

AI-Driven Monitoring of Marine Ecosystems During Vessel Sinking Incidents - A Comprehensive Review

P. Sachi Devi¹, B. Mahima²

¹Department of Zoology, SKR & SKR Government College for Women (A), Kadapa, A.P., India
Email: sachidevipureti[at]gmail.com

²Department of Computer Science, Vellore Institute of Technology, Vellore, Tamil Nadu

Abstract: *The marine ecosystem plays a crucial role in sustaining life on Earth, supporting a vast array of flora such as phytoplankton, sea grasses, and macroalgae, and fauna including corals, fish, marine mammals, planktonic organisms, and benthic species. These rich and diverse biological communities contribute to oxygen production, carbon sequestration, nutrient cycling, and shoreline protection. Moreover, marine ecosystems hold immense economic value by supporting global fisheries, maritime trade, tourism, biotechnology, and natural resource extraction- collectively contributing trillions of dollars to the world economy. However, vessel sinking incidents pose significant threats to these delicate ecosystems, causing oil spills, toxic chemical leakage, habitat destruction, and long-term ecological disruption. In recent years, Artificial Intelligence (AI) has emerged as a transformative tool for real-time monitoring, damage assessment, and mitigation of such marine environmental hazards. This comprehensive review examines the role of AI-driven technologies- such as remote sensing, computer vision, machine learning, autonomous underwater vehicles (AUVs), and predictive analytics- in monitoring marine ecosystems during and after vessel sinking events. The paper explores how AI enhances the detection of ecological disturbances, automates surveillance of impacted zones, supports rapid decision-making, and improves early warning and response systems. Additionally, it highlights AI's potential to model pollutant dispersion, assess biodiversity loss, predict marine species displacement, and forecast long-term ecological consequences with higher precision. The review also addresses key challenges, including data scarcity, model reliability, cost constraints, and ethical considerations, while proposing future research directions to develop sustainable, interoperable, and advanced AI frameworks. Ultimately, this work underscores AI's potential as a critical enabler for safeguarding marine ecosystems and enhancing disaster response strategies during vessel sinking incidents.*

Keywords: Biodiversity, economic value, vessel sinking, ecological destruction & AI-driven technologies

1. Introduction

70% of the world's surface is covered by the ocean. The ocean is extremely ecologically important as it plays a key part in human life. Marine ecosystems are among the most diverse, productive, and ecologically significant systems on Earth. They host a wide range of flora such as phytoplankton, mangroves, seagrasses, and macroalgae, along with rich fauna including corals, fish, marine mammals, crustaceans, molluscs, plankton, and deep-sea organisms. These ecosystems perform crucial ecological functions such as oxygen generation, carbon sequestration, nutrient cycling, and climate regulation. Marine ecosystems provide unique bioactive molecules with significant therapeutic potential, making them essential for drug discovery and biomedical innovation. They also act as natural buffers against coastal erosion and support critical food chains essential for the survival of aquatic and terrestrial life. Economically, marine ecosystems contribute significantly through fisheries, aquaculture, coastal tourism, biotechnology, and maritime industries, supporting the livelihoods of millions worldwide and contributing substantially to global GDP.

However, the stability of marine environments is increasingly threatened by anthropogenic activities, particularly maritime disasters such as vessel sinking. These events not only cause loss of life but pose severe environmental risks- oil and chemical leakage, marine habitat destruction, and long-term contamination.

The recent vessel sinking disasters vividly illustrate the need for real-time, high-resolution monitoring of marine ecosystems. Traditional monitoring methods- such as periodic sampling, manual inspections, and laboratory analysis- often fall short during sudden, rapidly evolving incidents. They lack the speed, scale, and responsiveness needed to assess ecological damage, guide emergency response, or model pollutant dispersion in dynamically changing conditions.

In this context, Artificial Intelligence (AI) emerges as a powerful ally. AI-driven technologies- including remote sensing, autonomous underwater vehicles (AUVs), machine learning, computer vision, and predictive modelling- can process large volumes of heterogeneous environmental data, detect anomalies, track pollutant plumes, and predict ecological consequences with high accuracy. These capabilities make AI an invaluable tool for early warning, real-time surveillance, and strategic decision-making in maritime disaster contexts.

2. Aim of the Review

This paper provides a comprehensive review of AI-driven approaches for monitoring marine ecosystems in the face of vessel disappearance or sinking incidents. We examine how AI can improve data acquisition, enhance situational awareness, support rapid response, and forecast long-term ecological impacts. We also discuss key challenges- such as data gaps, technological limitations, and policy or ethical barriers- and outline potential future directions for developing

resilient, scalable AI-based monitoring frameworks. By doing so, we highlight the critical role of AI in protecting marine biodiversity, coastal communities, and global environmental health during maritime disasters.

Marine Ecosystems and Threats from Vessel Sinking

Maritime transportation plays a central role in global trade, handling more than 80% of international cargo owing to its high load capacity and cost efficiency compared to air or land transport. Its critical role in sustaining the global economy is undeniable, yet the sector continues to face environmental, operational, and geopolitical challenges. Recent assessments indicate a rise in maritime incidents, with commercial vessel accidents increasing by approximately 6% in 2024 compared to the previous year. However, despite this short-term increase, long-term trends reveal a considerable decline in overall vessel losses. Notably, total vessel losses have dropped dramatically from 105 recorded cases in 2015 to just 26 in 2023, demonstrating notable improvements in maritime safety and risk management practices.

In response to growing safety concerns, the shipping industry has adopted several measures to enhance safety performance, including updated regulatory policies, improved navigational technologies, and enhanced crew training programs. However, despite these advancements, maritime accidents—particularly vessel collisions—continue to pose significant safety challenges (Chauvin, Lardjane, Morel & Clostermann, 2013, p. 26).

Recent high-impact incidents have highlighted the magnitude of this issue. For example, the **MSC Elsa 3**, a Liberian-flagged container vessel, sank off the coast of Kochi, India, carrying hazardous goods and heavy fuel oil, raising serious concerns of marine pollution and biodiversity exposure (NDTV, 2025). In the **Singapore Strait**, a ferry collided with an oil tanker, resulting in a significant oil spill near the Southern Islands, posing threats to nearby coral reefs and coastal ecosystems (Reuters, 2025). Similarly, crew-transfer operations near the Beira port in Mozambique resulted in a vessel capsizing incident with human casualties and environmental concerns (The Hindu, 2025).

Additionally, geopolitically induced maritime disasters are adding new layers of complexity. In Ukraine, an LPG tanker was ignited by a drone strike at the Izmail port, raising severe concerns about chemical leakage and marine toxic exposure (BBC News, 2025). Collisions in the open sea also pose considerable risks—such as the North Sea cargo vessel crash, which not only resulted in human loss but also highlighted the risk of accidental spills and debris dispersion in ecologically sensitive waters (Sky News, 2025). Furthermore, passenger and tourist vessels, although smaller, have also resulted in tragic incidents, such as the **Hạ Long Bay capsizing** in Vietnam, which had both human and ecological consequences (Reuters, 2025). Even naval and training vessels have caused environmental threats, such as the Mexican Navy training ship **Cuauhtémoc** crash into the Brooklyn Bridge, demonstrating how vessel instability can have multi-dimensional impacts (CNN, 2025).

Marine accidents can have significant adverse effects on human life, the marine environment, and property, both at sea

and along coastal regions. The consequences of such incidents range from minor injuries to loss of life, and from negligible material damage to catastrophic environmental destruction. While some accidents are primarily operational in nature, others escalate into severe environmental disasters, particularly when involving oil spills or hazardous cargo release (Akten & Gonencgil, 2002).

Vessel sinking incidents often lead to the release of petroleum hydrocarbons, hazardous chemicals, heavy metals, and other pollutants into marine waters. These contaminants severely impact water quality, disrupt coral reefs, damage seabed habitats, and affect the survival and behavioral patterns of marine organisms. Long-term exposure to these pollutants can lead to bioaccumulation, biodiversity loss, reproductive failure in species, and even ecosystem collapse. Moreover, vessel wreckage can physically destroy fragile ecosystems and alter ocean floor morphology, compounding ecological damage.

Challenges in Real-Time Monitoring and Risk Management During Vessel Sinking Incidents

Real-time monitoring and risk assessment during vessel sinking incidents face a multitude of operational, regulatory, and technological challenges. A major concern is the inadequate transparency in cargo declaration, where shippers frequently misdeclare or fail to properly disclose hazardous or sensitive cargo, hindering authorities' ability to accurately assess risks and implement timely mitigation strategies. Improper handling, packaging, and storage of hazardous materials further elevate the likelihood of fires, explosions, and marine pollution, particularly during wreckage and salvage operations, due to the absence of globally standardized protocols. Furthermore, complex ownership and management structures—such as vessels being Liberia-flagged, German-owned, and Cyprus-managed—lead to diluted responsibility, fragmented accountability, and difficulties in initiating coordinated emergency responses. In addition to these administrative challenges, real-time environmental monitoring is often impaired by harsh oceanic conditions, disrupted communications, and insufficient integration of satellite, sensor, and vessel-based data sources. The absence of an urgent global mechanism for rapid investigation and coordinated regulatory action often results in delayed responses, with safety protocols being revised only after major accidents rather than through preventive reform. These limitations underscore the necessity for AI-enabled decision-support systems, enhanced cargo transparency mechanisms, global regulatory harmonization, and advanced multisensor data fusion to strengthen maritime safety and environmental protection.

AI driven surveillance of marine ecosystem during vessel sinking

Traditional human-led maritime surveillance faces critical limitations, such as restricted observational coverage, cognitive fatigue, and delayed response in emergency situations. These issues become particularly serious during vessel sinking incidents, where rapid assessment of environmental threats—such as oil spills, chemical leaks, or disturbance to marine habitats—is essential. The problem is further aggravated by “dark vessels,” which intentionally disable AIS tracking systems, making them invisible to

standard monitoring platforms and increasing the risk of undetected ecological hazards. In this context, AI-driven systems provide advanced capabilities for real-time environmental monitoring through the integration of satellite imagery, remote sensing data, oceanographic sensors, and autonomous underwater vehicles (AUVs). These technologies enable early detection of oil slicks, toxic dispersions, and disturbances to marine flora and fauna, supporting predictive modeling of spill trajectories and ecological impact zones. Countries like India are integrating AI-enabled swarm drones and smart sensor networks to enhance maritime domain awareness, not only for security surveillance but also for ecological safeguarding during emergencies. AI's ability to detect anomalies early, generate actionable insights, and optimize response strategies significantly improves marine environmental protection efforts while reducing monitoring costs and improving ecosystem resilience.

Application of Remote Sensing in Monitoring Marine Ecosystems

Remote sensing plays a pivotal role in monitoring marine ecosystems during and after vessel sinking incidents by providing real-time, spatially extensive, and multi-temporal environmental data. When ships sink, they often release oil, hazardous cargo, heavy metals, and other pollutants that significantly alter the surrounding water quality and marine habitats. Satellite-based and aerial remote sensing technologies enable rapid detection and continuous tracking of oil spills, sediment plumes, and dispersing contaminants by analyzing spectral signatures in the visible, infrared, and microwave regions. Key water quality indicators—such as chlorophyll-a (Chl-a), total suspended solids (TSS), turbidity, colored dissolved organic matter (CDOM), and sea surface temperature (SST)—can be measured using optical, thermal, and radar sensors. These parameters help detect eutrophication, harmful algal blooms (HABs), suspended sediment disturbances, and temperature anomalies caused by pollutant dispersion or physical disruption of marine habitats.

Chl-a concentrations, derived from ocean color sensors, signal changes in phytoplankton activity and nutrient enrichment, which may indicate pollution-driven ecological imbalances. Similarly, elevated TSS levels and turbidity detected through reflectance in the red and near-infrared bands help track sediment resuspension and cargo leakage following a sinking event. CDOM measurements provide insight into dissolved organic pollutants and overall ecosystem health, while SST variations, monitored via thermal imaging, can reveal oil-induced thermal anomalies or stress conditions affecting marine flora and fauna. Moreover, remote sensing supports biodiversity monitoring using four established approaches: (1) identifying phytoplankton community structure through spectral reflectance, (2) mapping foundational species such as corals, kelp forests, and seagrass meadows, (3) delineating dynamic habitat features like eddies, fronts, and seascapes through multi-sensor fusion, and (4) estimating species distributions by linking remotely sensed data with biological surveys.

In the context of vessel sinking, these methods allow researchers to assess how pollutant dispersion affects trophic interactions, species habitats, and ecosystem resilience. They

also facilitate predictive modeling of spill trajectories, habitat vulnerability analysis, and post-disaster ecological recovery assessments. As a result, remote sensing technologies serve as a crucial early-warning system and long-term monitoring platform, supporting environmental decision-making, regulatory compliance, and habitat restoration efforts in impacted marine zones.

Role of Satellite Imagery in Monitoring Marine Ecosystems During Vessel Sinking Incidents

Satellite imagery plays a vital role in monitoring marine ecosystems affected by vessel sinking incidents by enabling large-scale, frequent, and cost-effective observation of environmental changes. While satellites cannot directly capture deep-sea fauna, they provide high-value data on pollution, water quality, and habitat conditions that influence marine flora and fauna. Synthetic Aperture Radar (SAR) satellites like Sentinel-1 detect oil spills by identifying dark, low-backscatter regions where oil dampens surface waves, offering reliable monitoring day and night, even under cloudy conditions. Optical satellites such as Landsat, Sentinel-2, and Pléiades Neo provide high-resolution imagery to visually map oil slicks, sediment plumes, and changes in water color. Time-series satellite data help track spill progression, predict movement using ocean current and wind models, and assess long-term ecological recovery. Satellites also monitor key water quality indicators such as chlorophyll-a (a proxy for phytoplankton abundance), turbidity, sea surface temperature (SST), and colored dissolved organic matter (CDOM), which signal nutrient changes, suspended sediments, or pollution impacts on ecosystems like coral reefs, mangroves, and seagrass beds. In some cases, corroding metal from wrecks leads to “black reef” formation, detectable via high-resolution imagery. Furthermore, satellite-based animal tracking, using tagged species like sea turtles or whales, combined with environmental datasets, helps assess fauna movement and behavioral responses to sinking-related disturbances. Overall, satellite imagery provides a comprehensive, scalable, and efficient tool for detecting, tracking, and evaluating the environmental impacts of ship sinking on marine ecosystems.

Role of Computer Vision and Machine Learning in Vessel Sinking Event Analysis

Computer Vision (CV) and Machine Learning (ML) form the analytical backbone of AI-driven marine ecosystem monitoring during vessel sinking incidents. These techniques enable automated interpretation of vast volumes of visual and sensor-based data generated from satellites, drones, underwater cameras, and ship-mounted systems. During sinking events, CV algorithms are employed to detect oil slicks, floating debris, vessel wreckage, and changes in water color or surface texture that indicate pollution. Deep learning models, particularly Convolutional Neural Networks (CNNs), have demonstrated high accuracy in classifying oil spill signatures from satellite and aerial imagery, even under complex sea-state and lighting conditions.

Machine learning techniques further support real-time risk assessment by integrating heterogeneous datasets such as ocean currents, wind speed, wave height, cargo type, and historical accident records. Supervised learning models are used to classify spill severity and pollution type, while unsupervised learning assists in anomaly detection—

identifying unusual environmental patterns that may indicate hidden or delayed ecological damage. Reinforcement learning models are increasingly explored for optimizing response strategies, such as prioritizing surveillance zones, allocating cleanup resources, and adjusting monitoring intensity based on evolving risk levels.

In addition, computer vision facilitates automated wildlife monitoring during and after vessel sinking incidents. AI-powered image and video analysis can detect changes in coral cover, fish density, marine mammal presence, and seabed conditions, enabling rapid biodiversity impact assessments. When combined with transfer learning and cloud-based processing, these systems allow scalable, near-real-time environmental intelligence, significantly reducing human workload and response delays.

Autonomous Underwater Vehicles (AUVs) and Robotic Systems in Post-Sinking Monitoring

Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs) play a critical role in assessing sub-surface and deep-sea impacts of vessel sinking incidents—areas beyond the reach of satellite and aerial platforms. Equipped with AI-enabled navigation systems, chemical sensors, sonar, and high-resolution cameras, these robotic platforms can conduct detailed inspections of wreck sites, map seabed disturbances, and detect underwater pollutant plumes.

AI algorithms enable AUVs to perform adaptive sampling, where data collection strategies dynamically change in response to detected anomalies such as hydrocarbon concentration spikes or unusual turbidity levels. Machine learning-based sonar interpretation allows precise mapping of wreckage dispersion and benthic habitat damage, while computer vision supports automated identification of coral damage, sediment smothering, and changes in benthic species composition.

Swarm robotics, where multiple AUVs coordinate using AI-driven communication and decision-making protocols, offers enhanced spatial coverage and redundancy during emergency monitoring. Such systems improve resilience in harsh marine environments and support faster, more comprehensive assessments of ecological damage following vessel sinking incidents.

Predictive Analytics and Pollutant Dispersion Modelling

Predictive analytics represents one of the most powerful applications of AI in maritime disaster response. By combining machine learning models with physical oceanographic data—such as currents, tides, wind patterns, and bathymetry—AI systems can forecast the trajectory, spread, and persistence of oil spills and chemical plumes released during vessel sinking events.

Data-driven models, including recurrent neural networks (RNNs) and long short-term memory (LSTM) architectures, are particularly effective in capturing temporal dynamics of pollutant movement. These models outperform traditional deterministic models in complex, non-linear marine environments by continuously updating predictions as new data streams become available. Predictive outputs assist

authorities in identifying high-risk coastal zones, ecologically sensitive habitats, and optimal intervention windows.

Beyond spill movement, AI-based predictive models also estimate long-term ecological consequences, such as recovery timelines, species displacement, and cumulative ecosystem stress. These insights support evidence-based policy decisions, habitat restoration planning, and compensation assessments following maritime disasters.

AI Applications in Biodiversity Impact Assessment

AI-driven biodiversity assessment tools enable rapid evaluation of ecological damage caused by vessel sinking incidents. By analyzing remotely sensed data, underwater imagery, acoustic signals, and species tracking information, AI systems can quantify changes in species abundance, distribution, and behavior. Machine learning classifiers are used to identify vulnerable species, detect mortality events, and assess habitat fragmentation.

Acoustic monitoring combined with AI-based signal processing allows detection of changes in marine mammal vocalization patterns, indicating stress or displacement. Similarly, AI-assisted image analysis helps monitor coral bleaching, seagrass loss, and invasive species proliferation following pollution events. These approaches enable continuous, non-invasive biodiversity monitoring, improving understanding of both immediate and delayed ecological impacts.

3. Limitations, Ethical Considerations, and Policy Challenges

Despite the significant advantages of AI-driven monitoring systems, several limitations constrain their widespread adoption in marine ecosystem surveillance during vessel sinking incidents. One of the primary challenges is data availability and quality. Marine environments are vast, dynamic, and often poorly instrumented, leading to sparse, noisy, or incomplete datasets that can reduce model accuracy and reliability. AI models trained on region-specific or historical data may also struggle to generalize across diverse oceanographic conditions.

Technological and infrastructural constraints further limit real-time deployment, particularly in developing regions. High costs associated with satellite data acquisition, AUV deployment, sensor maintenance, and computational infrastructure can restrict accessibility. Additionally, interoperability issues between different monitoring platforms and data standards hinder seamless data fusion and coordinated response.

Ethical and governance concerns also require careful consideration. The use of AI-powered surveillance raises questions regarding data ownership, privacy (especially when monitoring near coastal communities), and equitable access to technology. Moreover, reliance on automated decision-making systems without adequate human oversight may introduce risks during high-stakes emergency responses. From a policy perspective, fragmented international maritime regulations and inconsistent enforcement mechanisms complicate coordinated environmental protection efforts

during cross-border maritime disasters. Addressing these challenges requires transparent AI frameworks, human-in-the-loop systems, and harmonized global regulatory policies.

4. Future Perspectives and Research Directions

The future of AI-driven marine ecosystem monitoring lies in the development of integrated, adaptive, and scalable systems capable of supporting proactive disaster preparedness as well as post-incident assessment. Advances in deep learning, edge computing, and digital twin technologies are expected to enhance real-time analytics and predictive accuracy. Digital twins of marine environments, combining physical models with AI-driven simulations, can enable scenario testing, risk forecasting, and optimized response planning before and during vessel sinking incidents.

Greater emphasis on open-access data platforms, standardized data protocols, and international collaboration will be essential for improving model robustness and global applicability. Emerging technologies such as bio-inspired sensors, AI-enabled swarm robotics, and hybrid satellite-AUV monitoring networks hold promise for expanding coverage and resilience in harsh marine conditions. Future research should also focus on integrating socio-economic and ecological indicators to support holistic impact assessments and sustainable policy development.

Capacity building, interdisciplinary collaboration, and ethical-by-design AI development will play key roles in ensuring that AI technologies contribute equitably and responsibly to marine conservation and disaster response. By aligning technological innovation with environmental governance, AI can evolve from a reactive monitoring tool to a proactive guardian of marine ecosystems.

5. Conclusion

Vessel sinking incidents represent a significant and growing threat to marine ecosystems, with far-reaching ecological, economic, and social consequences. Traditional monitoring approaches are often insufficient to address the speed, scale, and complexity of environmental damage caused by such events. This review highlights the transformative potential of Artificial Intelligence in enhancing real-time monitoring, impact assessment, and mitigation of marine environmental hazards during vessel sinking incidents.

AI-driven technologies- including remote sensing, satellite imagery, computer vision, machine learning, autonomous underwater vehicles, and predictive analytics- enable comprehensive surveillance across spatial and temporal scales that were previously unattainable. These tools improve early detection of pollution, support rapid decision-making, and facilitate long-term ecological recovery assessments. While challenges related to data limitations, cost, ethics, and policy remain, continued technological advancement and international cooperation offer viable pathways to overcome these barriers.

Ultimately, the integration of AI into marine disaster management frameworks represents a critical step toward safeguarding marine biodiversity, protecting coastal

communities, and promoting sustainable use of ocean resources. As maritime activity continues to expand globally, AI-driven monitoring systems will be indispensable for ensuring resilient, responsive, and environmentally responsible ocean governance.

References

- [1] Akten, N., & Gonencgil, B. (2002). Marine accidents and their environmental impacts. *Journal of Maritime Studies*, 14, 45–58.
- [2] Bakirci, M. (2025). Advanced ship detection and ocean monitoring with satellite imagery and deep learning for marine science applications. *Regional Studies in Marine Science*, 81, 103975. <https://doi.org/10.1016/j.rsma.2024.103975>
- [3] BBC News. (2025, November 5). Russian drone attack sets tanker ablaze in Ukraine's Izmail port. *BBC News*.
- [4] Ceyhun, G. (2014). The impact of shipping accidents on marine environment: A study of Turkish seas. *European Scientific Journal*, 10, 1857–7881.
- [5] Chauvin, C., Lardjane, S., Morel, G., & Clostermann, J. P. (2013). Human and organisational factors in maritime accidents: Analysis of collisions at sea using the HFACS. *Accident Analysis & Prevention*, 59, 26–37.
- [6] CNN. (2025, May 6). Mexican Navy's Cuauhtémoc ship crashes into Brooklyn Bridge, killing two cadets. *CNN*.
- [7] Gajapathy, R., Dubey, A., & Rajendran, S. (2023). Collision avoidance of Maritime Autonomous Surface Ships (MASS) based on heading set approach with multiple ship encounters in compliance with COLREGs. *Journal of Marine Science and Engineering*, 11, 1–18.
- [8] Kilic, K. I., Maity, S., Sung, I., & Nielsen, P. (2025). Challenges and AI-driven solutions in maritime search and rescue planning: A comprehensive literature review. *Marine Policy*, 178, 106692. <https://doi.org/10.1016/j.marpol.2025.106692>
- [9] NDTV. (2025, May 26). Sunken MSC Elsa 3 sparks environmental concerns off Kerala coast; no oil spill reported yet. *NDTV*.
- [10] Reuters. (2025, July 20). Vietnam searches for missing after tourist vessel capsizes in Ha Long Bay storm. *Reuters*.
- [11] Reuters. (2025, November 10). Singapore-flagged ferry and oil tanker collide, causing oil spill near Southern Islands. *Reuters*.
- [12] Sky News. (2025, March 18). Portuguese cargo ship involved in deadly collision; captain arrested for negligence. *Sky News*.
- [13] The Hindu. (2025, October 22). Three Indian nationals dead, five missing after boat capsizes off Mozambique coast. *The Hindu*.
- [14] Wan, S., Yang, X., Chen, X., Qu, Z., An, C., Zhang, B., Lee, K., & Bi, H. (2022). Emerging marine pollution from container ship accidents: Risk characteristics, response strategies, and regulation advancements. *Journal of Cleaner Production*, 376, 134266. <https://doi.org/10.1016/j.jclepro.2022.134266>