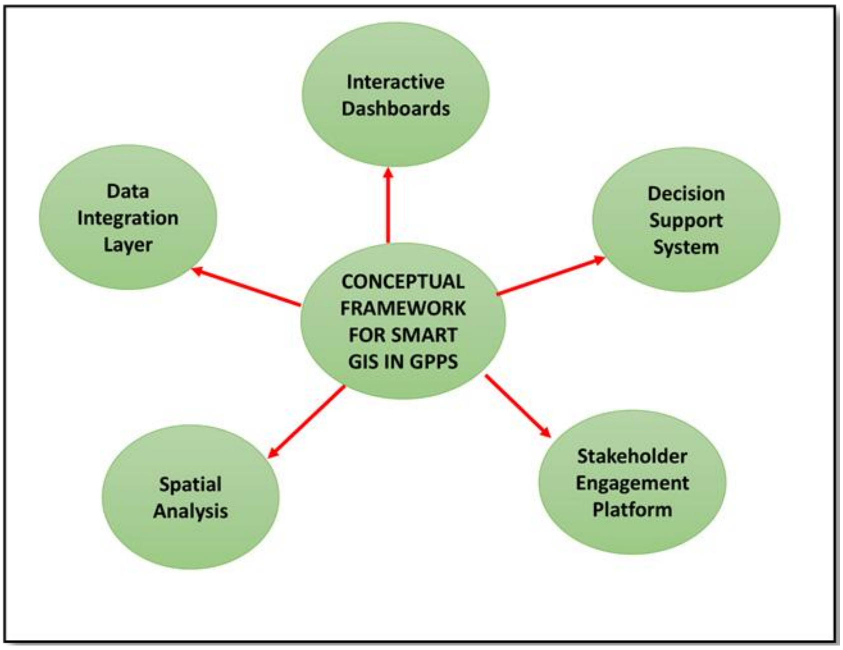

Fig. 1. A Proposed Conceptual Framework for Smart GIS in GPPs

The Data Integration Layer forms the backbone of the framework by aggregating data from multiple sources, including IoT sensors, satellite imagery, and operational databases. This centralised repository enables ports to collect and harmonise vast amounts of real-time data on emissions, energy usage, and waste generation. For instance, IoT sensors installed on port equipment can monitor fuel consumption, while satellite imagery can provide insights into land use changes and environmental impacts. The Port of Singapore has successfully implemented a data integration layer that consolidates data from its smart monitoring systems, enabling seamless information flow and real-time updates on environmental performance [15].

Spatial Analysis and Modelling leverages GIS tools to examine spatial patterns and trends in emissions, energy consumption, and waste management. By applying AI algorithms, ports can predict future trends and identify areas requiring immediate intervention. For example, the Port of Rotterdam uses predictive modelling to forecast emission hotspots based on historical data, allowing targeted investments in cleaner technologies. Similarly, advanced spatial analysis at the Port of Los Angeles has optimised cargo-handling equipment placement, reducing fuel consumption and emissions while improving operational efficiency [14].

The Interactive Dashboards component translates complex data into intuitive visualisations, providing real-time insights into key sustainability performance indicators (KPIs). These dashboards allow stakeholders to monitor metrics such as carbon emissions, renewable energy use, and waste recycling rates. The Port of Antwerp has adopted GIS-enabled dashboards that offer dynamic visualisations of its energy efficiency and carbon footprint, empowering decision-makers to act swiftly on sustainability goals [18].

A Decision Support System (DSS) enhances strategic decision-making by simulating various scenarios and evaluating their potential impacts. For instance, GIS-based DSS tools can assess the environmental consequences of proposed infrastructure projects, such as new berths or dredging operations. Johor Port in Malaysia has utilised a GIS-integrated DSS to evaluate the ecological impact of its expansion plans, enabling the port to strike a balance between development and environmental preservation. These simulations mitigate risks and provide a clear roadmap for implementing sustainable practices [26].

Finally, the Stakeholder Engagement Platform fosters collaboration among port authorities, regulatory bodies, and local communities. Ma *et al.,* [11] agreed that by presenting GIS visualizations in an accessible format, this platform ensures transparency and facilitates dialogue among stakeholders. For example, the Port of Los Angeles has implemented a public GIS portal that provides detailed maps of its air quality initiatives, enabling community members to track progress and offer feedback. Such initiatives enhance stakeholder trust and encourage collective action toward sustainability.

This conceptual framework for Smart GIS in GPPs exemplifies how advanced technologies can transform port environmental management. By integrating data-driven insights, predictive modelling, and collaborative platforms, ports can effectively address environmental challenges, enhance operational performance, and align with global sustainability objectives. This holistic approach not only supports environmental conservation but also strengthens ports' economic and social resilience in the face of evolving regulatory and market demands.

4. Discussion

Integrating Smart GIS in GPPs offers transformative potential for environmental sustainability, operational efficiency, and stakeholder collaboration. This discussion delves into the benefits, challenges, and global best practices, offering insights into how ports can leverage these technologies to achieve sustainable development goals.

One of the primary benefits of adopting Smart GIS is its ability to enable real-time monitoring of environmental metrics, such as emissions, energy consumption, and waste generation. Based on Ali *et al.,* [2] using IoT sensors and satellite imagery, ports can continuously track environmental performance and make immediate adjustments. For instance, the Port of Rotterdam has implemented GIS-enabled emission monitoring systems that provide real-time data on nitrogen oxide (NOx) and sulphur dioxide (SO2) levels, enabling the port to proactively reduce its pollution hotspots by 25% over five years. Similarly, the Port of Los Angeles uses GIS to track energy use and carbon footprints across its operations, facilitating a shift toward renewable energy solutions that have reduced greenhouse gas emissions by 15%.

Data-driven decision-making is another critical advantage, as Smart GIS integrates predictive analytics and scenario modelling. These tools allow port authorities to evaluate proposed actions' environmental and economic impacts, such as expanding port facilities or introducing electric cargo-handling equipment. For example, the Port of Antwerp leverages GIS-based decision support systems (DSS) to simulate the outcomes of various energy strategies, ultimately achieving a 20% reduction in operational energy costs by optimising solar panel placements [20]

This data-centric approach ensures that decisions are aligned with sustainability goals and economically viable.

In addition, Smart GIS facilitates enhanced stakeholder engagement by providing accessible visualisations of complex spatial data. Stakeholders, including local communities, regulatory agencies, and private operators, can interact with GIS dashboards to better understand ongoing initiatives and contribute to decision-making processes. For example, the Port of Los Angeles has developed a public GIS portal that displays air quality metrics, enabling community members to monitor progress and hold the port accountable for its sustainability targets [2]. This transparency builds trust and fosters collaboration, crucial for long-term success in Green Port Practices.

However, the adoption of Smart GIS in ports faces several significant challenges that can impede its implementation, particularly in developing regions such as Malaysia. High implementation costs remain one of the primary barriers, especially for smaller ports operating under constrained budgets [15]. The initial investment in IoT infrastructure, GIS software, and skilled personnel can be substantial. For instance, setting up a comprehensive Smart GIS platform requires deploying advanced IoT sensors across port facilities to monitor parameters such as emissions, energy use, and waste generation. Ports like Northport and Westport in Malaysia could address this financial challenge by exploring public-private partnerships (PPPs), where private technology providers collaborate with port authorities to share costs and benefits. Additionally, government grants or subsidies targeted at green initiatives could help alleviate the financial burden on port operators. For example, Singapore’s Green Port Programme provides financial incentives to ports adopting sustainable technologies, setting a precedent that Malaysia could follow.

Another key challenge is data integration. Ports deal with diverse and often incompatible datasets, including environmental monitoring, cargo handling, and vessel traffic data. This lack of standardization can create bottlenecks in the effective use of Smart GIS [26]. Developing robust data governance frameworks is essential to address this issue. These frameworks should include standardized data collection protocols, centralized data repositories, and interoperability standards to ensure seamless integration of data from multiple sources. For example, the Port of Rotterdam has implemented a centralized data platform that integrates real-time data from various sensors, enabling efficient decision-making and enhanced operational performance [22]. Malaysian ports could adopt similar centralized systems to streamline data integration and improve the utility of Smart GIS.

Apart from that, the shortage of skilled personnel with expertise in GIS, IoT, and data analytics is another significant hurdle. Designing, managing, and analyzing Smart GIS systems require specialized knowledge that is currently lacking in many ports [26]. To overcome this challenge, Malaysian ports need to invest in workforce development programs. Collaborations with academic institutions could play a vital role in bridging the skills gap. For instance, Singapore’s Maritime and Port Authority (MPA) has partnered with universities to create specialized training courses in innovative port technologies [16]. These programs encourage students with practical skills in GIS and data analytics, ensuring a steady pipeline of professionals ready to support Smart GIS implementation. Malaysian ports could emulate this approach by working with local universities to develop tailored training modules that focus on the specific needs of the port industry. Additionally, offering competitive salaries and clear career progression opportunities can help attract and retain talent in this specialized field.

In addition, operational resistance to change is also a challenge, as the adoption of Smart GIS often requires a shift in established workflows and practices [15]. Employees accustomed to traditional methods may resist adopting new technologies due to a lack of understanding or fear of redundancy. This resistance can be mitigated through targeted awareness campaigns and training programs that emphasize the benefits of Smart GIS for operational efficiency and environmental sustainability. For example, the Port of Los Angeles conducted extensive employee engagement sessions before implementing its GIS-based emissions tracking system, ensuring buy-in from all stakeholders [11].

Lastly, cybersecurity concerns arise as Smart GIS systems involve the transmission of sensitive data over digital platforms. Ports must safeguard their systems against cyber threats, which could compromise operational integrity [13]. Establishing robust cybersecurity measures, such as encrypted data transmission, regular system audits, and employee training on cybersecurity best practices, is critical. The Port of Singapore has successfully implemented a multi-layered cybersecurity framework to protect its digital infrastructure, serving as a model for other ports [16].

Global best practices from leading ports such as Rotterdam and Los Angeles provide a roadmap for overcoming these challenges. For instance, Rotterdam's phased approach to implementing Smart GIS—starting with pilot projects and gradually scaling up—has demonstrated how ports can manage costs and complexity while achieving tangible results. Similarly, Los Angeles's emphasis on community engagement through public GIS portals has underscored the importance of stakeholder trust in driving sustainability initiatives [19].

Adopting these lessons could position Malaysian ports as leaders in sustainable port management within the ASEAN region. By leveraging Smart GIS, they can balance economic growth and environmental preservation, aligning with global trends in green port development while addressing local challenges. Strategic investments in technology, workforce development, and collaborative frameworks will be essential to unlocking the full potential of Smart GIS in achieving long-term sustainability goals.

5. Conclusion

In conclusion, Smart GIS is more than a technological innovation; it is a strategic enabler of sustainable port management. Adopting Smart GIS offers a dual benefit for Malaysian ports: aligning with global sustainability standards and enhancing competitiveness in the international maritime industry. By leveraging Smart GIS, Malaysian ports can position themselves as regional leaders in green port practices, demonstrating that economic growth and environmental conservation are not mutually exclusive but mutually reinforcing. Moving forward, a commitment to integrating Smart GIS into port operations will be essential for achieving long-term sustainability goals and securing a competitive edge in global shipping to become greener.

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References

[1] Abdullah, Nor Liza, Mohamad Rohieszan Ramdan, Nurul Ashykin Abd Aziz, Hazrul Izuan Shahiri, and Mohd Danial Afiq Khamar Tazilah. "Managing the Adoption of Geospatial Information and Technologies in Multiple Industries." *Institutions and Economies* (2024): 79-112. https://doi.org/10.22452/IJIE.vol16no4.3

[2] Ali, Aitizaz, Muhammad Zakwan Hadeed, Seyedmostafa Safavi, and Munir Ahmad. "Leveraging GIS for Environmental Planning and Management." In *Global Challenges for the Environment and Climate Change*, pp. 308-331. IGI Global, 2024. https://doi.org/10.4018/979-8-3693-2845-3.ch016

[3] Barberi, Salvatore, Mariacrocetta Sambito, Larysa Neduzha, and Alessandro Severino. "Pollutant emissions in ports: a comprehensive review." *Infrastructures* 6, no. 8 (2021): 114. https://doi.org/10.3390/infrastructures6080114

[4] Chen, Chen, and Jasmine Siu Lee Lam. "Sustainability and interactivity between cities and ports: A two-stage data envelopment analysis (DEA) approach." *Maritime Policy & Management* 45, no. 7 (2018): 944-961. https://doi.org/10.1080/03088839.2018.1450528

[5] Durlik, Irmina, Tymoteusz Miller, Danuta Cembrowska-Lech, Adrianna Krzemińska, Ewelina Złoczowska, and Aleksander Nowak. "Navigating the sea of data: a comprehensive review on data analysis in maritime IoT applications." *Applied Sciences* 13, no. 17 (2023): 9742. https://doi.org/10.3390/app13179742

[6] Haraldson, Sandra, Mikael Lind, Zeeshan Raza, Johan Woxenius, and Fredrik Olindersson. "The concept of the sustainable port: ports becoming enablers of sustainability in transports and logistics." (2023).

[7] International Maritime Organization (IMO). (2022). Fourth GHG Study 2022. International Maritime Organization.

[8] Ismail, Isha Baizura Binti. "An Integration of Coastal Erosion Mapping Using Statistical Approach to Predict Shoreline Changes." PhD diss., Universiti Tun Hussein Onn (Malaysia), 2023.

[9] Jasmi, Muhamad Fairuz Ahmad, Yudi Fernando, and Ishak Ismail. "Adoption level of maritime green supply chain management: preliminary findings from a pilot study." *International Journal of Logistics Systems and Management* 37, no. 4 (2020): 556-575. https://doi.org/10.1504/IJLSM.2020.111826

[10] Kaur, Cheryl Rita. "Conservation and Sustainable Management of Marine Living Resources and the Environment: A National Perspective." Malaysia: A Maritime Nation-Hardcover (Editors: Ruhanas Harun & Sabirin Ja'afar) (2021).

[11] Ma, Siqi, and Daniel Q. Tong. "Neighborhood Emission Mapping Operation (NEMO): A 1-km anthropogenic emission dataset in the United States." *Scientific Data* 9, no. 1 (2022): 680. https://doi.org/10.1038/s41597-022-01790-9

[12] Mishra, Priyanka, and Ghanshyam Singh. "Energy management systems in sustainable smart cities based on the internet of energy: A technical review." *Energies* 16, no. 19 (2023): 6903. https://doi.org/10.3390/en16196903

[13] Oladeji, Olamide. "Data-Driven Sustainability: Advancing Electric Vehicle Adoption and Carbon Accounting Using Artificial Intelligence and Geospatial Analytics." PhD diss., Stanford University, 2023.

[14] Pirhadi, Milad, Trevor S. Krasowsky, George Gatt, and David C. Quiros. "Criteria pollutant and greenhouse gas emissions from cargo handling equipment operating at the Ports of Los Angeles and Long Beach." *Science of the Total Environment* 927 (2024): 172084. https://doi.org/10.1016/j.scitotenv.2024.172084

[15] Sadiq, Muhammad, Syed Wajahat Ali, Yacine Terriche, Muhammad Umair Mutarraf, Mustafa Alrayah Hassan, Khalid Hamid, Zulfiqar Ali, Jia Yin Sze, Chun-Lien Su, and Josep M. Guerrero. "Future greener seaports: A review of new infrastructure, challenges, and energy efficiency measures." *IEEE Access* 9 (2021): 75568-75587. https://doi.org/10.1109/ACCESS.2021.3081430

[16] Salleh, Nurul Haqimin Mohd, Jagan Jeevan, and Abdul Hafaz Ngah. "Analyzing the influence of the fourth industrial revolution (IR4.0) on seaport competitiveness through a sequential mediators' procedure." *WMU Journal of Maritime Affairs* (2024): 1-26. https://doi.org/10.1007/s13437-024-00352-7

[17] Supardi, I. H. K., N. M. Abdullah, A. Tugi, and B. H. Ismail. "Spatial and temporal analysis of marine water pollution in Port Klang: Developing a GIS database for assessing patterns and trends." In *IOP Conference Series: Earth and Environmental Science*, vol. 1347, no. 1, p. 012012. IOP Publishing, 2024. https://doi.org/10.1088/1755-1315/1347/1/012012

[18] Vagen, Drew Quenna. "Site Suitability Analysis for Implementing Tidal Energy Technology in Southern California." PhD diss., University of Southern California, 2021.

[19] Van den Berghe, Karel. Planning the port city: a contribution to and application of the relational approach, based on five case studies in Amsterdam (The Netherlands) and Ghent (Belgium). Ghent University, 2018. https://doi.org/10.1016/j.jtrangeo.2018.05.013

[20] Van der Kroft, Douwe FA, and Jeroen FJ Pruyn. "A study into the availability, costs and GHG reduction in drop-in biofuels for shipping under different regimes between 2020 and 2050." *Sustainability* 13, no. 17 (2021): 9900. https://doi.org/10.3390/su13179900

[21] Wang, Bei, Qing Liu, Lei Wang, Yongjun Chen, and Jisheng Wang. "A review of the port carbon emission sources and related emission reduction technical measures." *Environmental Pollution* 320 (2023): 121000. https://doi.org/10.1016/j.envpol.2023.121000

[22] Wild, Tom, H. Bulkeley, S. Naumann, Z. Vojinovic, C. Calfapietra, and K. Whiteoak. "Nature-Based Solutions." State of the Art in EU-funded Projects. Publication Office of the European Union: Luxembourg (2020).

[23] Yau, Kok-Lim Alvin, Shuhong Peng, Junaid Qadir, Yeh-Ching Low, and Mee Hong Ling. "Towards smart port infrastructures: Enhancing port activities using information and communications technology." *Ieee Access* 8 (2020): 83387-83404. https://doi.org/10.1109/ACCESS.2020.2990961

[24] Yusop, Zulkifli Mohd, Siti Atirah Ibrahim, Muhamad Zalani Daud, and Hadi Suyono. "Evaluating the Horizon of Renewable Power: A Comprehensive Review of Floating Photovoltaic Systems' Performance and Technologies." *Journal of Advanced Research in Applied Sciences and Engineering Technology* (2024): 67-88. https://doi.org/10.37934/araset.63.2.6788

[25] Zain, Rosmaizura Mohd, Jagan Jeevan, Nurul Haqimin Mohd Salleh, Abdul Hafaz Ngah, Ainon Ramli, Mohd Zaimmudin Mohd Zain, Liafisu Sina Yekini, and Ali Nur Dirie. "Future opportunities for port city development: A reciprocal evaluation for competitive advantage for Malaysian seaports." *Journal of Maritime Research* 21, no. 1 (2024): 265-282.

[26] Zaudi, M. A. Landfill site selection using geographical information system and multi-criteria decision analysis in Johor Bharu, Malaysia (Thesis Abstract). Universiti Putra Malaysia, Malaysia. 2023.

[27] Zhang, Zhechen, Chenghong Song, Jiawen Zhang, Zhonghao Chen, Mingxin Liu, Faissal Aziz, Tonni Agustiono Kurniawan, and Pow-Seng Yap. "Digitalization and innovation in green ports: A review of current issues, contributions and the way forward in promoting sustainable ports and maritime logistics." *Science of the Total Environment* (2023): 169075. https://doi.org/10.1016/j.scitotenv.2023.169075