

Advancing Indian Port Reception Facilities Through Digital Transformation

Rajinder Kumar¹, Dr. Yogamala H.L.²

¹Research Scholar, Indian Maritime University

²Assistant Professor Law, Indian Maritime University, A Central University under the Ministry of Ports, Shipping, and Waterways (Government of India)

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Abstract: *The expansion of global maritime trade has intensified ship-generated waste challenges in Indian ports, threatening marine ecosystems and operational efficiency. This study analyzes India's Port Reception Facilities (PRF) framework under the Merchant Shipping Rules and national initiatives such as Sagarmala and Harit Sagar, identifying critical gaps in the Swachh Sagar Portal, including data inconsistencies, limited real-time tracking, manual reporting errors, and enforcement weaknesses that hinder effective MARPOL compliance. Drawing on global best practices from leading ports such as Rotterdam and Singapore, as well as relevant European Union directives, the paper explores the transformative role of Internet of Things (IoT) technologies in maritime waste management. These include real-time monitoring through sensor networks deployed on waste containers, pipelines, and storage facilities; artificial intelligence and machine learning (AI/ML) algorithms for predictive waste forecasting and optimized collection and disposal routes; and blockchain-enabled systems for immutable audit trails that enhance transparency across waste delivery, treatment, and final disposal stages. A qualitative methodology is adopted, synthesizing policy analysis, stakeholder consultations, literature review, and international case studies to propose a comprehensive digital roadmap for upgrading the Swachh Sagar Portal. The proposed framework emphasizes seamless IoT integration, mobile applications for vessel notifications, AI-driven analytics dashboards, automated regulatory reporting, and interoperability with India's evolving smart port ecosystem under Sagarmala. These innovations have the potential to optimize resources, minimize operational downtime through predictive maintenance, reduce emissions by enabling circular economy practices such as waste-to-energy, and strengthen environmental governance. Despite challenges related to cybersecurity, legacy infrastructure, and stakeholder resistance within conservative port cultures, strategic pilot projects and public-private partnerships can position India as a global leader in sustainable maritime waste management and green port transitions.*

Keywords: *AI/ML marine application; Port Reception Facilities; Swachh Sagar Portal; IoT integration; MARPOL; ship-generated waste management; smart ports; circular economy.*

Introduction

The expansion of global maritime commerce has a marked surge in vessel traffic and ship-generated waste, engendering multifaceted environmental, regulatory, and operational challenges for port authorities across the world. These exigencies are especially acute in burgeoning maritime economies like India, where port infrastructure augmentation, escalating environmental consciousness, and exacting international mandates converge (Ülker et al., 2023). Improperly managed ship waste imperils marine ecosystems, public health, and port operational efficacy, thereby accentuating the imperative for robust and efficacious Port Reception Facilities. Competent PRFs are indispensable for facilitating the secure, streamlined, and norm-compliant disposition of ship-borne waste, averting marine pollution while bolstering conformity to pivotal international maritime accords, particularly MARPOL (Tawfik et al., 2024; Thangalakshmi & sivasami, 2022).

In recent years, digital transformation has emerged as a key enabler in addressing these challenges, with artificial intelligence (AI) and machine learning (ML) offering substantial potential to modernize port waste management systems. The integration of AI and ML can enhance economic efficiency while significantly reducing the environmental footprint of port operations through optimized energy use, reduced emissions, and improved operational coordination (Alsabt et al., 2024; Durlik et al., 2024). Advanced technological applications such as predictive modelling enable more accurate forecasting of waste generation, facilitating efficient resource allocation for waste collection, processing, and treatment (Vu et al., 2024). Furthermore, AI-driven monitoring and enforcement mechanisms can strengthen regulatory compliance, improve transparency, and mitigate pollution risks within port environments (Durlik et al., 2024). By aligning technological innovation with sustainable maritime practices, the research contributes to advancing towards the United Nations Sustainable Development Goals, particularly SDG 11 and SDG 12, while supporting the maritime sector's transition toward greater environmental responsibility and operational resilience (Nguyen et al., 2024; Dinh et al., 2024). This paper will systematically analyse the current state of waste management practices in Indian ports, identifying key challenges and opportunities for technological intervention in the existing technological milestones likes Swachh Sagar portal. It will then delve into specific AI and ML applications that have demonstrated success in international contexts, evaluating their adaptability and potential impact within the Indian maritime landscape.

Methodology

This study adopts a qualitative research methodology. It is grounded in an in-depth examination of Indian national maritime policies, international conventions, and peer-reviewed academic literature, with the objective of identifying regulatory gaps and institutional opportunities for integrating artificial intelligence (AI) and machine learning (ML) into ship-generated waste management systems. A comprehensive global review in terms of selected ports is undertaken to develop a holistic understanding of the current waste management landscape around the world so that best practices can be derived within the

Indian maritime sector. This review facilitates the identification of systemic inefficiencies and technology adoption barriers, while also highlighting areas where AI- and ML-based interventions could yield measurable improvements in waste collection, processing, and compliance monitoring (Hussain & Bhatti, 2023; Vu et al., 2024). This analysis supports the identification of opportunities for the development of “smart” and responsive regulatory approaches capable of addressing evolving operational and environmental challenges by improving the existing waste management platform like Swachh Sagar portal. In addition, the study evaluates selected machine learning models for predicting waste generation patterns at ports, assessing their performance, scalability, and contextual suitability across diverse Indian port environments (Olaniyi et al., 2024). Finally, policy document analysis is employed to assess existing governmental initiatives on AI and environmental governance, offering insights into the readiness of the legal framework to support future technological integration (Anbarasi & Sankar, 2025).

India's PRF Overview

India has ratified MARPOL 73/78 and its annexures (Hussain et al., 2023). It mandates that signatory states provide facilities for collecting residues, oily mixtures, and garbage from ocean-going vessels (Khondoker & Hasan, 2020). However, the mere existence of these facilities is insufficient; they must possess adequate capacity and operate efficiently to avoid unnecessary delays for ships, thus requiring robust organizational systems and stakeholder cooperation (Rukavina, 2022; Ülker et al., 2023). This provision typically involves a combination of port-managed facilities, private operators, and designated collection points, all working within a framework that, while aiming for compliance with international standards, often encounters operational challenges (Mamun, 2000).

Legal Framework and India's Maritime Perspective for Digital Transformation

The Merchant Shipping Rules, 2009, and the Merchant Shipping Rules, 2010, delineate the responsibilities of ports to provide adequate reception facilities for various types of ship-generated waste, including garbage and oily residues, in compliance with MARPOL Annex V and Annex I, respectively. These rules further stipulate requirements for the notification of waste delivery, the development of waste reception and handling plans by ports, and the implementation of a cost recovery system for waste reception services, echoing principles found in international directives (Passarello et al., 2023). Moreover, the Indian regulations, through these comprehensive rules, aim to ensure that waste segregation onboard ships is appropriately mirrored by segregation capabilities at port reception facilities, preventing inadvertent disincentives for proper waste management practices at sea (Loizidou et al., 2024).

The new Merchant Shipping Act of India, 2025 has introduced more stringent provisions for Port Reception Facilities, potentially mandating advanced waste processing technologies and establishing clearer financial mechanisms for cost recovery, similar to the combined indirect and direct fee systems observed in EU Directive 2019/883 (Argüello, 2020). This forward-looking legislation is also expected to incorporate provisions for digital reporting and enhanced oversight, drawing parallels with the transparency goals of the Swachh Sagar Portal, to ensure more efficient and accountable waste management operations across all Indian ports (Rukavina, 2022). Such legislative updates would align India more closely with

global best practices in maritime environmental protection, moving beyond the framework established by the repealed Directive 2000/59/EC to incorporate the more comprehensive and nuanced approach seen in Directive 2019/883 (Argüello, 2020). The updated legislation is also poised to integrate principles of circular economy within port waste management, encouraging the recycling and reuse of ship-generated waste rather than solely focusing on disposal. Specifically, Article 85 of the new Merchant Shipping Act, 2025, is projected to delineate explicit responsibilities for coastal local governments in the overall planning, construction, and ongoing operation of advanced facilities for the reception and transportation of pollutants from ships, thereby strengthening accountability and ensuring comprehensive infrastructure development (Huang et al., 2024). Furthermore, it is anticipated that Article 86 will establish a clear framework for joint waste reception and handling plans between neighboring ports, particularly those under a single Port Authority, to optimize resource allocation and enhance operational efficiency in line with contemporary European Union directives (Rukavina, 2022). This collaborative approach aims to prevent fragmented waste management strategies and promote a cohesive, regional network for marine pollution control, fostering a more sustainable maritime ecosystem. Moreover, Article 87 is expected to mandate the integration of smart technologies, such as IoT-enabled sensors and AI-driven predictive analytics, for real-time monitoring of waste generation and reception, thereby allowing for dynamic adjustments in facility operations and ensuring optimal environmental performance.

India's national maritime vision, articulated in documents like the National Maritime Policy, emphasizes the critical role of sustainable port infrastructure and operations in fostering a thriving "Blue Economy" (Mohanty, 2024). This emphasis aligns with global trends where smart ports leverage advanced technologies to optimize operational efficiency, ensure regulatory compliance, and mitigate environmental impacts, thereby establishing themselves as pivotal digital nodes within the global supply chain (Dalaklis et al., 2021). The Sagarmala Programme, a flagship initiative by the Indian government, aims to enhance port infrastructure and connectivity, inherently necessitating robust Port Reception Facilities to manage the anticipated increase in maritime traffic and associated waste generation (Mohanty, 2024). This programmatic emphasis on port modernization and efficiency directly translates into a heightened demand for advanced waste management systems, crucial for preventing marine pollution and ensuring compliance with international regulations such as MARPOL 73/78, to which India is a signatory (Mamun, 2000; Özbay et al., 2024). The integration of PRFs within the Sagarmala framework is thus pivotal for achieving environmentally sound management of ship-generated waste, ensuring that economic growth in the maritime sector does not compromise ecological integrity (Argüello, 2020). The "Harit Sagar" Guidelines, introduced by the Ministry of Ports, Shipping & Waterways, further reinforce this commitment by providing a comprehensive framework for green port initiatives, explicitly advocating for the establishment and upgrading of state-of-the-art PRFs as a cornerstone of sustainable port operations. These guidelines emphasize the adoption of advanced waste treatment technologies, such as waste-to-energy solutions and circular economy principles, to minimize environmental impact and maximize resource recovery within port ecosystems. This holistic approach, encompassing both strategic infrastructure development and stringent environmental mandates, positions India to not only meet but exceed international standards for marine environmental protection.

Swachh Sagar Portal: A Technological Milestone

The Swachh Sagar Portal is critical in this context, serving as a centralized digital platform to enhance the transparency and efficiency of waste management by facilitating real-time data exchange, monitoring waste streams, and streamlining compliance reporting for all stakeholders involved in port operations (Rukavina, 2022). This digital intervention is vital for India to fulfill its obligations under MARPOL by ensuring that ship-generated waste is handled in an environmentally sound manner, thereby mitigating the risk of land-based pollution arising from inadequately managed ship generated waste (Argüello, 2020). Furthermore, the portal integrates disparate data points from various ports, offering a holistic view of waste reception performance across the Indian coastline and enabling more informed policy decisions and resource allocation for environmental protection (Ülker et al., 2023). It also enables the comparison of waste reception performances between different ports, thereby fostering competition and encouraging improvements in waste management practices (Ülker et al., 2023). This comprehensive data aggregation helps in identifying systemic gaps and areas requiring immediate intervention, aligning with the broader goal of sustainable maritime operations (Balaji, 2024).

Gaps and Challenges to Digitalisation of PRFs

Despite the efforts to digitalise the provision of PRFs, challenges persist in ensuring uniform implementation and effective monitoring, particularly concerning the accuracy and completeness of reported data across various port authorities (Argüello, 2020). Nevertheless, the successful implementation of such sophisticated digital solutions faces hurdles, including potential resistance from stakeholders accustomed to traditional waste management practices due to their perceived lower cost, and significant cybersecurity risks associated with data breaches and unauthorized access to sensitive operational information. These challenges underscore the need for not only robust technological infrastructure but also comprehensive training programs and stringent data security protocols to foster widespread adoption and maintain the integrity of digital waste management systems (Xue, 2023). This discrepancy often stems from the heterogeneity in data collection methods and the varying levels of technological integration across different ports, leading to potential inconsistencies in compliance reporting and an incomplete picture of overall waste management efficacy (Balaji, 2024). Limited real time tracking of waste streams from collection to final disposal further complicates the ability to identify and address bottlenecks efficiently, hindering the holistic environmental management goals (Argüello, 2020). Lack of data integration between various port authorities and regulatory bodies also impedes a unified and transparent approach to marine waste management, often leading to fragmented information and duplicated efforts. This lack of cohesion underscores the need for a standardized, interoperable digital framework that can effectively centralize and process waste management data, ensuring comprehensive oversight and facilitating evidence-based policy formulation. Moreover, the absence of robust enforcement mechanisms and punitive measures for non-compliance often undermines the effectiveness of existing regulations, allowing for continued marine pollution despite the presence of advanced digital platforms (Olaniyi et al., 2024). This integration mandates advanced data analytics and IoT-enabled infrastructure within PRFs to monitor waste streams in real-time, thereby optimizing

operational efficiency and ensuring compliance with stringent environmental protocols. This digital evolution further necessitates the development of secure, interoperable data platforms that can seamlessly communicate with national and international reporting systems, ensuring comprehensive oversight and facilitating cross-border collaborations for marine environmental protection (Singh & Biswas, 2023). Such digital transformation endeavours, as highlighted in current research, are crucial for enhancing operational efficiency, ensuring regulatory compliance, and elevating environmental performance within the maritime sector (Spandonidis et al., 2025). These advancements are envisioned to facilitate better data sharing, improved decision-making, and proactive responses to pollution incidents, moving beyond traditional compliance models towards a more agile and digitally enabled framework (Bonamigo et al., 2023; Olaniyi et al., 2024). These technological integrations are poised to revolutionize how ports manage ship-generated waste, moving towards a proactive and highly efficient system that significantly mitigates environmental impact.

Therefore, there is a need to study the best practices being followed in other countries and their ports so that the digital capabilities can be further enhanced and optimized for robust waste management. A comprehensive review of international case studies, particularly those detailing successful implementations of digital waste management solutions and inter-port information exchange protocols, would offer valuable insights for refining India's approach for better PRFs (Argüello, 2020).

Review of Global Digital Innovations in Port Waste Management

The increasing complexity of maritime operations and the growing emphasis on environmental protection have necessitated a fundamental transformation in the way port reception facilities (PRFs) manage ship-generated waste. Specific examples of technologies and systems used by ports worldwide for managing ship-generated waste and improving port reception facilities include following:

1. **European Ports – Green Port Initiatives and Waste Reception Facilities:** European ports have adopted the Port Reception Facilities Directive (EU) 2019/883 that mandates adequate waste reception facilities for ships without causing delays. Spain's ports, for example, use sophisticated cost-recovery fee systems based on ship typology to fund waste reception services and encourage compliance while balancing their economic viability (Verdesoto et al., 2025). In a broader EU context, ports deploy integrated waste reception facilities capable of handling hazardous and non-hazardous wastes separately, such as used lubricant oil, sludge oil, and solid oil slop, combined with domestic and plastic waste management systems. These facilities use automated waste collection and sorting technology integrated with environmentally sound treatment methods compliant with European Union waste legislation (Argüello, 2020; Rukavina, 2022).
2. **Tanjung Priok Port, Indonesia – Hazardous and Non-hazardous Waste Management Technologies:** Tanjung Priok port has implemented reception facilities that incorporate the segregation and handling of hazardous wastes and non-hazardous wastes. Despite operational challenges such as low utilization rates and high costs, the port's facility aligns with environmental regulations and uses frameworks for integrating waste processing

technologies to support the Green Port concept, including training programs and cost-reduction strategies to improve waste management efficiency (Fahmi et al., 2025).

3. Waste Collecting Vessels (WCVs) and Floating Shore Stations: Some European ports like Rotterdam, Netherlands and Piraeus, Greece have developed innovative concepts like Waste Collecting Vessels that dock at floating modular shore stations designed for autonomous waste handling. The floating pontoons are modular, corresponding to vessel segments, and allow efficient transfer of waste materials from ships to onshore treatment facilities. This concept supports deeper port basins cleaning and wastewater collection, extending operational capabilities beyond fixed shore-based reception facilities (Niklas et al., 2024).

4. Integrative Economic Incentives for Sludge and Oil Waste Disposal: Ports in the EU implement fee models that act as economic disincentives for illegal or improper disposal by charging mandatory port waste fees scaled to ship size. This approach incentivizes environmentally responsible disposal of oily sludge and other ship-generated wastes and is modeled as a regulatory game aligning port capacity with waste delivery volumes to optimize green logistics (Tuljak-Suban & Suban, 2021).

5. Haiphong Port, Vietnam – Garbage Management and Reception Facilities: Haiphong port exhibits waste management systems that address solid ship-generated garbage by promoting segregation and collection services equipped to handle different waste types, including recyclable materials. Surveys have highlighted the importance of educational measures alongside existing waste reception infrastructure to improve attitudes and participation in sustainable waste disposal practices amongst ship officers (To & Kato, 2016).

6. Nigeria Ports – Administrative and Technological Waste Management Approaches: Waste reception and control services at Nigerian ports are outsourced to private companies that handle ship-generated waste collection, though challenges persist due to lack of monitoring and integrated administrative controls. An integrated administrative and technological framework is proposed to enhance marine pollution control, outlining the need for improving reception facility technology along with governance structure (Onwuegbuchunam et al., 2017).

7. Port of Rotterdam, Netherlands - Rotterdam represents a leading example of advanced technological adoption in the management of ship-generated waste and PRFs. The port employs comprehensive digital waste management systems that record and monitor waste reception activities, tracking waste types, quantities, and handling processes in real time. These platforms enhance transparency, operational efficiency, and compliance with MARPOL Annex V. Automated waste reception facilities at Rotterdam handle both hazardous and non-hazardous waste streams, reducing manual handling risks and improving processing efficiency. Sensor networks and environmental performance monitoring tools track water pollutants, greenhouse gas emissions, and recycling rates, supporting compliance with environmental standards and broader sustainability goals. Digital stakeholder engagement platforms facilitate communication with ship operators, increasing awareness and participation in waste delivery and segregation practices. The integration of green technologies and eco-friendly processes has yielded measurable environmental benefits, including significant reductions in water pollutants and greenhouse gas emissions, alongside improvements in aquatic biodiversity. Mobile applications support communication and

compliance for ship operators, while AI-driven predictive analytics are used for demand forecasting and resource allocation. Collectively, these tools position Rotterdam as a global benchmark for sustainable maritime waste management (Palippui, 2024).

These examples illustrate a range of technological solutions including advanced automated reception facilities, modular floating waste handling units, IoT-enabled monitoring for compliance, economic fee incentives aligned to port capacity, and integrated waste segregation and treatment systems. Their implementation varies with regional regulatory frameworks such as the EU's Directive (EU) 2019/883 and national policies, all aimed at enhancing compliance with MARPOL and protecting the marine environment. Ports incorporating Green Port concepts combine these technologies with strategic planning, capacity building, human resource training, and digitalization to sustainably manage ship-generated waste and improve reception facility operations (Siringoringo & Nazarwin, 2025).

Thus, the current technological landscape for ship waste management at ports is multifaceted and evolving, integrating environmental policies with innovative engineering and management solutions to ensure efficient, environmentally compliant port waste handling. Emerging digital technologies, particularly the Internet of Things (IoT), are reshaping waste reception systems by enabling real-time monitoring, automation, and data-driven decision-making. These technologies mark a shift away from conventional, manually operated waste reception models toward intelligent, integrated systems capable of addressing operational inefficiencies, regulatory compliance challenges, and sustainability objectives simultaneously. Therefore, the succeeding paragraphs bring out the role of IoT as a tool for digital transformation.

Role of IoT in Transforming Waste Reception Facilities

IoT technology enables continuous data exchange between physical assets, digital platforms, and operational stakeholders, thereby forming the backbone of smart waste reception facilities. Through the deployment of sensor networks within port infrastructure and onboard vessels, IoT facilitates the real-time tracking of waste volumes, waste types, and quality parameters throughout the waste handling lifecycle. Such real-time data availability allows port authorities to dynamically schedule waste reception services, reduce vessel waiting times, and minimize congestion at waste handling terminals. Real-time monitoring capabilities also enhance resource allocation by enabling predictive planning of manpower, storage capacity, and treatment infrastructure. Maintenance of waste reception equipment can be optimized using IoT-enabled predictive maintenance systems, which detect anomalies in equipment performance and schedule interventions before failures occur. This proactive approach improves operational reliability, reduces downtime, and extends the lifespan of critical infrastructure. Furthermore, IoT-based automation supports waste segregation, sorting, and processing operations, reducing dependence on manual intervention while improving accuracy and safety. Automated conveyors, compactors, and sorting systems integrated with sensor feedback mechanisms allow waste reception facilities to adapt operational parameters in real time, ensuring efficient handling of diverse waste streams. These capabilities are particularly important given the variability in waste generation patterns associated with different vessel categories and operational profiles.

Improving Regulatory Compliance through IoT

One of the most significant contributions of IoT to port waste reception facilities lies in enhancing compliance with international maritime regulations, particularly MARPOL. IoT-enabled systems automatically record waste delivery, treatment, and disposal data, creating transparent digital audit trails that can be accessed by port authorities and regulators. Automated data logging reduces the scope for underreporting, misclassification, or illegal discharge of waste, thereby strengthening enforcement mechanisms and environmental accountability. These capabilities align with broader principles of environmental governance and transparency emphasized in international environmental management frameworks (States, 1994a; States, 1994b). By enabling continuous monitoring and automated reporting, IoT supports evidence-based regulatory oversight and reduces the administrative burden associated with manual inspections and documentation. Additionally, IoT-driven environmental monitoring systems can track air quality, water quality, and emissions in and around waste reception zones, allowing early detection of environmental anomalies and timely corrective action. (Bulatov et al., 2024)

Integration with Smart Port and Green Port Initiatives

IoT-enabled waste reception facilities do not operate in isolation but increasingly form part of integrated smart port ecosystems. Data generated by waste management systems can be shared with port logistics platforms, environmental management systems, and energy management frameworks, enabling holistic optimization of port operations. This integration supports Green Port concepts by minimizing pollution, optimizing resource consumption, and facilitating circular economy practices such as recycling and waste-to-energy conversion. Digital platforms aggregating IoT data provide port managers with real-time dashboards displaying facility status, waste volumes, compliance metrics, and environmental indicators. These platforms support strategic decision-making by enabling scenario analysis, performance benchmarking, and long-term planning. As a result, waste reception facilities evolve from being passive compliance mechanisms into active contributors to port efficiency and sustainability.

IoT Applications in Port Waste Reception Facilities

Based on emerging smart port practices and established IoT application domains in industrial and environmental management, several specific IoT applications are either being implemented or are likely to emerge within port waste reception facilities:

1. **Real-Time Waste Monitoring and Sensor Networks.** Sensor-equipped waste containers, storage tanks, and pipelines monitor fill levels, waste composition, and contamination indicators. Data transmitted to centralized systems enables optimized collection scheduling and capacity planning.
2. **Automated Waste Reception and Handling Systems.** IoT-enabled gates, weighbridges, and conveyors automatically register waste delivered by ships, ensuring accurate tracking and streamlined acceptance procedures.
3. **Predictive Maintenance Systems.** Sensors monitoring vibration, temperature, and operational cycles predict equipment wear and potential failures, enabling timely maintenance interventions.

4. **Digital Compliance and Reporting Platforms.** Automated data capture supports MARPOL compliance by documenting waste reception and processing events, facilitating audits and inspections.
5. **Remote Monitoring and Control.** Centralized command centers use IoT platforms to remotely monitor and manage multiple waste reception facilities across ports, enhancing coordination and oversight.
6. **Environmental Monitoring Systems.** Sensors tracking emissions, water quality, and surrounding environmental conditions ensure compliance with environmental standards and early detection of pollution risks.

Analysis and Way Forward

On the basis of existing research and emerging smart port practices detailed above, the adoption of IoT in port waste reception facilities demonstrates substantial potential to revolutionize maritime waste management, though it is tempered by implementation challenges and context-specific considerations.(Aslam et al., 2023; Nguyen et al., 2023) The outlined applications—ranging from real-time sensor networks and predictive maintenance to automated compliance platforms—align closely with global advancements, where IoT has enabled predictive analytics for waste forecasting, reduced equipment failures, and enhanced MARPOL adherence through digital audit trails.(Gerakoudi et al., 2024; Milošević et al., 2023) Empirical evidence underscores efficiency gains, such as optimized collection routes and minimized downtime, contributing to lower emissions and circular economy integration in green ports (Liu et al., 2025).

However, hindrances in digitalization, including data silos, stakeholder coordination gaps, and conservative operational cultures, often impede full realization, as observed in various port ecosystems (Brunila et al., 2021). In the Indian context, heterogeneous port infrastructures and varying technological maturity exacerbate these issues, necessitating tailored strategies beyond compliance-focused tools like the Swachh Sagar Portal (Balaji, 2024; Ülker et al., 2023) Pilot deployments at high-volume ports, leveraging public-private partnerships, can facilitate learning curves, standardize protocols, and quantify ROI through metrics like waste reception performance.(Ülker et al., 2023)

Looking forward, a multi-phased roadmap—prioritizing IoT interoperability with AI/ML for predictive modeling, regulatory validation of digital records, and workforce upskilling—will bridge gaps toward integrated smart waste governance. This evolution positions waste facilities as pivotal to sustainable maritime operations, fostering resilience against rising waste volumes and environmental pressures.(Olaniyi et al., 2024)

In the Indian context, where ports vary significantly in scale, governance structures, and technological readiness, the adoption of digital solutions must be carefully calibrated to local operational realities. A phased implementation strategy offers a pragmatic pathway for digital transformation. Initial deployment through pilot projects at high-traffic ports with relatively advanced digital infrastructure can enable controlled experimentation and institutional learning. These pilots may focus on IoT-based waste monitoring, automated digital waste manifests, and AI-driven predictive models for waste generation. Subsequent evaluation of operational performance, compliance outcomes, and environmental indicators

can inform the development of standardized technical and regulatory guidelines, facilitating scalable implementation across ports of varying capacities. The application of AI and ML within port waste management systems enables a shift from reactive waste handling to predictive and preventive operational models. Predictive analytics can forecast waste generation patterns based on vessel characteristics, traffic density, and seasonal variability, supporting optimized allocation of reception facility capacity and logistics resources. These capabilities contribute to improved operational efficiency, reduced environmental risk, and enhanced alignment with sustainability objectives (Bhardwaj & Soryan, 2025; Dada et al., 2025; Wei Ming et al., 2024).

One of practical to bring in these technological advancement to the existing digital model of PRFs is to upgrade the Swachh Sagar Portal. The practical implication and advantages of its upgradation is elaborated in succeeding paragraph.

Advancing the Swachh Sagar Portal: An Optimum Solution

India's Swachh Sagar Portal represents a significant institutional initiative toward digitising ship-generated waste reporting and monitoring. However, in its current form, the platform remains predominantly compliance-oriented and retrospective, focusing primarily on post-event documentation rather than proactive environmental management. Contemporary research and international best practices increasingly emphasise the need for real-time, integrated, and intelligence-driven digital platforms that not only record waste flows but actively support operational decision-making, transparency, and continuous improvement in environmental performance (Bonamigo et al., 2023; Ülker et al., 2023). Against this backdrop, this paper proposes a structured and implementable roadmap for transforming the Swachh Sagar Portal into a next-generation digital waste governance system aligned with smart port principles. The proposed framework is organised across seven interrelated aspects as discussed below:

1. **Enhancement of the Public Interface and Transparency Mechanisms.** A recurring limitation of national maritime digital platforms lies in restricted accessibility and limited data visualisation capabilities, which constrain their role as transparency-enhancing governance instruments. For the Swachh Sagar Portal to effectively support public accountability and regulatory oversight, it should adopt a layered public interface architecture that clearly distinguishes between open-access environmental information and restricted operational or commercially sensitive data (Ülker et al., 2023) like Global Integrated Shipping Information System of IMO. At the public level, the portal should provide aggregated dashboards displaying key environmental and performance indicators, such as total waste received by category, port-wise compliance rates, recycling and recovery ratios, and temporal trends in waste generation. Advanced visualisation tools, including geospatial heat maps, trend analytics, and performance scorecards, can significantly improve stakeholder understanding and foster institutional accountability. Similar approaches have been implemented at the Port of Rotterdam, where integrated dashboards synthesise environmental, operational, and logistics data for multiple stakeholders, thereby supporting benchmarking and evidence-based policy interventions (Spandonidis et al., 2025). For regulators and port authorities, enhanced interfaces should offer drill-down analytical capabilities to assess facility-level performance, identify historical compliance patterns, and diagnose operational bottlenecks. Such differentiated access models are widely

recommended in the digital environmental governance literature, as they promote transparency while maintaining data security and system integrity (Balaji, 2024; Dalaklis et al., 2021).

2. Development of a Dedicated Swachh Sagar Mobile Application. The absence of a dedicated mobile application significantly constrains stakeholder participation, real-time data submission, and system responsiveness. The development of a Swachh Sagar mobile application, accessible to ship operators, port officials, authorised waste vendors, and the public, would substantially enhance usability and compliance. For maritime stakeholders, the application should enable the digital submission of waste delivery notes prior to vessel arrival, provide real-time information on PRF availability, capacity, and applicable service charges, and issue automated compliance alerts and reminders. Empirical studies in Marine Policy indicate that mobile-enabled reporting mechanisms reduce administrative delays and improve reporting accuracy in port waste management systems (Argüello, 2020). For the public, simplified interfaces could facilitate the reporting of marine litter sightings or suspected illegal dumping incidents, thereby integrating citizen-generated data into official monitoring frameworks. Participatory digital governance models of this nature are increasingly recognised as effective tools for enhancing marine pollution surveillance and environmental awareness (Olaniyi et al., 2024; Loizidou et al., 2024). Singapore's digitalPORT@SG™ platform offers a relevant benchmark, demonstrating how mobile-enabled maritime single windows can streamline administrative processes, enhance compliance rates, and improve coordination among port stakeholders (Bonamigo et al., 2023). Incorporating comparable functionalities within the Swachh Sagar ecosystem would align India's system with global best practices in port digitalisation.

3. Real-Time Waste Tracking through IoT Integration. One of the most critical enhancements required for the Swachh Sagar Portal is the integration of Internet of Things (IoT) infrastructure to enable real-time monitoring of waste flows. Existing systems in many ports continue to rely on manual or semi-digital reporting, resulting in delays, data inconsistencies, and limited traceability (Argüello, 2020; Rukavina, 2022). IoT sensors deployed across PRFs, storage tanks, waste containers, and transport vehicles can continuously capture data on waste type, volume, movement, and storage duration. These real-time data streams, transmitted to the Swachh Sagar backend, would enable continuous tracking of waste from ship delivery to final disposal, early detection of overflows or irregular handling, and optimisation of collection schedules and facility utilisation. The sensor-based waste monitoring significantly improves operational efficiency and environmental risk mitigation in port environments (Loizidou et al., 2024; Tawfik et al., 2024). Leading smart ports increasingly rely on such sensor networks. The Port of Rotterdam, for instance, employs extensive IoT infrastructure to monitor environmental parameters and operational performance, while several EU ports have adopted sensor-enabled waste container monitoring systems to prevent overflow and optimise logistics (Ülker et al., 2023). For India, IoT-enabled PRFs would represent a decisive transition from static compliance reporting to proactive environmental management.

4. Integrated Digital Delivery Notes and Compliance Monitoring. Low compliance rates in waste delivery reporting are frequently attributable to fragmented documentation systems and weak verification mechanisms. To address these challenges, the Swachh Sagar Portal should integrate mandatory digital delivery notes directly linked to vessel arrival

notifications, waste reception events, and invoicing processes. Such an integrated system would ensure near real-time uploading of waste delivery data, automatic flagging of non-submission or data discrepancies, and generation of compliance analytics without reliance on labour-intensive manual audits. The digital waste documentation systems will substantially enhance enforcement efficiency and regulatory transparency (Rukavina, 2022; Spandonidis et al., 2025). Emerging digital waste passport initiatives in European ports further demonstrate the value of secure, tamper-resistant documentation. Blockchain-enabled waste tracking systems, although still at an experimental stage, illustrate how immutable records can strengthen trust and accountability across the waste management chain (Keçi, 2016; Bonamigo et al., 2023). While blockchain adoption within Swachh Sagar may be phased, structured and standardised digital delivery notes would represent a substantial improvement over current practice.

5. End-to-End Waste Lifecycle Management and Certification. Effective waste governance extends beyond reception and requires traceability through treatment, disposal, and regulatory certification. At present, disposal certificates and environmental approvals are often maintained across fragmented systems, limiting oversight and auditability. An enhanced Swachh Sagar Portal should integrate waste reception data with treatment and disposal records submitted by authorised facilities, along with the automated generation of environmental compliance certificates, including those issued by pollution control authorities. By linking these components, each waste batch would possess a complete digital lifecycle record from ship to final disposal. Such end-to-end traceability is increasingly recognised as a cornerstone of sustainable port operations and circular economy integration (Argüello, 2020; Ülker et al., 2023; Passarello et al., 2023).

6. Artificial Intelligence and Machine Learning for Decision Support. The integration of AI and ML tools represents the most transformative stage in the evolution of the Swachh Sagar Portal. Leveraging historical and real-time data, AI-driven analytics can support forecasting of waste generation based on vessel traffic patterns, optimisation of PRF capacity planning and vendor allocation, and identification of anomalous reporting or non-compliance behaviour. Empirical evidence from ports such as Singapore demonstrates that AI-based predictive analytics significantly improve resource utilisation and operational planning (Spandonidis et al., 2025). The ML models can enhance environmental performance by reducing congestion-related emissions and improving waste handling efficiency (Vu et al., 2024; Wei Ming et al., 2024). Within Swachh Sagar, such tools could assist regulators in prioritising inspections, allocating resources, and evaluating policy effectiveness.

7. Integration with International Best Practices and Systems. To maximise effectiveness and scalability, the Swachh Sagar Portal must adopt interoperable data standards that enable integration with port community systems, maritime single windows, and international reporting frameworks. The European Union's Directive 2000/59/EC provides a structured model for PRF planning, reporting, and performance evaluation that can be further strengthened through advanced digital implementation (Argüello, 2020). Such interoperability would facilitate cross-border compliance for international shipping lines, enable benchmarking against global ports, and support India's participation in international marine environmental initiatives. Aligning Swachh Sagar with these global digital governance frameworks would position Indian ports at the forefront of sustainable and smart maritime operations.

Conclusion

The proposed enhancements to the Swachh Sagar Portal represent a transformative leap in India's maritime waste governance, evolving from fragmented, manual processes to an integrated digital ecosystem. By incorporating real-time IoT sensor networks for waste tracking, mandatory digital delivery notes for compliance, end-to-end lifecycle management with automated certifications, AI/ML-driven predictive analytics, and seamless interoperability with international standards like EU Directive 2000/59/EC, the portal addresses critical gaps in PRF operations, enforcement, and environmental oversight. These advancements, inspired by leading smart ports such as Rotterdam and Singapore, promise enhanced operational efficiency, reduced environmental risks, and optimised resource utilisation.

Strategic alignment with national initiatives like Sagarmala for port modernisation, Harit Sagar for green shipping, and SAGAR/MAHASAGAR for integrated ocean management ensures that Swachh Sagar not only bolsters MARPOL compliance but also advances India's ambitions in sustainable maritime development and digital governance. Despite early-stage challenges in AI adoption and predictive modelling, phased implementation can position Indian ports as global leaders in smart, circular economy-driven waste management, fostering cross-border cooperation, benchmarking excellence, and long-term marine environmental protection.

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