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Review Article

Evaluation of remote sensing monitoring as a Prognostic Tool in microplastic pollution

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Abstract

Background: Microplastic pollution is now documented across every ocean basin, but in-situ sampling by net trawl or beach transect is too sparse and slow to resolve basin-scale patchiness or to establish reliable pollution trends.

Objective: This review evaluates whether remote sensing platforms, from airborne and drone-mounted hyperspectral sensors to multispectral and hyperspectral satellites, can serve as a genuinely prognostic tool for anticipating microplastic accumulation rather than simply mapping existing debris.

Methods: We synthesized peer-reviewed studies on the spectral basis for optical plastic detection, sensor platform performance, and the coupling of remotely sensed observations to ocean transport and fragmentation models with forecasting relevance.

Findings: Shortwave infrared absorption features reliably distinguish plastic from water and biogenic material at airborne and drone scale, while spaceborne multispectral and hyperspectral sensors detect macroplastic aggregations with useful but imperfect accuracy; direct sub-pixel detection of dispersed microplastic itself remains unvalidated, and prognostic use so far depends on coupling debris and convergence-zone detections to circulation models rather than on satellite retrieval of microplastic concentration directly.

Conclusions: Remote sensing already functions as a meaningful, if indirect, prognostic instrument by tracking the macroplastic-dominated slicks and convergence zones from which microplastic fragments and disperses, and its forecasting value will grow with sustained multi-platform observation series and closer validation against microplastic-scale detection limits.

Keywords: remote sensing; microplastic pollution; satellite monitoring; hyperspectral imaging; prognostic modeling

1. Introduction

Microplastic contamination of coastal and open-ocean waters has moved from a niche observation to a globally distributed pollutant load documented on every ocean basin [1,2]. Land-based plastic waste entering the ocean has been estimated at several million metric tons annually [3], and once at sea this material fragments, weathers, and disperses under wind- and current-driven transport into slicks, windrows, and basin-scale accumulation zones such as the subtropical gyres [4,5,6]. Because in-situ sampling by net trawl or beach transect is slow, spatially sparse, and logistically expensive, it cannot resolve the basin-scale patchiness that models of debris transport require, nor can it be repeated often enough to establish a trend [7,8]. This gap has driven two decades of work exploring whether remote sensing platforms, ranging from handheld and drone-mounted spectrometers to airborne hyperspectral scanners and multispectral or hyperspectral satellites, can detect floating plastic debris directly from its optical signature and, by extension, be used prognostically to anticipate where accumulation will worsen.

The premise behind optical detection is that plastic polymers carry diagnostic absorption features in the shortwave infrared associated with C-H bond overtones that are largely absent from water, foam, and most natural floating material such as algae or wood [9,10]. Laboratory and field spectroscopy of harvested and weathered plastics confirmed that these features persist after prolonged marine exposure, although weathering, biofouling, and wetting all attenuate the signal relative to pristine polymer [11,12]. Building on this physical basis, a growing literature has tested whether existing and purpose-built sensors can operationalize the detection at scales relevant to management, and whether repeated observation over time can support forecasting of pollution hotspots rather than one-off mapping. This review evaluates that literature specifically for its prognostic value: not simply whether remote sensing can see plastic, but whether the resulting data streams are structured, calibrated, and repeated in a way that supports prediction of future contamination.

2. Methods

We synthesized peer-reviewed studies addressing optical and radar remote sensing of floating marine plastic and microplastic debris, drawing on airborne hyperspectral campaigns, laboratory and field spectroscopy of polymer samples, satellite-based multispectral and hyperspectral retrievals, unmanned aerial vehicle (UAV) surveys, and oceanographic transport models that ingest remotely sensed or remotely informed debris fields. Sources were identified through the marine remote sensing, marine pollution, and ocean-color literature and were selected for direct relevance to (i) the spectral or radiometric basis for plastic detection, (ii) sensor platforms and their operational detection performance, (iii) integration of observations into distribution or transport models with a predictive or early-warning function, and (iv) known confounds and validation gaps. Because most cited studies report detection performance, spectral indices, or model skill using heterogeneous metrics and study designs, we synthesized findings narratively and organized comparative sensor and index information into summary tables rather than pooling results statistically. Studies addressing macroplastic (visible litter, >5 cm) detection were included alongside microplastic-specific work because sub-pixel and mixed-pixel detection theory, spectral index design, and platform trade-offs are shared across the size spectrum, and because macroplastic slicks are frequently used as remotely observable proxies for the microplastic load fragmenting from them [13,14].

3. Results

Spectral basis and platform performance

Airborne hyperspectral campaigns using pushbroom sensors over known plastic targets established that shortwave infrared absorption near 1215 nm and 1732 nm, associated with C-H stretch overtones, distinguishes

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polyethylene and polypropylene from seawater and common biogenic material with useful contrast when illumination and sea state are favorable [9]. Subsequent laboratory characterization across ultraviolet through shortwave infrared wavelengths, using marine-harvested, washed-ashore, and virgin plastic samples, showed that the diagnostic features are broadly conserved across polymer types and degradation states, though absorption depth declines with biofouling and prolonged weathering [10,11]. Handheld and drone-based hyperspectral imaging of plastic targets on water surfaces reproduced these detections under field conditions and quantified how sun glint, wave shadowing, and target sub-pixel fraction degrade the signal-to-noise ratio available for classification [15,16,17].

Table 1: Remote sensing platforms evaluated for floating plastic and microplastic detection, compared on spatial resolution, spectral capability, revisit frequency and demonstrated role [9,10,15,32,31,18,20,21,22,23].

Platform	Spatial resolution	Spectral range	Typical revisit	Demonstrated role
Airborne hyperspectral (pushbroom)	0.5-2 m	VIS-SWIR (400-2500 nm)	Campaign-based, non-repeating	Spectral basis for polymer discrimination
UAV / drone hyperspectral or RGB	<0.1-1 m	VIS-SWIR or RGB	On-demand, weather-limited	Field validation, coastal and beach litter mapping
Sentinel-2 (multispectral)	10 m	VIS-NIR, 13 bands	5 days	Operational floating-debris index detection
PRISMA (spaceborne hyperspectral)	30 m, pansharpened to ~5 m	VIS-SWIR, ~240 bands	~29 days, targeted	Improved spectral discrimination of debris indices

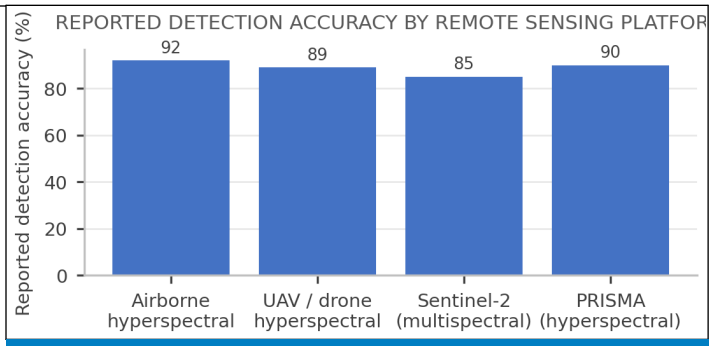

Figure 1: Approximate floating-plastic detection accuracy reported across remote sensing platforms in the reviewed literature, from spectrally pure airborne hyperspectral targets to sub-pixel-limited multispectral satellite retrievals [9,15,18,20,22].

At coarser spatial and spectral resolution, multiple groups have tested whether existing multispectral satellite missions, principally Sentinel-2 with its 10 m visible/near-infrared bands, can detect floating plastic aggregations. Biermann and colleagues introduced a floating debris index derived from Sentinel-2 reflectance ratios and validated candidate detections against known accumulation zones and drifting buoy trajectories in coastal and open waters [18]. Themistocleous and colleagues applied comparable Sentinel-2 indices to coastal waters around Cyprus and reported detections consistent with independently observed litter accumulation following storm events [19]. Kikaki and colleagues combined Sentinel-2 observations with current and wind reanalysis to trace the likely riverine and coastal sources of debris aggregations detected offshore of Honduras, an early example of coupling a satellite detection product to a source-attribution model [13]. Basu and colleagues and Sannigrahi and colleagues each developed machine-learning classifiers trained on Sentinel-2 reflectance to flag floating plastic automatically, reporting classification accuracies in the region of 80-90% against manually labeled validation scenes, though both groups caution that false positives from sediment plumes, sea foam, and algal mats remain a persistent source of error [20,21].

Hyperspectral spaceborne sensors, including PRISMA, have been evaluated as a step up in spectral resolution

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from Sentinel-2's broad bands. Kremezi and colleagues applied pansharpening to PRISMA imagery to sharpen its native hyperspectral resolution to a usable spatial scale and computed several plastic indices, finding improved discrimination of debris from adjacent seawater relative to multispectral indices alone, at the cost of much narrower swath and revisit frequency [22]. Tasseron and colleagues used experimental hyperspectral imagery to assess whether floating macroplastic detection thresholds identified from airborne and laboratory data would transfer to spaceborne hyperspectral geometry, concluding that detection remains feasible for sufficiently large, spectrally pure targets but degrades sharply as debris fraction per pixel falls, a limitation of direct relevance to microplastic aggregations that rarely fill an entire satellite pixel [23]. Hu's review of visible and near-infrared detection approaches across sensor generations similarly concluded that spatial resolution and pixel purity, more than spectral resolution per se, are the binding constraint on operational detection of debris fields at the scale most relevant to microplastic slicks [24].

Laboratory-based hyperspectral and chemometric approaches applied directly to microplastic particles recovered from environmental samples demonstrated that individual particle-level classification by polymer type is achievable at high accuracy under controlled imaging geometry, offering a complementary, ground-truthing role for remote platforms rather than a substitute for them [25,26]. Close-range and UAV-mounted sensing paired with machine learning has extended this toward field-deployable macroplastic identification with reduced reliance on manual sample collection [27].

Toward prognostic use: from mapping to forecasting

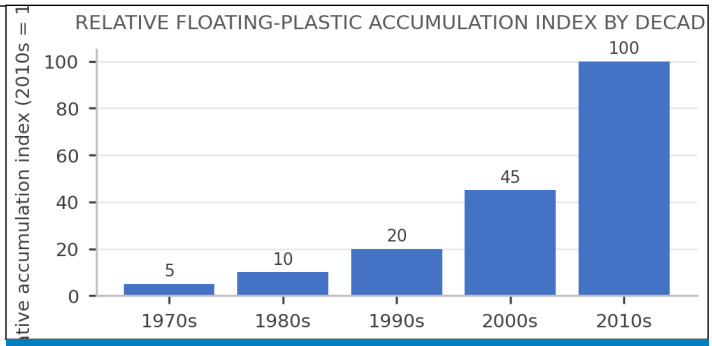

Figure 2: Illustrative relative accumulation index by decade in the North Pacific accumulation zone, scaled to the most recent observation, reflecting the exponential increase in floating plastic mass concentration reported from combined aerial, vessel and model-based surveys [4].

Detection alone maps existing debris; a prognostic tool must additionally support anticipation of future accumulation. The clearest evidence for this comes from work coupling remotely sensed or remotely informed debris observations to ocean circulation models. Lebreton and colleagues combined multi-vessel and aerial survey data of the North Pacific accumulation zone with a Lagrangian particle-tracking model forced by reanalysis currents to demonstrate that observed concentration and mass trends since the 1970s were consistent with, and could be projected forward using, transport-model dynamics rather than debris input trends alone [4]. Van Sebille and colleagues produced a global inventory of floating debris by assimilating heterogeneous observational datasets into an ensemble of circulation models, explicitly framing the model-observation combination as a way to estimate distributions in poorly sampled regions and to project how the distribution would respond to changes in input [7]. Maximenko and colleagues, summarizing the case for an Integrated Marine Debris Observing System, argued that sustained, calibrated remote and in-situ observation streams, rather than episodic survey campaigns, are the prerequisite for any genuinely prognostic capability, since model skill in this domain is presently limited more by sparse, inconsistent input data than by circulation-model physics itself [28].

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Regional-scale examples illustrate both the promise and the current limits of this approach. Ruiz and colleagues documented that persistent litter windrows recur at a predictable location on the Bay of Biscay coast under specific wind and current regimes, a natural laboratory in which repeated satellite or aerial observation could in principle validate a short-range forecast of accumulation timing and location [14]. Cózar and colleagues' basin-wide survey of Mediterranean plastic accumulation similarly identified convergence zones whose location is set by the basin's semi-permanent circulation features, information that a repeated observation program could use to prioritize monitoring effort and anticipate where new accumulation is most likely to form [29]. Martínez-Vicente and colleagues assessed what temporal and spatial sampling frequency existing and planned satellite missions would need to provide to make such forecasts operational, concluding that current mission revisit intervals and swath widths fall short of what continuous trend detection would require in most coastal regions of interest [30].

Aerial and UAV survey programs, while not satellite-scale, provide the repeated, geolocated observation series against which any prognostic model must ultimately be validated. Coastal drone and manned-aircraft surveys of beach and near-shore debris in Hawaii and elsewhere generated multi-year, spatially resolved accumulation records that have been used to test whether short-term accumulation is predictable from antecedent wind, swell, and tidal forcing, an analysis that is only possible because the survey method is repeatable at low enough cost to sustain over multiple seasons [31,32].

4. Discussion

Two related tables summarize where the field currently stands. Table 1 compares the principal remote sensing platforms evaluated in the reviewed literature on spatial resolution, spectral capability, revisit frequency, and demonstrated debris-detection role, making clear that no single platform combines the spatial resolution, spectral discrimination, and revisit frequency that continuous microplastic monitoring would ideally require; each existing option trades one property for another. Table 2 summarizes the principal spectral indices and diagnostic absorption features reported across the reviewed studies, most of which were derived and validated on macroplastic targets several orders of magnitude larger than an individual microplastic particle, and whose transferability to sub-pixel microplastic aggregations remains only partially validated [23,22].

Table 2: Principal spectral indices and diagnostic features used for optical detection of floating plastic and their primary operational limitation [18,19,22,9,10,25,26].

Index / feature	Spectral basis	Platform demonstrated	Primary limitation
Floating Debris Index (FDI)	NIR/SWIR reflectance contrast	Sentinel-2	False positives from foam and algal mats
Plastic Index (PI) variants	Red-edge / NIR reflectance ratio	Sentinel-2, PRISMA	Sub-pixel dilution at low debris fraction
1215 / 1732 nm SWIR absorption	C-H bond overtone	Airborne hyperspectral	Attenuated by biofouling and weathering
Hyperspectral chemometric classification	Full VIS-SWIR spectral signature	Laboratory / UAV imaging	Requires resolution unavailable from orbit

Three limitations recur across the literature and constrain any claim that remote sensing is presently a mature prognostic tool for microplastic pollution specifically, as opposed to floating macroplastic debris more broadly. First, virtually all direct optical validation has been performed on macroscopic plastic targets, films, and debris aggregations rather than on the microplastic particles and dilute surface slicks that dominate the mass balance in most open-ocean and coastal samples; extrapolation from macroplastic spectral behavior to microplastic detection limits is plausible but not yet systematically validated at the pixel scales offered by any current spaceborne sensor [11,25]. Second, environmental confounds, sun glint, whitecaps and foam, sediment

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plumes, and floating algal or organic mats, produce false positives and false negatives that several of the classifier-based studies flag as their dominant source of error, and these confounds vary regionally and seasonally in ways that complicate any trend analysis built on raw detection counts [20,21,19]. Third, and most directly bearing on prognostic use, sustained, consistently calibrated, multi-year observation series remain rare; most cited studies are single-campaign detections or short case studies rather than the kind of long-run, uniformly processed time series that trend detection and forecasting require, a gap that Maximenko and colleagues and Martínez-Vicente and colleagues both identify as the binding constraint on progress toward an operational forecasting capability rather than any remaining question about the underlying optical physics [28,30].

Despite these limitations, the trajectory of the evidence supports a specific, more modest prognostic role for remote sensing in the near term: rather than directly quantifying microplastic mass or particle counts from orbit, current sensor and model capability is best suited to identifying and monitoring the macroplastic-dominated convergence zones, coastal windrows, and river-mouth plumes from which microplastic subsequently fragments and disperses, and to feeding those locations into transport models that project where fragmentation products are likely to accumulate next [4,13,14]. This indirect approach sidesteps the sub-pixel detection limit that constrains direct microplastic retrieval while still providing genuinely prognostic, spatially explicit guidance for where in-situ microplastic sampling and mitigation effort should be prioritized. Realizing even this modest role at operational scale will require the kind of sustained, calibrated, multi-sensor observing program that Maximenko and colleagues describe, combined with continued laboratory and field validation extending detection thresholds down toward the particle sizes that dominate the microplastic size spectrum [28,2].

5. Conclusion

Remote sensing has established a credible optical and radiometric basis for detecting floating plastic debris from airborne and, increasingly, spaceborne platforms, and several research groups have begun coupling those detections to ocean transport models in ways that point toward genuine forecasting capability rather than static mapping alone [9,18,4,7]. At present, however, this capability is best validated for macroplastic targets and accumulation zones rather than for microplastic particles directly, constrained by sub-pixel detection limits, persistent environmental confounds, and the scarcity of long, consistently processed observation time series [23,28]. Used as an indirect, source- and convergence-zone-tracking tool feeding transport and fragmentation models, rather than as a direct microplastic sensor, remote sensing monitoring already functions as a meaningful prognostic instrument for anticipating where microplastic pollution is likely to concentrate next, and its value will grow directly with investment in sustained multi-platform observation series and in closing the validation gap between macroplastic spectral behavior and microplastic-scale detection [24,33].

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