Review Article
Turkish Journal of Maritime and Marine Sciences

DOI: 10.52998/trjmms.1707732
Volume: XX Issue: XX (20XX) XX-XX

Artificial Intelligence in Port Environmental Management: A Strategic Analysis

Liman Çevre Yönetiminde Yapay Zeka: Stratejik Bir Analiz

Türk Denizcilik ve Deniz Bilimleri Dergisi

Cilt: XX Sayı: XX (20XX) XX-XX

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ABSTRACT

Maritime activities play a crucial role in global trade. However, seaports cause various environmental problems, particularly pollution in coastal and urban areas. Artificial intelligence (AI) and its subfields, machine learning and deep learning have emerged as promising tools for addressing these problems, garnering increasing interest within the maritime sector. Nevertheless, existing studies in literature often focus on a limited scope and fail to incorporate environmental priorities in seaport operations. This study explored the potential of AI and its subfields to enhance resilience to environmental problems posed by operational activities in seaports. Ten port environmental priorities from the ESPO's report were included as environmental indicators. The study was conducted in two phases. The first phase involved a systematic literature review of 117 sources from the Web of Science and Scopus databases. In line with the systematic analysis, the second phase was evaluated using a SWOT analysis. Thereafter, a series of strategic recommendations were formulated on the based on an analysis of both internal and external factors. The study provided twelve strategic recommendations for enhancing current practices. AI and its subfields has the potential to become a strategic tool for achieving seaport sustainability goals that align with environmental priorities.

Keywords: Artificial Intelligence, Machine Learning, Deep Learning, Environmental Priority, Seaport Management, ESPO

Article Info
Received: 27 May 2025
Revised: 20 June 2025
Accepted: 21 June 2025

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To cite this article: Önal, E., Toygar, A. and Tehci, A., (2025). Artificial Intelligence in Port Environmental Management: A Strategic Analysis, *Turkish Journal of Maritime and Marine Sciences*, XX (XX): XX-XX. doi: 10.52998/trjmms.1707732.

ÖZET

Denizcilik faaliyetleri küresel ticarette çok önemli bir rol oynamaktadır. Ancak limanlar, özellikle kıyı ve kentsel alanlarda kirlilik olmak üzere çeşitli çevre sorunlarına neden olmaktadır. Yapay zekâ (YZ) ve alt alanları olan makine öğrenimi ve derin öğrenme, bu sorunları çözmek için umut vaat eden araçlar olarak ortaya çıkmış ve denizcilik sektöründe giderek artan bir ilgi görmüştür. Bununla birlikte, literatürdeki mevcut çalışmalar genellikle sınırlı bir alana odaklanmakta ve liman operasyonlarında çevresel öncelikleri dikkate almamaktadır. Bu çalışma, deniz limanlarındaki operasyonel faaliyetlerin yol açtığı çevresel sorunlara karşı dayanıklılığı artırmak için YZ ve alt alanlarının potansiyelini araştırmıştır. ESPO raporundaki on liman çevresel önceliği çevresel göstergeler olarak dahil edilmiştir. Çalışma iki aşamada gerçekleştirilmiştir. İlk aşamada, Web of Science ve Scopus veritabanlarından 117 kaynağın sistematik bir literatür taraması yapılmıştır. Sistematik analizle uyumlu olarak, ikinci aşama SWOT analizi kullanılarak değerlendirilmiştir. Ardından, iç ve dış faktörlerin analizine dayalı olarak bir dizi stratejik öneri formüle edilmiştir. Çalışma, mevcut uygulamaları geliştirmek için on iki stratejik öneri sağlamıştır. YZ ve alt alanları, çevresel önceliklerle uyumlu liman sürdürülebilirlik hedeflerine ulaşmak için stratejik bir araç olma potansiyeline sahiptir.

Anahtar sözcükler: Yapay Zekâ, Makine Öğrenimi, Derin Öğrenme, Çevresel Öncelik, Liman Yönetimi, ESPO

1. INTRODUCTION

The maritime sector is a cornerstone of the global economy, carrying over 80% of international trade by volume (UNCTAD, 2024). The growth of the world economy accelerates maritime trade volumes, which in turn increases cargo-handling capacities at seaports (Munim and Schramm, 2018; Sogut and Erdoğan, 2022). Seaports play a strategic role in international transportation, logistics, and trade by providing essential connections between the shore and sea. This connectivity positions seaports at the center of both maritime and shore traffic. However, this centrality makes seaports a significant sources of atmospheric pollution (Owusu-Mfum *et al.*, 2023). A case study quantified this pollution and found that the annual share of regulated pollutants attributable to shipping and land movements in seaports was 33% for PM10, 43% for NO2, and 60% for SO2 (Gobbi *et al.*, 2020). The expansion and intensification of seaport operations lead to the release of dust and pollutants, disruption of marine ecosystems, air and water pollution, and adverse impacts on environmental sustainability and the quality of life of local communities (Notteboom et al., 2020; Quintana et al., 2016; Woo et al., 2018; Y. C. Yang and Chen, 2016).

In recent years, seaport management has become increasingly focused on sustainability. Ensuring a safe operating environment and minimizing environmental harm have emerged as primary goals for seaports (Verschuur et al., 2020). In this context, the European Seaports Organization (ESPO) has identified ten different environmental priorities in the seaport since 1996 and regularly updates these priorities every year. The priorities identified in the latest report are climate change, energy efficiency, air quality, noise, seaport development (land-related), ship waste, garbage/seaport waste, water quality, relationship with the local community and seaport development (water-related) (ESPO, 2024).

It is widely considered that the negative impacts of seaport activities can be mitigated through technological innovation (Nogué-Algueró, 2020). There are several studies in the literature that examine the environmental impact of Artificial Intelligence (AI) in the maritime sector. AI has transformative potential to reduce the sector's environmental footprint by addressing emissions, optimizing energy consumption, and improving operational efficiency (Durlik et al., 2024; Zare et al., 2024). Digital technologies, including AI, facilitate the management of resource emissions, raw materials, and waste in seaport cities (D'Amico et al., 2021). AI is being used to monitor environmental threats and provide early warning of emergencies in seaports (Zheng et al., 2020). In this regard, AI and its subfields, machine learning, can predict traffic patterns and enable simulations that explore alternative solutions to traffic congestion. In addition, AI could significantly reduce greenhouse gas emissions (Lehmacher et al., 2022). The implementation of AI in container handling operations at seaports contributes to both operational efficiency and environmental sustainability, particularly in terms of travel distance, gas emissions, and energy efficiency (Lee et al., 2023; Tsolakis et al., 2022).

1.1. Aims and Contributions of the Study

The study systematically examines the potential contributions of AI and its subfields within the seaport sector, focusing on the ten environmental priorities defined by ESPO. Although numerous studies in the literature explore the potential of AI to contribute to environmental sustainability in port operations, they often tend to examine the problem within a narrow scope and may overlook strategic frameworks such as the environmental priorities outlined by ESPO. The study differs from the existing literature by evaluating AI as three categories (artificial intelligence, machine learning, and deep learning). The environmental priorities examined are organized into ten categories, aligned with ESPO definitions. The literature review conducted as part of this study is illustrated in the Figure 1 that will be made available to all readers and researchers. Through SWOT analysis, the integration of AI into seaport operations is assessed from four different perspectives, and strategic decision-making approaches are developed by constructing a TOWS matrix.

2. THEORETICAL FRAMEWORK

2.1. Environmental Priorities in Seaports

Seaports are strategic coastal facilities that play an essential role in sustaining global trade and fostering economic development. However, their significant involvement in maritime logistics contributes to global warming, air and marine pollution, and increased energy consumption by ships (Jeevan et al., 2023). Environmental sustainability in seaport management is about using natural resources efficiently and minimizing environmental impact. Nevertheless, the environmental challenges posed by seaport operations have positioned this sector as a focal point for sustainability efforts. In particular, ESPO's environmental priorities are a fundamental guide for promoting environmental sustainability in seaport management. Since 2016, ESPO has published the Environmental Report, which outlines the progress, challenges and aspirations of seaports with regard to environmental sustainability. The environmental priorities detailed in the final report, which form the conceptual framework for this study, are listed below:

Climate Change - It is recognized as a significant environmental priority for European seaports (Puig et al., 2024). The increase in hazardous weather events has a direct impact on navigation, infrastructure and seaport operations (Jiang et al., 2020). It is emphasized that seaport operators should focus on these criteria to mitigate the negative impacts of climate change and global warming (Di Vaio et al., 2018).

Energy Efficiency - Since there is a correlation between seaport efficiency and energy consumption, seaport equipment utilization has a significant impact on energy consumption (Martínez-Moya et al., 2019). Reducing energy consumption in seaport operations is a critical objective for port operators to meet their sustainability goals. The rising cost of energy consumption and the climate change objectives of seaport operators have led operators to prioritize energy efficiency (Acciaro et al., 2014; Iris and Lam, 2019). In this context, seaports have launched initiatives to formulate business strategies aimed at reducing emissions. These strategies include the development of renewable energy technologies that use natural resources to power seaport operations (Agostinelli et al., 2022). The adoption of renewable energy sources, the capture and storage of CO2, and the formulation of energy efficiency plans are cited as key components of seaport sustainability (Lam and Notteboom, 2014).

Air Quality - In seaport operations, various vehicles, including marine vessels, trucks, yard vehicles-cranes, and other equipment, contribute to air pollution due to their differing characteristics. Fuel-related emissions and combustion gases from vehicle traffic are significant sources of air pollution (Twrdy and Zanne, 2020).

Noise - Pollution is a significant issue in cities due to the proximity of seaports to residential areas, impacting both port workers and the surrounding population (Schenone et al., 2014). The rise in traffic entering and exiting seaports further contributes to increased noise emissions in the environment. Additionally, roadways, railways, shipping activities, seaport operations, and industrial resources play an essential role in the development of this environmental concern (Fredianelli et al., 2021).

Port development (land related) - Coastal areas consist of more complex structures than those found in other regions (Susman et al., 2021). This development includes the construction and expansion of terminals, the establishment of road-rail connections, and the installation or modernization of logistics-related facilities. This environmental priority is defined as a strategic focus aimed at improving infrastructure to support increasing trade volumes while simultaneously ensuring minimal environmental impact (ESPO, 2024).

Ship Waste - The continuous advancement of global transportation raises significant environmental concerns regarding the management of waste generated by ships in maritime transportation, which is the most commonly utilized mode of transport (Zuin et al., 2009). Ships contribute to pollution through the production of various types of waste, including oily liquids, contaminated water, and both disinfected and undisinfected sewage (Abdellaoui et al., 2023; Butt, 2007; Özbay et al., 2024; Shu et al., 2022).

Garbage/Port Waste - Port waste refers to the waste generated in connection with seaport-related activities. Inadequate processing or the failure of seaport operators to properly dispose of waste can pose significant risks to public health and the environment. This environmental issue has garnered considerable attention due to its substantial impact on marine ecosystems and the operational efficiency of seaports (Puig and Darbra, 2024). Seaport waste management aims to prevent pollution and ensure environmental protection, taking into account the waste generated during ship berthing as well as all types of waste generated during loading and unloading operations (Özbay et al., 2024).

Water Quality - The industrial presence in seaports poses a significant risk to the water quality of port basins, potentially harming the marine ecosystem and its living resources. The rapid expansion of coastal facilities, coupled with the construction and metal pollution associated with global economic development, is raising increasing concerns about water quality in seaports (Cecchi et al., 2023; Guo et al., 2024).

Relationship with the Local Community - In response to the increasing levels of pollution associated with seaports, governments have begun to implement regulations aimed at promoting green seaports to ensure the sustainability of maritime activities (Zhou et al., 2024). It is crucial that the regulations established for green seaports are approached with an integrated perspective that encompasses social, economic, and environmental dimensions to enhance the processes necessary for achieving sustainable seaport status (Schipper et al., 2017). The adherence of seaport operators to green seaport regulations, along with the compliance of logistics companies with green seaport transportation guidelines, represents the most effective combination of the government's environmental regulatory strategies (Deng and Han, 2024). In all of these cases, collaboration between seaports and other organizations has a positive impact on sustainability policies (Lim et al., 2019).

Port Development (Water-Related) - Aquatic port development is a priority that emphasizes the importance of expanding and upgrading coastal infrastructure. This type of development encompasses activities conducted offshore, such as dredging and deepening, the construction or renovation of quays, the building of breakwaters, and the reclamation of space in aquatic areas (ESPO, 2024). Underwater dredging activities not only generate noise disturbances but also essentially impact marine ecosystems (Sugrue and Adriaens, 2022). Sediments in seaports are often contaminated with metals due to human activities. Regular dredging is essential to decrease the impact of pollutants on the environment and to achieve appropriate water depths (Norén et al., 2020). Furthermore, substantial amounts of waste material derived from mud have been discovered during the dredging process (Barraza et al., 2024).

2.2. Use of Artificial Intelligence

AI explores methods for increasing computer efficiency through advanced programming techniques, enabling machines to acquire human-like capabilities such as learning, reasoning, and self-improvement (Abbass, 2019; Kok et al., 2009). The uses of AI in maritime transportation are very varied. It optimizes navigation routes, ensures safety, and introduces a new level of intelligence to autonomous ships. The capacity of AI to analyze and respond to dynamic marine environments enables autonomous ships to be used effectively under changing conditions. This presents a substantial opportunity for the widespread adoption of autonomous marine systems in the future (Andrei and Scarlat, 2024). By leveraging advanced predictive modeling techniques, seaports can improve efficiency, reduce costs, and remain competitive in international maritime trade (Dinh et al., 2024). AI has been categorized into various subfields by numerous organizations and studies (ISO, 2024; Kotsiopoulos et al., 2021; NASA, 2024; Sun et al., 2022). The study evaluates AI as a technology encompassing machine learning (ML) and deep learning (DL).

ML is a subfield that enables computers to learn and evolve by imitating or surpassing human learning capabilities (Arel, Rose and Karnowski, 2010; Taye, 2023). It also gives machines the ability to analyze data for pattern recognition and future prediction (Agrawal et al., 2019). Numerous studies indicate that ML contributes to environmental sustainability in seaports. Study conducted between 2017 and 2021 on emissions and energy consumption, focusing on environmental indicators, highlights the advancements in ML applications (Mansoursamaei et al., 2023). Furthermore, energy-saving strategies for vessels in seaports have been developed using ML-supported methods, which provide more accurate estimations of ships' energy consumption and aim to reduce energy usage in the context of green seaports (Peng et al., 2020).

DL enables machines to analyze patterns, categorize information, and think in more advanced and complex ways without human intervention (Abonamah et al., 2021). DL processes intricate data by utilizing information from various sources, allowing it to solve pattern detection tasks and address problems that lack mechanical solutions (Borowiec et al., 2022). DL contributes to advanced time series analysis, which is crucial in maritime operations (Wang et al., 2024).

AI applications are increasingly being used to optimize energy consumption, monitor water quality, and improve waste management. However, there is a lack of studies that examine the potential contributions of AI applications on environmental sustainability in the seaport sector, especially in an integrated manner with the priorities set by ESPO. This study addresses a significant gap in existing literature by examining the environmental potential contributions of AI on seaport operations in relation to ESPO priorities. In addition to making a theoretical contribution, the study intends to serve as a guiding resource for policymakers and seaport managers in achieving environmental sustainability goals by providing practical application suggestions.

3. EXPLANATION OF CONCEPT

This study consists of two phases. The first phase of the study included a systematic review to understand the potential contributions of AI and its subfields to environmental indicators in seaports. The process followed in this context is visualized in Figure 1. To examines sources relevant to the conceptual framework of the study, the following keywords were employed: "artificial intelligence" OR ai OR "machine learning" OR "deep learning" AND "port development (water-related)" "relationship with the local community" or "water quality" or "climate change" or "energy efficiency" or "air quality" or noise or "port development (land-related)" or "ship waste" or "garbage waste" or “port waste” “seaport” “port” “harbour” “ports” and “harbours”. During the screening process, the keywords, titles, and abstracts of the sources were taken into consideration. Examining these sources alone was insufficient for evaluating the current situation and developing strategic recommendations. In the second phase, the current situation was evaluated through a SWOT analysis. In the last step of this phase, TOWS analysis was employed to develop strategies addressing the potential contributions of AI and its subfields on ten environmental priorities.

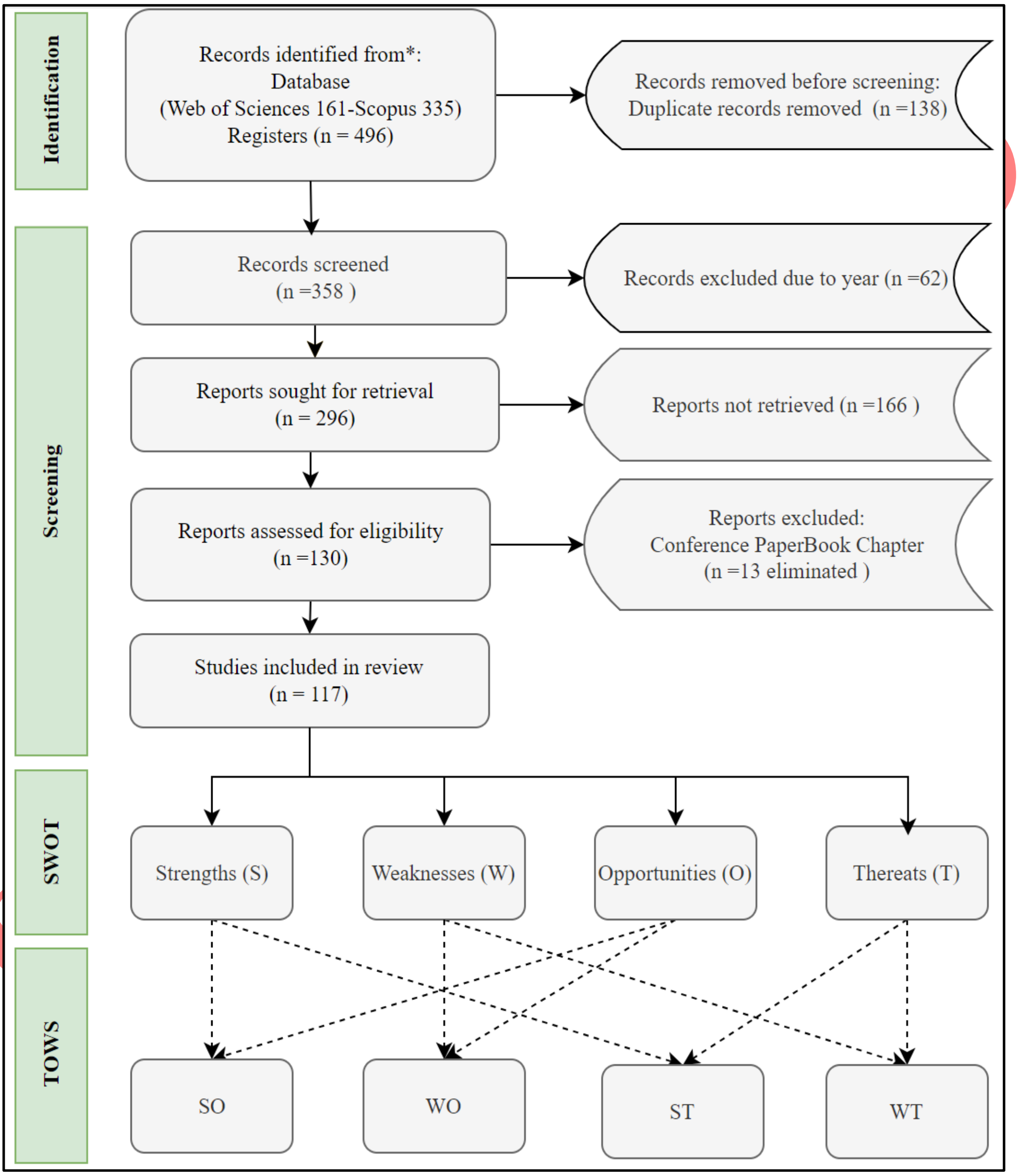

Figure 1. The Study Framework

4. RESULTS

First, a total of 496 sources were identified. After cleaning the duplicate records and removing irrelevant content, 358 sources were selected. Next, 296 sources were chosen based on their publication within the last five years. Additionally, only accessible sources were included in the selection process. Specifically, only sources with full-text access and review sources were considered for analysis; consequently, a total of thirteen sources, including book chapters and conference proceedings, were excluded from the evaluation. 117 sources were selected for detailed review and analysis. Second, the findings were organized using SWOT analysis, systematically examining the strengths, weaknesses, opportunities, and threats of the current situation. In addition, given the specific focus of the study, both sectoral reports and the authors' expert perspectives were incorporated as complementary references in the SWOT analysis. The findings are presented in Table 1.

Table 1. Strategic Assessment of AI Integration Based on ESPO Environmental Priorities

		Definition	References			Definition	References
STRENGTHS	Operational Efficiency and Optimization (S1)	AI and its subfields enhance efficiency in various domains, including traffic management in seaports, ship speed optimization, fuel consumption reduction, emissions control, container handling and storage optimization, predict and explain and marine pilot occupational accidents.	(Camliyurt et al., 2023; Dinh et al., 2024; Lee et al., 2023; Lee et al., 2021; Martínez et al., 2023)	WEAKNESSES	Large Data Storage Capacity and Cooling Needs (W1)	In order to implement AI based technologies, the large data storage facilities associated with AI must be adequately cooled.	(Kshetri, 2024; Ren and Wierman, 2024; Safdie, 2024; Yang et al., 2018)
	Decision Support (S2)	AI enhance decision-making and improve reliability by extracting meaningful insights from large data sets.	(Dinh et al., 2024; Duan et al., 2019; Raj and Brown, 2023)		Dependency on Non-Renewable Energy in AI Deployment (W2)	AI frequently depend on energy sources powered by fossil fuels. The limited use of renewable energy represents a significant drawback in terms of environmental sustainability.	(Safdie, 2024; Zhuk, 2023)
	Environmental Sustainability and Emission Reduction (S3)	AI and its subfields play a role in enhancing energy efficiency and contribute to green, assessing noise emissions, predicting environmental impacts, and reducing greenhouse gas emissions while protecting marine ecosystems.	(Deng et al., 2021; Drungilas et al., 2023; Lehmacher et al., 2022)		High Training and Operational Costs (W3)	As AI and its subfields become more complex, the associated costs of running algorithms, preparing data, and training can increase.	(Lemley et al., 2017; Study's Authors)

Table 1. continue

		Definition	References			Definition	References
OPPORTUNITIES	Environmental Regulations and Raising Awareness of the EcoPorts (O1)	AI and its subfields may enable the development of international environmental regulations and sustainable seaport management policies.	(Durlik et al., 2024; Kusumawati et al., 2023; Saafi et al., 2022)	**THEREATS**	Cybersecurity Risks and Data Privacy (T1)	Cyber-attacks (DDoS, hacking, malware, SQL injection, ransomware, going dark, and zero-day) were conducted on 21 different ports and port authorities between 2001 and 2022.	(NHL Stenden University, 2024; Ejjami and Boussalham, 2024)
	Autonomous Port Management and Digitalization (O2)	AI-based autonomous ships, digital twins in port system, and intelligent containers systems provide a competitive advantage in the industry by increasing operational efficiency.	(Toygar, 2024; Yao et al., 2021; Study's Authors)		Global Economic and Political Uncertainty (T2)	Uncertainties in global trade policy may negatively impact the integration of AI and its subfield into seaport management.	(Toygar, 2024; Study's Authors)
	AI and ML based Maintenance Systems (O3)	AI and ML can be used to develop real-time monitoring and preventive maintenance systems for port equipment, minimizing operational interruption.	(Chaibi and Daghrir, 2023; Kimera and Nangolo, 2020; Safuan and Syafira, 2024)		Uncertainties of Unmanned Control Systems (T3)	Over-reliance on AI and its subfields can reduce operational flexibility and limit the ability to act on unexpected technical failures.	(Fallon and Blaha, 2018; Study's Authors)

The data presented in the first phase provide a solid foundation for the second phase, allowing the study to progress with a holistic perspective. SWOT analyses are organized using the TOWS matrix to develop strategic recommendations. Twelve strategic recommendations were developed from these findings, which is detailed in Table 2. Figure 2 shows the internal and external factors of the twelve recommendations.

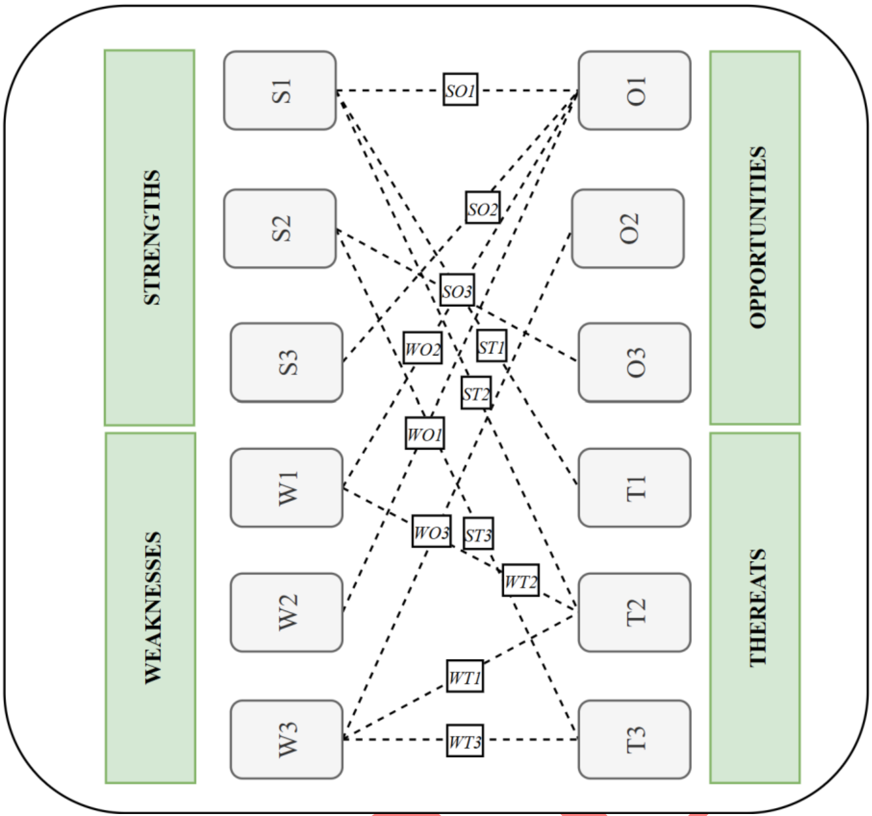

Figure 2. Interaction Diagram of Internal and External Factors

Table 2. Strategic Scenarios for Environmental Sustainability in Seaports

SO1	Optimizing the efficiency of seaport operations through the use of AI and its subfields, thereby reducing the carbon footprint by minimizing energy and fuel consumption.	ST1	Developing cybersecurity and privacy protocols using maritime cybersecurity detection systems based on AI and its subfields.
SO2	Ensuring sustainability in seaport operations through the monitoring and optimization of emissions using AI.	ST2	Avoiding global economic and political uncertainty by applying AI and its subfields to simulate the environmental impact of seaport operations and real-time monitoring.
SO3	Monitoring seaport operations through real-time optimization to predict air quality and emission levels, thereby minimizing the negative impact on the ecosystem.	ST3	Supporting sustainable policies that enable AI and its subfields to collaborate with humans and increase flexibility in seaport operations.
WO1	Implementing environmentally sustainable seaport operations by developing AI infrastructures that utilize renewable energy sources.	WT1	Increasing the resilience of seaports against economic changes and ensuring long-term operational sustainability by using AI-supported trade forecasting algorithms and market analysis.
WO2	Reducing energy and water consumption in data centers by developing cooling systems that minimize energy usage, thereby promoting environmentally friendly data processing.	WT2	Optimizing operational costs with AI-enabled intelligent data management systems and energy-efficient, high-performance cooling solutions
WO3	Developing innovative algorithms to reduce the energy consumption of complex models.	WT3	Using AI-powered risk simulation and security mechanisms for unmanned control systems

4. DISCUSSION

This study systematically examines the potential contributions of AI and its subfields to the environmental sustainability of seaports, using the framework of ten environmental priorities defined by ESPO. The findings indicate that AI and its subfields may have certain negative impacts on environmental sustainability in seaports; however, these impacts can be limited and potentially eliminated by focusing on strengths and opportunities. The steps undertaken and the findings obtained are discussed in detail below.

The first phase of the study shows that ML and DL are subfields of AI, and these technologies are currently the focus of investigation (Kotsiopoulos et al., 2021; Sun et al., 2022; Xiao et al., 2024). This means a growing demand for ML and DL in the integration of big data and AI. The phase also demonstrates that ML and DL algorithms can effectively optimize seaport operations while minimizing environmental impacts. These are in line with the study by Durlik et al. (2024), which pointed to the potential of AI to enhance operational efficiency in sustainable seaport management. All of these findings showed that AI has transformative potential for environmental indicators, including energy efficiency, emissions reduction, and water quality monitoring.

The second phase of the study, the SWOT analysis, provided a comprehensive assessment of the strengths, weaknesses, opportunities, and threats associated with integrating AI into seaport operations. The SWOT analysis shows that AI has several strengths in seaport operations. AI and its subfields can serve as effective approaches for optimizing ship speed to enhance energy efficiency, reducing fuel consumption, minimizing greenhouse gas emissions and underwater noise, improving container handling operations, predicting environmental impacts, and supporting data-driven decision-making. This is aligns with the research by Palomares et al. (2021), which demonstrated that AI's subfields can predict weather conditions to prevent environmental damage, and Durlik et al. (2024), who argue that AI's advanced ML algorithms and Internet of Things (IoT) integration can make more accurate predictions and better decisions. This finding is supported by Priya et al. (2023), which emphasizes the role of AI in reducing CO2 emissions, asserting that it is a crucial instrument for achieving environmental sustainability goals. In addition, this study demonstrates that AI can enhance efficiency in seaport operations, aligning with the findings of Kovalishin et al. (2023), who emphasized the significance of AI in optimizing seaport operations and demand forecasting. The strengths of AI in traffic management, ship speed optimization, and fuel consumption reduction significantly contribute to reducing environmental impacts. The capability of AI applications to conduct real-time data analytics suggests that environmental impacts in the seaport sector can be reduced. This is coherent with the findings of Chen et al. (2024), which indicate that AI's real-time data analytics in the logistics sector can effectively reduce negative environmental impacts. All of these findings reveal that AI has the potential to improve energy efficiency and reduce environmental contributions in the seaport sector.

Some of the weaknesses of AI are also pointed out in the SWOT analysis. Large data storage capacity and cooling needs, dependency on non-renewable energy in ai deployment and high training and operational costs have been identified as weaknesses. The insufficient utilization of renewable energy resources poses an additional challenge to achieving environmental sustainability (Zhuk, 2023). Furthermore, cybersecurity risks and data privacy, global economic and political uncertainty, over-reliance on AI and its subfields have been determined as threats. Both the literature and the findings of this study have revealed the need to develop more efficient AI applications concerning energy consumption, as well as the necessity for data centers powered by renewable energy sources.

So strategies propose that AI can serve as an effective tool for enhancing efficiency in seaport operations while reducing the carbon footprint. Specifically, the ability of AI to monitor and optimize emissions, as well as to predict air quality through AI-based real-time optimization systems, has been identified as a key strategic approach. Within the framework of ST strategies, AI-driven simulation and real-time monitoring systems are suggested as effective means to mitigate risks arising from global economic and political uncertainties. Furthermore, the necessity of developing sustainable policies that enable AI to collaborate with human operators in autonomous port management systems has been emphasized. WO strategies aim to overcome AI's weaknesses in environmental sustainability by leveraging opportunities. In this context, the integration of AI infrastructures with renewable energy sources, the implementation of energy-efficient cooling systems, and the development of innovative algorithms to reduce energy consumption have emerged as strategic priorities. WT strategies focus on preventing AI's weaknesses from exacerbating existing threats. Accordingly, the use of AI-powered forecasting algorithms is proposed to enhance the resilience of ports against economic fluctuations. Additionally, the adoption of AI-driven intelligent data management systems and energy-efficient cooling solutions is highlighted as a crucial step toward optimizing operational costs. The implementation of AI-based security mechanisms and risk simulation models is recommended to ensure the safe and sustainable deployment of AI in port operations.

5. CONCLUSION

SWOT and TOWS analyses indicate that the strengths of AI applications can be effective in eliminating environmental threats, while the weaknesses can be balanced by the opportunities they provide. The study reveals that AI has significant potential to improve operational efficiency, optimize energy consumption, and reduce emissions. However, challenges such as high energy consumption, dependence on fossil fuels, and cybersecurity risks should not be underutilized. The twelve strategies developed have the potential to significantly impact the environmental damage caused by seaport operations.

Some limitations of this study should be acknowledged, and future research should take them into account. First, SWOT and TOWS analyses were conducted; the study did not include insights from industry experts; recommendations were developed based solely on findings from the literature. Second, the study focused more on the positive aspects of AI's environmental impact within the seaport sector. However, it did not thoroughly address the negative implications of AI applications, such as energy consumption, reliance on fossil fuels, and the environmental impact of data centers. Future studies could focus on the development of innovative AI-based models aimed at reducing energy consumption and integrating renewable energy sources into seaport operations.

AUTHORSHIP CONTRIBUTION STATEMENT

Esma Önal: Methodology, Data curation, Conceptualization, Resources, Validation, Formal analysis**. Arda Toygar:** Writing–original draft, Writing—review and editing, Conceptualization, Visualization. **Ali Tehci:** Writing—review and editing, Supervision, Project administration. All authors have read and agreed to the published version of the manuscript.

CONFLICT OF INTERESTS

The author declares that there is no conflict of interest.

ETHICS COMMITTEE PERMISSION

No ethics committee permissions are required for this study.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this study the author(s) used [Grammarly, ChatGPT and Deepl] in order to improve its language and readability with caution. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

FUNDING

No funding was received from institutions or agencies for the execution of this research.

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