Gauging the Effectiveness and Translatability of Oil Spill Response Technologies to Plastic Pellet Spills

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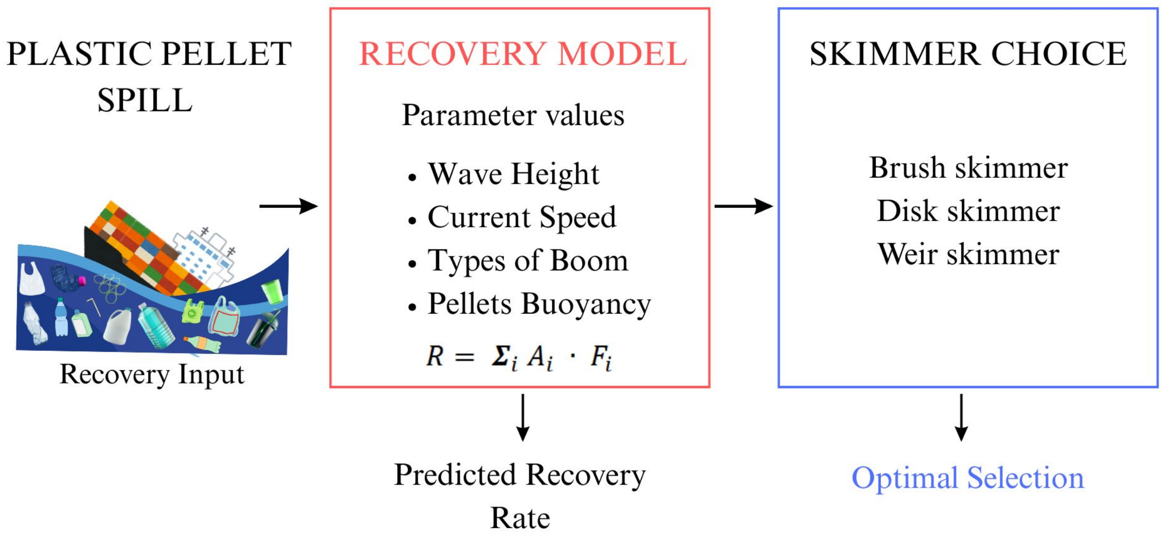
GRAPHICAL ABSTRACT



ABSTRACT

Plastic pellet spills are a growing environmental concern, yet response strategies remain limited and poorly adapted. This study evaluates whether existing oil spill recovery tools, including booms, skimmers, and specialized vessels, can be repurposed to respond to acute releases of plastic pellets. Plastic pellets, while small (typically 1–5 mm in diameter), are characterized by complex physical properties including varied polymer types, sizes, shapes, colors, and especially densities. These features strongly influence dispersion dynamics and cleanup feasibility. Our analysis reveals critical limitations in current response technologies, primarily due to their oil-centric design and lack of consideration for the unique behavior of plastic pellets. By bridging oil spill expertise with emerging plastic threats, we outline opportunities for adaptive, cross-sector response strategies tailored to the realities of plastic pellet spills. This study includes field demonstrations in the northern Adriatic, where oil-spill skimmers and booms were successfully tested for plastic pellet recovery under real-world marine conditions.

1. INTRODUCTION

Plastic pellets have been found in coastal and open ocean environments since the 1970s, resulting from chronic and acute spills. These microplastic-sized pellets, commonly referred to as nurdles, are pre-production polymer granules that are melted to manufacture plastic products. They typically measure 1–5 mm in diameter, have a lentil or cylindrical shape, have smooth hydrophobic surfaces, and are primarily white or translucent in color (**Figure 1**).

Polyethylene (PE) and polypropylene (PP) pellets are among the most prevalent types found in the marine environment. These polymers have densities ranging from 0.89 to 0.96 g/cm^3, giving them positive buoyancy in seawater, which aids in their dispersal via wind, surface currents, and wave dynamics. Their small size and physical behavior make recovery efforts, especially containment and collection, challenging (Osrl, 2025). Other polymers such as PS, polyethylene terephthalate (PET), or polyvinyl chloride (PVC) may also be released into the marine environment; however, due to their greater density and negative buoyancy in seawater, these materials are more likely to accumulate in sediments and are therefore less commonly observed during surface spill events

The largest spill occurred in May 2021, the cargo vessel M/V *X-Press Pearl* suffered a major accident while anchored 18 km off the western coast of Sri Lanka. A fire broke out on board, leading to explosions and a complex rescue operation. Because the vessel carried 1,486 containers filled with various raw materials, hazardous chemicals, and finished goods, the incident became even more challenging for the crew and rescuers. The fire was extinguished on June 1, but salvage efforts failed to prevent the ship from completely sinking on June 17. During this time, many containers burned, fell into the sea, or washed ashore, and their contents—including plastic pellets ended up in the environment. More than 1,000 metric tons of pellets and debris were collected from affected shorelines. Although some booms were reportedly deployed, there was no large-scale offshore recovery of floating pellets. Most of the plastic was transported by wind and currents to the shore, where clean-up was conducted manually and mechanically (Osrl, 2024).

In another study by (James and Reddy 2025) provides a detailed account of an accidental release of plastic pellets into the environment that occurred in the Port of New Orleans in 2020. During cargo handling operations at the port, the vessel CMA CGM *Bianca* was caught in a sudden storm. Strong winds caused the loss of four containers, one of which held approximately 20 metric tons of PE pellets. Upon impact, the container ruptured, and a large portion of its contents spilled into the Mississippi River. The situation was further complicated by additional pellet leakage during subsequent container recovery operations. Recognizing that responding to pellet spills will demand a different approach and technologies, (James and Reddy 2025) recommended future work on how best to respond.

Responding to pellet spills is challenging because pellets disperse rapidly and are difficult to recover, often leaving significant amounts in the ecosystem (Folbert *et al*., 2024; Mayorga Adame *et al*., 2025). For instance, due to their small size and low density, floating plastic pellets can be transported several kilometers offshore within a few hours by wind and surface currents. In contrast, oil slicks tend to remain more cohesive and typically drift more slowly under similar conditions. A swift and well-coordinated response is essential to recover plastic pellets before they disperse or become stranded along shorelines. A swift and well-coordinated response is essential to recover plastic pellets before they disperse or become stranded along shorelines. Equally necessary is the use of equipment that is appropriately matched to the physical behavior of plastic materials and prevailing sea conditions. Delays in action significantly reduce recovery efficiency and increase the likelihood of long-term environmental impacts. Using poorly matched tools may result in incomplete removal or unintended redistribution of pollutants.

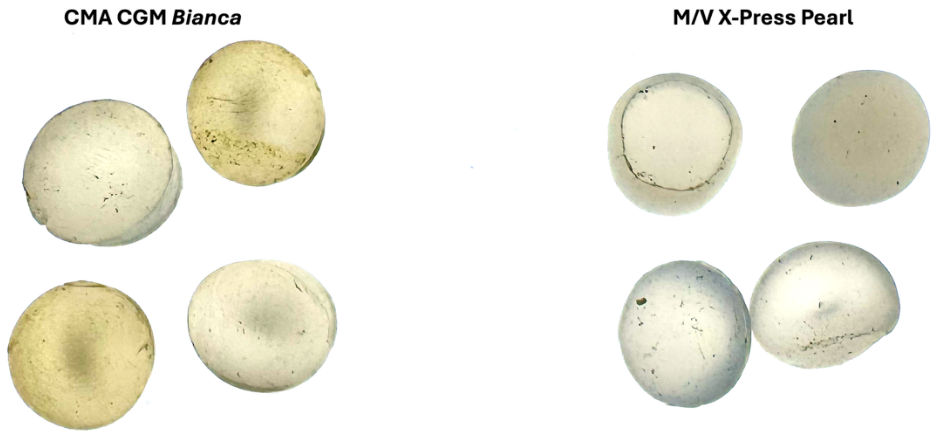


Figure 1. Representative images of PE pellets from the CGA CMA *Bianca* and the M/V *X-Press Pearl* spills.

Plastic pellet pollution, while chemically distinct from oil, shares similar surface behaviors and dispersion dynamics in marine environments. This similarity suggests that certain oil spill response tools might be adapted for addressing plastic pellet incidents. Oil spill response has benefited from decades of development, standardization, and field validation, as documented in resources like the ExxonMobil Oil Spill Response Field Manual (ExxonMobil, 2008). In contrast, plastic pellet pollution remains largely unaddressed by formal response frameworks (James and Reddy 2025). Although plastic pellets have long been excluded from formal response protocols due to their classification as non-hazardous materials, recent efforts, including NOAA and U.S. Coast Guard workshops, indicate a shift in regulatory awareness. Legislation is currently under consideration in the U.S. Congress to address this regulatory gap. This gap highlights the need to explore existing technologies for potential adaptation, especially from skimmers, which are mechanical devices designed to remove floating contaminants from the water surface. According to the U.S. Environmental Protection Agency (EPA, 2025), skimmers can be self-propelled, used from shore, or operated from vessels, and their efficiency depends on sea conditions and the type of oil being recovered. A seemingly straightforward solution is to repurpose existing oil spill recovery technologies, such as booms, skimmers, and response vessels, for plastic pellet collection. Different types of skimmers include disk, weir, and brush, each with specific operational characteristics (Đorđević, *et al*., 2022). Brush skimmers utilize rotating bristles that collect material through contact, providing flexibility for variable surface textures, albeit with generally lower purity of recoveries (**Figure 2a**). Disc skimmers employ rotating oleophilic discs that adhere to floating material, demonstrating high selectivity and low water uptake in calm conditions (**Figure 2b**). Weir skimmers function by floating weirs that allow the water surface layer, including floatable matter, to overflow into a collection chamber, proving highly effective at capturing large volumes but also entraining more water and debris (Osrl, 2024). These systems, originally developed for oil recovery, operate under the assumption of oleophilic adherence or surface overflow, both of which differ when collecting discrete solid particles, such as pellets. Operational efficiency is significantly influenced by wave height, current speed, and pellet buoyancy, motivating the need for a robust performance modeling approach tailored to pellet recovery under variable marine conditions, a gap that this study addresses.

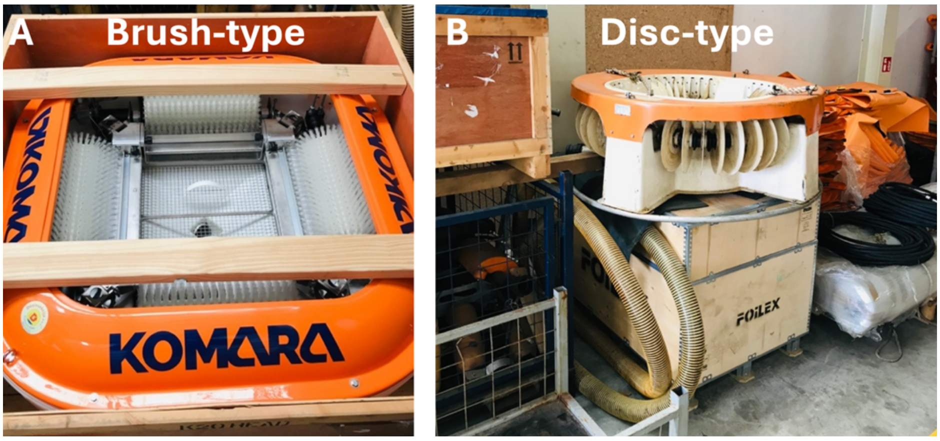


Figure 2. Examples of A) brush-type and B) disc-type skimmers.

The following section aims to evaluate the adaptability of oil spill response technologies for plastic pellet recovery, considering operational constraints and environmental conditions.

2. MATERIALS AND METHODS

Plastic pellet density plays a critical role in determining whether pellets will float or sink in marine environments. Positively buoyant polymers, such as HDPE and PP (density < 1 g/cm³), tend to remain on the surface and are thus accessible to conventional skimming systems, whereas denser polymers (e.g., PET, PVC) may submerge, requiring alternative recovery strategies. In all modeling exercises presented herein, we focused on high-density polyethylene (HDPE) and polypropylene (PP) pellets, as these polymers are positively buoyant in seawater and represent the most observed types during surface spill events (Folbert *et al.*, 2024).

2.1. Model of Theoretical Plastic Recovery

To evaluate the applicability of oil spill response equipment in the recovery of plastic pellets, a theoretical model was developed to quantify the effective recovery rate of various skimmer types under realistic marine conditions. The primary objective is to estimate the volume of floating plastic pellets and entrained seawater collected per hour (R, in m³/h), considering the performance characteristics of the equipment and the influence of key environmental variables.
The model is based on the following general expression:

$$R = \Sigma_i \, A_\mathrm{i} \cdot F_\mathrm{i} \ , \qquad i = 1, \dots, n \tag{1}$$

In this model, R represents the estimated gross recovery rate (m³/h), i.e., the total volume of floating surface material (plastic pellets and entrained water) collected by a combination of n skimmers. Nominal recovery values (A_i) provided by manufacturers are typically based on controlled conditions and target material efficiency, with minimal water uptake. However, under real sea conditions, environmental factors such as wave height and current speed reduce both the selectivity and the overall recovery performance, which is reflected through correction functions (F_i). The actual pellet-only fraction within R may vary and can be approximated through field calibration, as demonstrated in this study using popcorn as a biodegradable proxy.

Popcorn serves as an appropriate proxy for floating plastic pellets because it exhibits comparable floating behavior and surface area-to-mass ratio, enabling realistic simulation of surface dispersion patterns without posing ecological risk. While the model aims to estimate the volume of plastic pellets collected per hour, expression (1) reflects the gross recovery volume, including both pellets and entrained water. This choice was made to align with standard skimmer performance ratings, which are typically expressed in m^3/h. However, because the actual fraction of plastic pellets within recovered volume can vary depending on environmental conditions and material distribution, isolating the true pellet volume or mass requires additional data on pellet density or concentration. This distinction is important when evaluating skimmer efficiency specific to plastic pellet recovery.

The skimmer-specific performance factor F_i is defined as function of environmental and operational correction terms:

$$F_i = f_i(w) \cdot g_i(c) \cdot k_i(s) \cdot m_i(p) \quad (2)$$

Each correction term represents a normalized scaling function (from 0 to 1). The scaling depends on the skimmer's sensitivity to environmental and operational parameters. In this model, the skimmer efficiency factor F_i is expressed as a product of four correction terms that reflect environmental and operational influences: wave height, current velocity, pellet characteristics, and deployment orientation (**Table 1**).

The wave height correction factor $f_i(w)$ accounts for the loss of skimmer efficiency under increasing wave conditions. It is defined within the normalized range, where $f_i(w) = 1$ for calm seas ($w \leq 0.2$ m) and decreases as the height of waves increases. This reflects reduced surface stability.

The current velocity correction factor $g_i(c)$ is defined to reflect the effect of horizontal water movement on skimmer performance. A value of $g_i(c) = 1$ is assigned for current speeds up to 0.2 m/s, representing optimal conditions, while the factor decrease toward $g_i(c) = 0$ is assumed for increasing wave height to reflect a reduced residence time of particles next to the skimmer and increased turbulence. The boundaries span the transition between operational feasibility and turbulent disruption during recovery.

The pellet-specific correction factor $k(s)$ accounts for differences in buoyancy, shape, and density. It is normalized to 1.0 for HDPE pellets ($\rho \leq 0.95$ g/cm^3) and takes values < 1 for other polymers. Popcorn was used in this study as a biodegradable proxy to validate the behavior of floating pellets (already mentioned).

The deployment orientation factor $m(\alpha)$ represents the positional effectiveness of the skimmer during recovery. It is defined as $m(\alpha) = \cos(\alpha)$, where α is the inclination angle from the horizontal. The function yields $m(0°) = 1$ (optimal positioning), and decreases to $m(90°) = 0$, reflecting loss of performance due to vertical misalignment.

Table 1. Description of model correction factors and their parameter ranges

Symbol	**Description**	**Range**
$f(w)$	Wave height correction factor	$f(w) = 1$ for wave height $w \leq 0.2$ m; the function decreases as w increases.
$g(c)$	Current velocity correction factor	$g(c) = 1$ for sea current $c \leq 0.2$ m/s; the function decreases as c increases
$k(s)$	Pellet-specific factor (e.g. buoyancy, shape, density)	e.g., HDPE = 1, <1 for others; validated with popcorn
$m(\alpha)$	Deployment angle i.e. orientation factor	$m(\alpha) = \cos(\alpha)$, where α is the angle between the skimmer orientation and the direction of incoming water.

All correction terms are specific to skimmer configuration and expressed as functions of environmental variables. Although the precise relationship between skimmer orientation and recovery performance may vary across device types, a cosine-based correction function was selected to approximate the general reduction in recovery efficiency as the deployment angle increases relative to the incoming flow direction.

2.2. Model Implementation

The formulation enables quantitative comparison of different skimmer types under various marine conditions. It is particularly useful for response planners to simulate spill scenarios using a range of environmental inputs. To implement and analyze this model, two programming environments were used: R (RStudio) for statistical simulations and plotting, and MATLAB_R2020a for numerical modeling and sensitivity analyses. This dual approach enabled precise control over parameter testing and reproducible scenario simulations.

3. RESULTS

3.1. Theoretical modeling of skimmer recovery under varying sea conditions

The theoretical assessment aimed to evaluate the applicability of oil spill recovery equipment for collecting floating plastic pellets and determining the minimum recovery time, analogous to oil spill scenarios (Đorđević *et al.*, 2022). Using a structured model, we simulated the gross recovery rates of various skimmer types, including disk, brush, and weir, under different wave heights and current speeds. The objective was to identify which technologies perform most efficiently across varying sea conditions, and to assess the extent to which environmental parameters influence skimmer effectiveness.

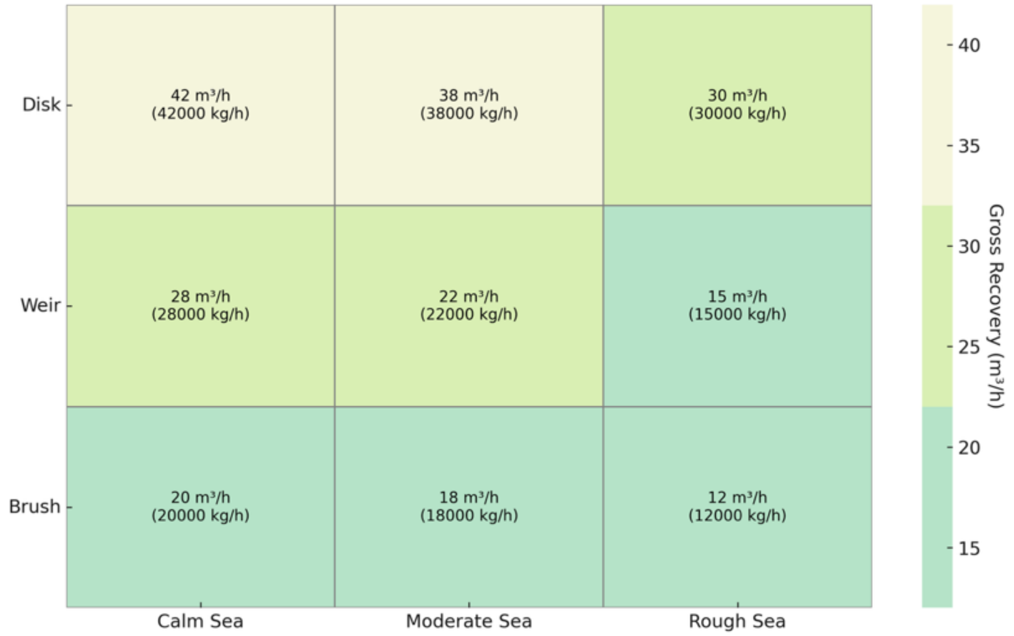
Figure 3A represents the gross recovery efficiency (R, in m^3/h) with equivalent mass conversion (kg/h) of different skimmer types under varying sea conditions. Sea states were categorized based on wave height: calm sea (<0.5 m), moderate sea (0.5–1.25 m), and rough sea (>1.25 m). The results presented in Figure 2 refer specifically to positively buoyant plastic pellets, namely high-density polyethylene (HDPE) and polypropylene (PP), which dominate during surface spill events.

Disk skimmers show the highest overall efficiency, followed by weir and brush skimmers. Performance drops for all types under rough sea conditions, highlighting environmental sensitivity. These values represent recovery rates based on modeled correction factors for environmental conditions. The maximum value of 42 m^3/h corresponds to optimal disk skimmer performance under calm sea conditions, reflecting nominal equipment capacity (Vikoma, 2025) adjusted for wave height, current velocity, and system configuration. The figure illustrates the decrease in recovery efficiency across sea states, emphasizing the importance of environmental correction in skimmer selection. Skimmer performance for oil is also known to decline under rough sea conditions, particularly for weir and brush systems. However, pellet recovery may be even more sensitive to wave action due to the small size, low inertia, and tendency of pellets to spread widely and disperse more rapidly than cohesive oil slicks.

Figure 3B shows a plot illustrating the relationship between wave height and the calculated gross recovery rate (R, in m^3/h) for different skimmer types. The results indicate that increased wave height consistently reduces skimmer efficiency, particularly for weir systems. Notably, while disk and brush skimmers differ significantly in recovery rate for calm sea, they are almost equally efficient for a wave height of 1.1 m. This trend highlights the importance of matching skimmer technology to prevailing sea conditions during spill response operations.

Figure 3C shows a contour plot illustrating how the gross recovery rate R (in m^3/h) varies with wave height and current speed, assuming optimal skimmer performance. The simulation incorporates environmental correction factors to capture the nonlinear response surface, emphasizing the decline in recovery efficiency under increasingly rough sea conditions.

A



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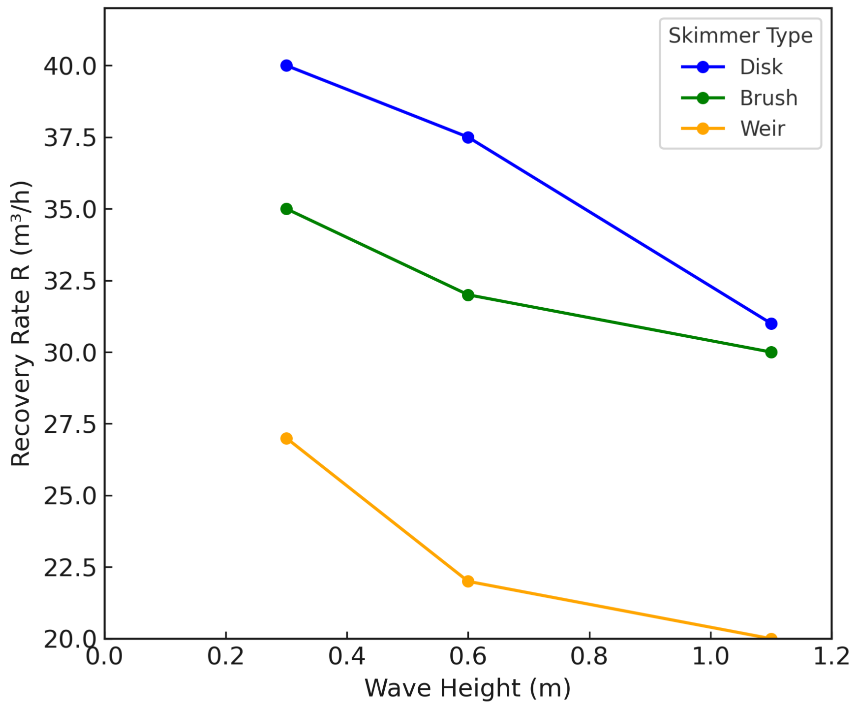

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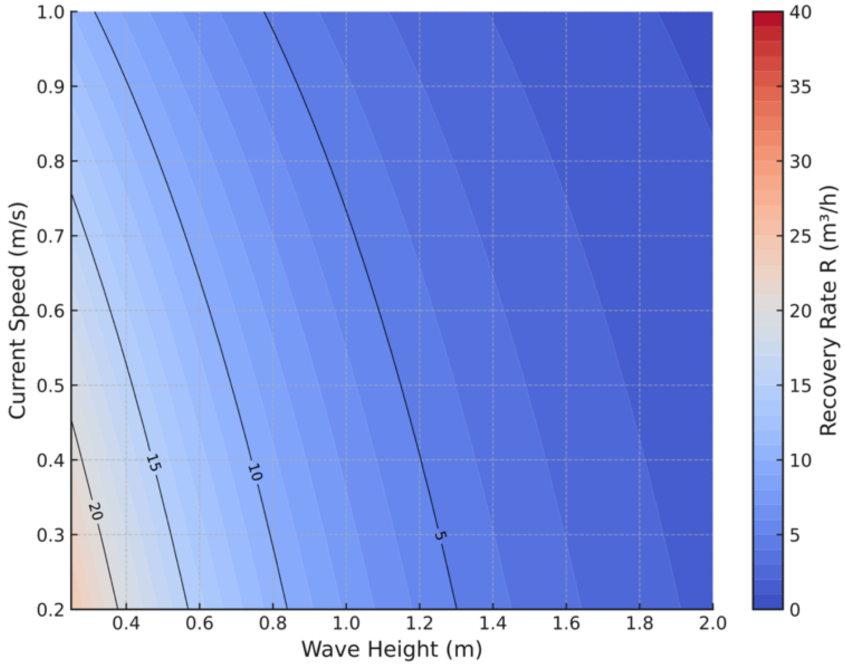

Figure 3. A) Heatmap of the gross recovery efficiency (R, in m^3/h) with the equivalent mass conversion (kg/h) for different skimmer types. B) The relationship between wave height and the calculated gross recovery rate (R in m^3/h) for low-density polyethylene (LDPE) pellets with a typical diameter of 3-5 mm, density of 0.91-0.93 g/cm^3, and rounded cylindrical shape. C) Modeled the relationship between wave height and current speed on recovery rate (R in m^3/h), based on brush skimmer performance data. Calculations refer to low-density polyethylene (LDPE) pellets with a diameter of 3-5 mm, a density of 0.91-0.93 g/cm^3, and a rounded cylindrical shape.

3.2. Field test of skimmer performance with popcorn proxy

In addition, as empirical support for this approach, a full-scale field exercise was conducted in the coastal waters of the Adriatic Sea, where popcorn was used as a proxy material to simulate a plastic pellet spill response.

The exercise was organized by the Adriatic Training and Research Centre (ATRAC) in collaboration with the Primorje-Gorski Kotar County, the Port Authority of Rijeka, and the specialized marine pollution response company Dezinsekcija d.o.o. It was conducted on September 28, 2018, under calm sea conditions. Eight bags containing approximately 500 liters of popcorn were released into the sea, serving as a proxy for floating solid pollutants such as plastic pellets. Two specialized vessels equipped with skimmer systems participated in the response. All released material was successfully recovered within thirty minutes of deployment. These results demonstrate that floating solid matter, similar in behavior to plastic pellets, can be efficiently collected under favorable conditions using existing oil spill response equipment. The firsthand involvement provided valuable insight into the practical deployment and efficiency of skimmer-equipped vessels in recovering both oil-like and solid floating pollutants under controlled conditions. Popcorn was chosen due to its ecological safety and buoyant properties, similar to floating plastic pellets. The skimming vessels, originally designed for oil recovery, successfully collected the floating popcorn under real-world sea conditions. This exercise was intentionally conducted at sea rather than in a laboratory to simulate a realistic marine accident scenario with variable and uncontrolled conditions. The skimmer equipment and recovery procedures were not modified and followed standard oil spill protocols. Popcorn was selected as a proxy because it floats, disperses similarly, and has comparable size and buoyancy to low-density plastic pellets.

Unlike laboratory experiments, where environmental parameters can be held constant, this open-water setting provided a more credible assessment of the equipment's effectiveness in the face of wind, waves, and surface currents.

Figure 4. Marine response exercise: popcorn recovery by a specialized vessel simulating a plastic particle spill response.

Figure 4 shows the field deployment of a specialized oil vessel equipped with a weir-type skimmer, commonly used for port and coastal operations, making it suitable for surface recovery. Two types of booms were considered: curtain and fence. Curtain booms are generally considered effective in wave heights up to 1 m, while fence booms are recommended for calmer conditions with waves below 0.5 m (ITOPF, 2025). These practical thresholds reflect operational field guidelines, which may differ from the model's stricter correction function range ($f(w) = 1$ for $w \leq 0.2$ m; and decreasing for higher wave height, introduced to capture gradual efficiency loss in dynamic conditions.

Additionally, the correction model accounts for deployment orientation as a performance factor, further refining skimmer selection under varied environmental scenarios. As well, the analysis incorporated varying sea conditions based on the Beaufort scale, which correlates wind speed with wave height (NOAA, 2025). Density ρ, defined as the ratio of mass to volume ($\rho = \frac{m}{V}$) is used to estimate the buoyancy of plastic pellets in seawater. Plastics with a density less than that of seawater (approximately 1.025 g/cm³) will float, while those with a higher density will sink. This study focused on floating pellets.

4. DISCUSSION

This study explored the applicability of existing oil spill response technologies, particularly mechanical skimmers, for addressing plastic pellet pollution events of characteristic types of plastic polymers. Through a modeling framework based on the recovery rate, we integrated performance characteristics, such as nominal gross recovery rates and compatibility with environmental conditions, with environmental parameters including wave height, current velocity, and equipment-pellet interaction. While disk skimmers demonstrated the highest recovery rates across tested scenarios, their deployment is not universally optimal. Brush skimmers, for example, are often preferred in high-viscosity or debris-laden environments due to their robustness and lower maintenance requirements. Weir skimmers, though less efficient in calm conditions, offer operational simplicity and are widely available in emergency stockpiles maintained by coast guards and spill response organizations. Additionally, procurement costs, ease of deployment, and compatibility with specific spill scenarios all influence the selection of skimming technology. Therefore, the recovery rate should be considered alongside logistical, economic, and operational constraints when selecting appropriate equipment.

Conversely, brush and weir skimmers, while effective in calmer waters, showed a significant decline in performance with increasing wave height and current velocity. The negative correlation between sea state intensity and gross recovery performance, consistently observed across model outputs, points to the importance of selecting response equipment based on site-specific hydrodynamic conditions. The gross recovery rates used in our analysis are based on publicly available manufacturer specifications intended for oil spill scenarios. While these values offer a practical benchmark, plastic pellets differ from oil in density, cohesion, and hydrodynamic behavior, and actual field performance may vary. For instance, weir skimmers often ingest substantial amounts of water along with debris, necessitating the integration of separation systems to isolate plastic particles.

Brush skimmers, though designed for viscous hydrocarbons, could be enhanced using engineered mesh systems with increased surface area and capture efficiency. Disk skimmers, which rely on adhesion-based recovery, may be upgraded with surfaces modified using superhydrophobic or triboelectric materials to attract and retain floating plastics. These proposed modifications would maintain mechanical compatibility with existing platforms but require targeted field validation. Although the current work is theoretical, it draws partial grounding from real-world response exercises conducted in the northern Adriatic Sea, where popcorn was used as a biodegradable proxy for floating plastics. In this field simulation, a dedicated oil spill response vessel successfully recovered floating popcorn using conventional skimming technology.

The exercise was conducted in coastal waters under realistic wind and wave conditions, providing greater ecological and operational relevance compared to laboratory trials. Given the similarity in floating behavior between popcorn and plastic pellets, the exercise provides empirical plausibility for our modeled assumptions. Overall, this research presents a structured evaluation method for matching available response technologies with plastic pellet spill scenarios. The use of dimensionless weighting parameters allowed for cross-comparison of diverse environmental and mechanical variables, while the use of gross recovery rates in m^3/h offered operational relevance.

Government agencies and industry responders worldwide are equipped with oil spill response equipment, including skimmers and booms. Assessing whether this existing arsenal can be effectively repurposed for floating plastic pellet spills is not only practical but also potentially transformative for real-world preparedness and mitigation.

The findings contribute a decision-support framework for selecting optimal equipment combinations under different marine conditions. Further empirical validation and targeted engineering enhancements are recommended to translate these findings into actionable protocols.

5. CONCLUSIONS

The global rise in plastic pellet spills presents a novel and complex challenge for marine pollution response. Despite their solid form and hydrophobic properties, pellets behave similarly to oil in surface dispersion yet demand tailored collection approaches due to their discrete nature. Field exercises conducted in the northern Adriatic Sea provided the first operational proof-of-concept that existing oil recovery equipment, such as skimmers and booms, can be effectively applied to collect floating plastic pellets. Using popcorn as a harmless analogue for floating pellets, the response teams successfully conducted recovery operations under realistic sea conditions, confirming the mechanical compatibility and deployment feasibility of oil spill tools in plastic spill scenarios. Building on this, our study developed a response suitability model that integrates skimmer type, environmental factors (wave height, current velocity), and pellet behavior to calculate expected recovery rates. This modeling framework enabled a comparative analysis of skimmer performance under varying marine conditions, demonstrating that disk skimmers offer the highest resilience and efficiency in moderate seas, while brush and weir skimmers show greater sensitivity to wave dynamics. A timely response is critical, as plastic pellets can rapidly disperse across wide areas. Employing containment booms early in the incident can help isolate and concentrate the pellets, thereby increasing their local density and significantly improving the efficiency of recovery operations.

While our model preserves core manufacturer parameters (e.g., recovery speed, swath width), actual performance may vary and should be verified through controlled field trials. Further, although this study introduced conceptual equipment modifications, some, particularly those involving advanced material integration, require additional research before operational implementation. By grounding its assumptions in realistic sea conditions and response data, and by focusing on adaptation rather than replacement, this framework enables both immediate application in contingency planning and long-term innovation in response design. In addition to adapting skimmer technologies for plastic pellet collection, the effective handling and offloading of recovered pellets remains an operational challenge. Addressing storage capacity and disposal logistics represents an important direction for future research and field preparedness. These findings support the practical use of existing oil spill response tools for floating plastic pellets under certain conditions. While further refinements may enhance efficiency, the ability to respond with the same core equipment improves preparedness and operational readiness for mixed pollution scenarios. As pellet transport volumes increase globally, building this preparedness capacity becomes not just advisable, but essential.

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