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Advancing Marine Debris Monitoring through Artificial Intelligence and Remote Sensing: A Systematic Review for Environmental Education and Sustainable Development Goals (SDGs) Integration

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ABSTRACT

This systematic review investigates how artificial intelligence and remote sensing technologies contribute to advancing marine debris monitoring in support of environmental education and sustainable development goals. A structured literature review was conducted on selected studies published between 2019 and early 2025, focusing on the integration of deep learning and various remote sensing platforms, including satellite imagery and unmanned aerial systems. The findings demonstrate that AI-enabled systems enhance detection accuracy and monitoring scalability. This improvement matters because conventional methods are limited in spatial coverage, frequency, and reliability. The review identifies persistent barriers, such as insufficient ground truth data and the inability of models to generalize across regions. These challenges highlight the need for educational programs that strengthen data literacy, cross-disciplinary collaboration, and environmentally conscious digital practices. The study provides actionable insights for educators, researchers, and policymakers, offering a technological foundation to promote sustainability learning and informed decision-making in response to global marine plastic pollution.

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1. INTRODUCTION

Marine debris, particularly plastic litter, has become one of the most pressing environmental issues of the 21st century. Each year, millions of tons of plastic waste enter the world's oceans, harming marine wildlife, degrading ecosystems, and threatening coastal economies (Abreo *et al*., 2023). South-east Asia is a global hotspot for marine plastic pollution, largely due to high plastic use, inadequate waste management, and riverine inputs. Countries such as Indonesia, the Philippines, Vietnam, and Thailand rank among the top contributors to ocean plastics. The region's tropical coastlines and archipelagic waters are inundated with debris, from floating trash mats offshore to accumulated litter on beaches, with severe ecological and socio-economic impacts. However, the true extent and dynamics of marine debris remain poorly quantified, in part because traditional monitoring (ship surveys, beach audits) is labor-intensive, spatially limited, and infrequent (Radjawane *et al*., 2025). There is an urgent need for innovative monitoring tools that can systematically track marine debris over a broad spatio-temporal scale (Cozar *et al*., 2024).

Remote sensing has rapidly advanced as a promising solution for large-scale observation of marine debris. Satellite imagery, aerial photography from drones (UAVs), and other remote platforms provide synoptic and repeated views of oceans and coastlines (Abreo *et al*., 2023). Recent studies have demonstrated that optical satellite sensors can detect aggregations of floating plastics under certain conditions (Cozar *et al*., 2024). Multispectral instruments (like the Sentinel-2 MSI) have shown spectral signatures that distinguish plastics from natural organic matter (e.g., seaweed) by exploiting differences in visible to shortwave-infrared reflectance (Cozar *et al*., 2024). Novel spectral indices such as the Floating Debris Index (FDI) have been developed to highlight marine plastic in imagery (Cozar *et al*., 2024). At finer scales, UAVs carrying RGB or multispectral cameras have been used to map debris on coastlines and nearshore waters with high resolution, even identifying individual litter items (Abreo *et al*., 2023). Beyond optical methods, researchers are also exploring hyperspectral sensors, thermal infrared imagery, and even radar (SAR) for marine litter detection (Abreo *et al*., 2023), aiming to overcome limitations like cloud cover or low contrast in visible bands.

Critically, the effectiveness of remote sensing for debris detection has been greatly enhanced by artificial intelligence (AI) and machine learning. Traditional image analysis techniques (thresholding, band ratios) often struggle with the complexity of differentiating plastics from lookalike materials and dealing with variable environmental conditions (glint, turbidity, etc) (Cozar *et al*., 2024; Kruse *et al*., 2023). AI approaches – particularly deep learning – have proven adept at learning subtle spectral, textural, and contextual features of debris from large datasets. Convolutional Neural Networks (CNNs) trained on labelled satellite or drone images can automatically detect and classify marine debris with higher accuracy than manual or rule-based methods. For instance, the application of a CNN-based classifier on Sentinel-2 images led to successful discrimination of suspected plastic patches with ~86% accuracy in a 2020 study (Abreo *et al*., 2023). Likewise, deep learning models applied to UAV imagery have identified plastic litter on beaches and nearshore waters, even in challenging developing country contexts (Abreo *et al*., 2023). Besides CNNs, recent research is beginning to investigate transformer-based models and other advanced architectures for remote sensing image analysis, which could further improve debris detection by capturing long-range dependencies and multi-modal data.

The convergence of geospatial data and AI holds enormous potential for near-real-time, automated marine debris monitoring on a global scale (Cozar *et al*., 2024; Kruse *et al*., 2023). However, realising this potential requires surmounting several challenges. One issue is the

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scarcity of ground truth data – obtaining sufficient labelled examples of marine debris in satellite images is difficult, limiting supervised model training (Kruse *et al*., 2023). The complex environment (e.g., water color, waves, mixed debris, and seaweed) leads to false positives and false negatives in detection. Additionally, models trained in one region may not generalize elsewhere due to different backgrounds or debris types (a problem of domain shift) (Karakus, 2023). Computational constraints are also significant; analyzing high-resolution imagery over large areas or frequent time steps demands efficient algorithms and sometimes distributed processing (Kruse *et al*., 2023). Nonetheless, progress in this field has accelerated in recent years.

While most of the reviewed literature focuses on technical efficacy, there is growing recognition that such innovations must be accompanied by strong educational integration to maximize societal impact. The complexity of marine debris monitoring using AI and remote sensing presents a valuable opportunity for environmental education. Embedding these tools into educational contexts fosters critical thinking, spatial reasoning, and data literacy. By learning how to interpret satellite imagery, understand spectral patterns, and engage with AI-based environmental analysis, students and citizens alike gain a deeper appreciation of both the marine environment and the technologies used to protect it. These skills are increasingly essential in the face of global challenges and align directly with education for sustainable development. In this regard, marine debris monitoring is not only a technological endeavor but also a pedagogical platform for promoting interdisciplinary, sustainability-oriented learning. As such, the potential of AI and remote sensing should be extended into classrooms, public engagement programs, and teacher training modules to support long-term behavioral change and informed environmental stewardship.

Given the rapid development of the literature since 2020, a systematic review is needed to synthesize the state-of-the-art and guide future research. Several narrative reviews have touched on aspects of marine debris remote sensing (Karakus, 2023), and broad bibliometric analyses have highlighted AI's rising role in ocean waste management (Adeoba *et al*., 2025). Building on and going beyond these, we present a comprehensive review focusing specifically on AI-enabled remote sensing of marine debris, with a spotlight on Southeast Asia. We adopt a formal systematic methodology to identify relevant studies from 2019 through early 2025, ensuring inclusion of the latest advances, such as those published in 2024 and 2025. We aim to: (i) characterize the integration of AI (especially machine learning and deep learning) with various remote sensing platforms for detecting and monitoring marine debris; (ii) summarize the key methodologies, sensors, and models deployed, using tables for clear comparison; (iii) analyze bibliometric trends such as keywords co-occurrence and thematic clusters of research topics; (iv) emphasize findings from or applicable to Southeast Asian contexts; (v) identify knowledge gaps, practical challenges, and opportunities for future innovation; and (vi) explore how these advances can be integrated into environmental education to support sustainable development goals (SDGs). By consolidating findings across dozens of recent studies, this review provides an up-to-date reference for environmental scientists, educators, and policymakers seeking scalable, interdisciplinary approaches to marine plastic monitoring and education.

2. METHODS

This study adopts a systematic review approach to critically examine and synthesize existing literature on the application of artificial intelligence (AI) in marine debris monitoring using remote sensing technologies, with a particular focus on Southeast Asia. The review process involved structured steps including identification, screening, eligibility assessment, and data extraction, following the PRISMA 2020 framework.

From each included study, we extracted data on the authors, year of publication, geographic scope, remote sensing platform used, AI model employed, detection accuracy, sensor resolution, and key findings. We paid special attention to studies relevant to the Southeast Asian context. Comparative tables were developed to analyse methodology, sensor performance, and AI accuracy.

The results were synthesized through descriptive analysis, supported by summary tables to compare methodological approaches, sensor types, and AI models used across studies. Special emphasis was placed on identifying research conducted in or applicable to Southeast Asia, as this region represents a global priority area for marine debris mitigation. This methodological framework enables a clear understanding of the current technological landscape, key advances, and ongoing gaps in the field of AI-enabled remote sensing for marine plastic pollution monitoring. The selection process followed the PRISMA 2020 guidelines, covering four databases (PubMed, ScienceDirect, Google Scholar, and ResearchGate), and applied strict inclusion/exclusion criteria.

After removing 23 duplicate records, 15 automation-filtered records, and 9 non-peer-reviewed or non-English sources, 88 records remained for title and abstract screening. Of these, 55 were excluded based on relevance. The remaining 33 full-text reports were assessed, with 5 not retrievable and 17 excluded due to scope mismatch or lack of methodological clarity. Finally, 11 studies me*t al*l inclusion criteria and were analyzed in this review. The detailed screening process is illustrated in **Figure 1**, which presents the PRISMA flow diagram summarizing identification, screening, and inclusion stages.

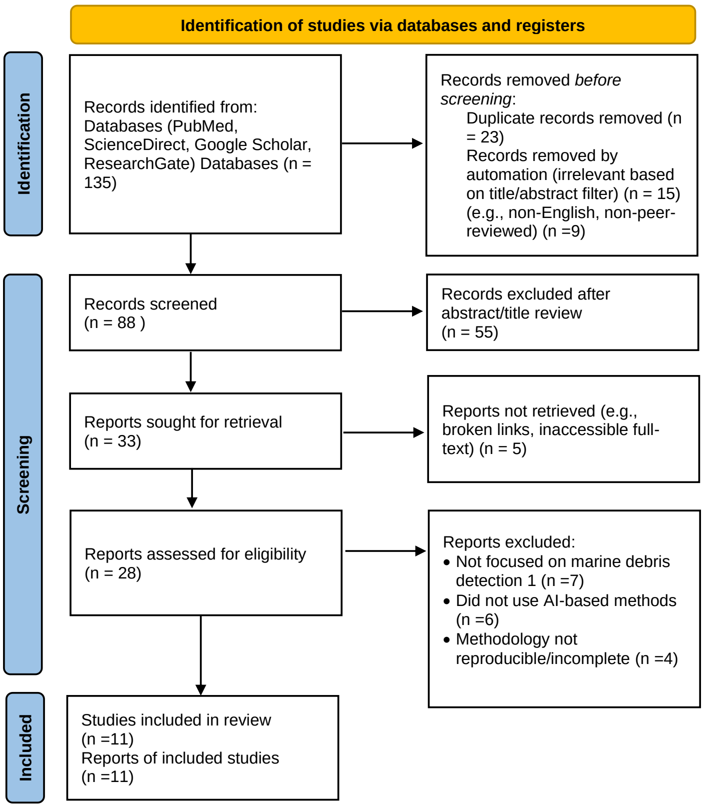

Figure 1. PRISMA 2020 flow diagram of study identification, screening, and inclusion process.

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3. RESULTS AND DISCUSSION

Across the 11 studies reviewed (2019–2025), a growing body of evidence shows the increasing effectiveness of combining remote sensing platforms (satellite, UAV, SAR, thermal, and hyperspectral imagery) with artificial intelligence (AI) primarily deep learning to detect, classify, and map marine debris. The studies demonstrated strong potential for scaling these tools for operational environmental monitoring, especially in Southeast Asia, where debris density and ecological vulnerability are high. The systematic review is shown in **Table 1**.

Table 1. Results Summary and Methodological Comparison

No	Study	Platform and Sensor	AI/ML Method	Region/Test Area	Key Findings
1	Biermann *et al.* (2021)	UAV + Hyperspectral (VNIR–SWIR)	Linear Discriminant Analysis (LDA)	Coastal Europe	~85% accuracy in separating PE/PET plastics from organic matter.
2	Topouzelis *et al.* (2019)	Sentinel-2 MSI	Floating Debris Index + SVM	Mediterranean Sea	Added pansharpening; >80% classification accuracy.
3	Themistocleous *et al.* (2020)	Sentinel-2 Imagery	Custom CNN (PLD-CNN/PLQ-CNNs)	Cyprus	83–86% accuracy for plastic detection in aerial images.
4	Maximenko *et al.* (2019)	Satellite & UAV	Review ML, CNN, and object detection	Global	UAV + CNN is the best for nearshore monitoring, provided workflow taxonomy.
5	Papageorgiou *et al.* (2022)	Sentinel-2 MSI	Spectral unmixing + comparison	Mediterranean (Plastic Litter Project)	Successfully distinguished plastics from natural materials using spectral unmixing.
6	Danilov & Serdiukova (2024)	Satellite + UAV	Review DL methods	Global	Compiled ML/AI methods, 13practical limitations, mitigation strategies.
7	Shen *et al.* (2024)	Satellite images	YOLOv7 + attention (CBAM)	Global dataset	CBAM-enhanced model achieved F1 = 77% (box) and 73% (mask).
8	Nivedita *et al.* (2024)	Sentinel-2 MSI	Naive Bayes	Brazil coast	87% total accuracy; best at 92% in urban estuary.

3.1. Synthesis of Key Findings: A Transformative Shift in Marine Debris Monitoring

Our systematic review unequivocally demonstrates that the convergence of Artificial Intelligence (AI) and remote sensing is ushering in a transformative era for marine debris

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monitoring. The rapid increase in publications since 2019, as highlighted in the 11 studies reviewed, underscores a critical shift from traditional, labor-intensive methods to more scalable, automated, and often near-real-time solutions. This directly addresses the "urgent need for innovative monitoring tools that can systematically track marine debris over a broad spatio-temporal scale" identified in our Introduction. Satellite platforms, particularly those equipped with multispectral sensors like Sentinel-2 MSI, have proven invaluable for broad-scale detection of floating plastic aggregations. These platforms offer unprecedented synoptic views crucial for identifying global hotspots and long-term accumulation trends. The utility of satellite data is profoundly amplified by AI, especially deep learning, which moves beyond simple spectral indices to learn complex, subtle patterns. This enables the effective differentiation of plastics from natural lookalikes such as seaweed – a persistent challenge for conventional methods – with reported accuracies often exceeding 80%.

For instance, Themistocleous *et al*. (2020) achieved 83–86% accuracy for plastic detection using a custom CNN on Sentinel-2 imagery, and Topouzelis *et al*. (2019) demonstrated over 80% classification accuracy with a Floating Debris Index combined with SVM. Booth *et al*. (2023) even reported 95% precision for density mapping across locations using deep learning on satellite multispectral imagery. At finer spatial scales, the proliferation of Unmanned Aerial Vehicles (UAVs) combined with advanced deep learning models has revolutionized high-resolution mapping. Maximenko *et al*. (2019) highlighted UAVs coupled with CNNs as best for nearshore monitoring and provided a workflow taxonomy. The granular detail provided by UAV imagery allows for the identification of individual litter items, offering a level of precision not easily achieved by satellite data. This high-resolution capability is especially relevant for diverse and complex coastlines, like those prevalent in Southeast Asia, where detailed, frequent mapping is crucial but often hindered by logistical challenges. The emphasis on AI's role is not merely an incremental improvement but a fundamental paradigm shift; as acknowledged in our Introduction, traditional image analysis techniques struggled with environmental variability, a challenge AI is demonstrably better equipped to handle by learning intricate features from vast datasets.

3.2. Strengths and Limitations of Current Approaches in Practice

The primary strength of AI-enabled remote sensing for marine debris monitoring lies in its scalability and objectivity. Unlike manual surveys, these technologies can cover vast, often inaccessible areas repeatedly and systematically, providing consistent, quantifiable data. This has enormous implications for tracking marine debris dynamics over time and space, informing policy development, and evaluating the effectiveness of mitigation strategies. The automated nature of AI detection significantly reduces human bias, speeds up analysis, and offers a more efficient use of resources, directly addressing the "labor-intensive, spatially limited, and infrequent" nature of traditional monitoring methods identified in our Introduction. The demonstrated successes in Southeast Asian contexts, such as interannual detection potential over coastal Indonesia by Dimyati *et al*. (2023), further underscore the practical applicability of these solutions for regions with limited resources. However, significant limitations and challenges persist, many of which were anticipated in our Introduction.

A critical issue is the scarcity of high-quality, geographically diverse ground truth data. Obtaining sufficient, accurately labeled examples of marine debris in satellite and drone images is difficult and time-consuming, severely limiting the supervised training of robust AI models. This directly impacts the generalizability of models; as highlighted in our Introduction, models trained in one region often do not perform well elsewhere due to

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domain shift, caused by variations in backgrounds, water conditions, or debris types. The complex marine environment (e.g., water color, waves, glint, turbidity, mixed debris, and seaweed) leads to persistent challenges with false positives and false negatives, impacting overall detection accuracy. For instance, while Nivedita *et al*. (2024) reported 87% total accuracy, performance varied based on the urban estuary environment. Furthermore, current remote sensing capabilities are primarily limited to surface-level debris, offering minimal insight into debris in the water column or on the seafloor, which constitutes a significant portion of marine plastic pollution. While SAR and thermal infrared show promise, their application for marine debris remains largely experimental, with lower reported accuracies. Finally, computational constraints are substantial, as analyzing high-resolution imagery over large areas or frequent time steps demands efficient algorithms and significant processing power, which can be a barrier for resource-limited regions. Danilov & Serdiukova (2024) compiled practical limitations and mitigation strategies in their review of deep learning methods.

3.3. Gaps in Current Research and Future Directions

Based on the synthesis of the reviewed literature, several critical knowledge gaps and promising future directions emerge, aligning with the final aim of our review. There is an urgent need for standardized, high-quality, and publicly accessible ground truth datasets of marine debris, ideally incorporating diverse geographical locations and environmental conditions. Future research should explore advanced data augmentation techniques, synthetic data generation, and few-shot or semi-supervised learning to train robust AI models with limited labeled data. This is paramount for improving model generalizability across varying marine environments. While individual platforms show promise, the next frontier lies in the intelligent integration of data from various sensors (e.g., optical, SAR, hyperspectral, and thermal infrared) and platforms (satellite, UAVs, in-situ sensors). Fusing these diverse data streams using sophisticated AI models (e.g., transformer-based architectures capable of handling multi-modal inputs) could overcome individual sensor limitations, providing a more comprehensive and resilient monitoring system, particularly for challenging conditions like persistent cloud cover in tropical regions. Despite some exploratory work, effective remote sensing of microplastics remains a significant challenge.

Future research should prioritize the development of novel hyperspectral or electrochemical sensing techniques combined with highly sensitive AI algorithms capable of detecting and quantifying microplastics at sea, which currently falls outside the scope of most macro-debris detection methods. Developing AI models that can generalize across different marine environments and debris types is crucial. Research should focus on transfer learning, domain adaptation, and meta-learning techniques to create models that are less susceptible to regional variations and can be more readily deployed globally, including across the diverse Southeast Asian coastlines where debris characteristics can vary significantly. While promising, many studies remain in the research phase. Future efforts should focus on transitioning these technologies into operational monitoring systems. This includes developing user-friendly platforms, establishing clear protocols for data collection and analysis, and fostering closer collaboration between researchers, environmental agencies, and policymakers to ensure that the generated data directly informs effective waste management strategies and policy decisions. The focus on Southeast Asia in this review is particularly pertinent here, as translating technological advances into actionable insights for this critically impacted region will be key to addressing the global plastic crisis. Beyond mere detection, future research should explore the integration of debris transport models with AI-

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enabled remote sensing data to predict debris accumulation zones and identify potential land-based or ocean-based sources of pollution, moving towards proactive mitigation rather than just reactive monitoring. This could provide a crucial tool for intervention strategies.

3.4. Educational and Sustainable Development Implications

The integration of artificial intelligence and remote sensing in marine debris monitoring presents transformative opportunities not only for environmental science but also for educational and sustainable development agendas. The reviewed studies demonstrate the value of these technologies in generating accurate, scalable, and near-real-time data about marine plastic pollution. This capability, however, is not solely technical; it holds pedagogical power when embedded in educational frameworks aimed at fostering data-driven environmental awareness.

Introducing geospatial analysis and AI-based environmental monitoring into school and university curricula can enhance sustainability education by equipping learners with the skills to interpret satellite imagery, analyze spatial patterns of pollution, and engage with AI-assisted decision-making processes. This aligns with the Sustainable Development Goals, particularly those related to quality education, responsible consumption, life below water, and climate action. By promoting interdisciplinary learning, environmental education can bridge technology, ecology, and civic responsibility.

Moreover, the visualization of marine debris through open-access platforms, UAV imagery, or mobile apps—when responsibly adapted—can empower local communities and students to participate in citizen science efforts. These activities encourage critical reflection on local waste practices, plastic use, and ocean stewardship. Schools and universities, especially in vulnerable regions like Southeast Asia, can serve as hubs for combining technological tools with sustainability narratives. This approach helps transform complex environmental data into accessible, actionable knowledge that influences behavior and supports local policy dialogue. Thus, the technological advances identified in this review are not ends in themselves but should be viewed as components of a broader educational ecosystem. Integrating these methods into formal education, public outreach, and teacher training programs will enhance both awareness and capacity for tackling marine plastic pollution. In this way, the study contributes not only to marine debris science but also to the evolving field of environmental pedagogy that supports the achievement of the Sustainable Development Goals.

4. CONCLUSION

This systematic review underscores the profound impact of the synergy between Artificial Intelligence and Remote Sensing in advancing marine debris monitoring capabilities since 2019. These technologies offer unprecedented opportunities for large-scale, efficient, and objective tracking of marine plastic pollution, critically addressing the limitations of traditional methods. While significant progress has been made, particularly with satellite-based detection of large floating aggregations and high-resolution UAV mapping of coastlines, key challenges remain, notably the scarcity of labeled ground truth data, environmental variability, and the difficulty of detecting subsurface or micro-debris. The emphasis on Southeast Asia within this review highlights both the region's acute vulnerability to marine plastic pollution and its potential as a proving ground for the practical application of these innovative monitoring tools. Addressing the identified knowledge gaps through robust data generation, multi-sensor integration, advanced AI model development, and stronger policy alignment will be crucial for realizing the full potential of AI-enabled remote sensing as a cornerstone in the global fight against marine plastic pollution.

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6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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