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Emerging Plastic Pollution Threats to Ecosystem Sustainability: A Systematic Review

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Abstract

This systematic review examines emerging threats of plastic pollution to ecosystem sustainability based on research published between 2021 and 2024. A comprehensive analysis of peer-reviewed literature named seven studies (n = 7), of which five (n = 5) met the inclusion criteria. The analysis revealed three distinct categories of ecosystem impacts: terrestrial (microplastic soil contamination), aquatic (marine and freshwater systems), and novel threats associated with global events, such as the COVID-19 pandemic. The highest-quality studies (n = 3) focused on terrestrial microplastic pollution, impacts on seagrass meadows, and freshwater macroplastic contamination. Other supporting studies provided insights into lifecycle impacts and pandemic-related pollution patterns. Overall, this review synthesizes evidence across multiple ecosystem types, highlighting the interconnected nature of emerging plastic pollution threats.

Introduction

Plastic pollution stands for one of the most pressing environmental challenges of the 21st century, affecting both terrestrial and marine ecosystems. Global plastic production has surged from 1.5 million tons in the 1950s to 374.8 million tons by 2019, with approximately 79% of plastic waste accumulating in environmental compartments (Geyer et. al., 2017; OECD, 2022). While initial research focused primarily on marine impacts, evidence now shows that terrestrial ecosystems experience 4-23 times more plastic pollution annually than marine environments, highlighting the need for comprehensive assessment across all ecosystem types.

The accumulation of plastics in environmental systems presents complex challenges through multiple pathways. In terrestrial environments, plastics interact with soil physical properties, chemical processes, and biological communities, potentially disrupting essential ecosystem functions. Similarly, in marine ecosystems, particularly seagrass meadows, plastic pollution can affect habitat quality, species interactions, and ecosystem services. These impacts are especially concerning in regions where communities rely directly on ecosystem services for their livelihoods.

Objectives

1. Find and categorize emerging threats of plastic pollution across different ecosystems
2. Evaluate the impacts of these threats on ecosystem sustainability
3. Assess current methodological approaches in plastic pollution research

Methods

Search Strategy

A comprehensive systematic search was conducted across major scientific databases including Science Direct and MDPI, following the PRISMA guidelines. The search covered peer-reviewed articles published between 2021 and 2024.

Categorization Framework

Following current research approaches (Bodor et al., 2024; Douglas et al., 2024; Barrett et al., 2024), impacts were categorized by:
1. Environmental compartments: terrestrial systems (soil physicochemical properties, biological communities); marine systems (seagrass meadows, ecosystem services); freshwater systems (rivers, streams).
2. Physical characteristics: size categories (macro-, meso-, and microplastics); material composition (films, hard plastics, foams, fabrics, rubber); physical condition (fragmented vs. non-fragmented); original functional use where identifiable.
3. Impact categories: direct physical impacts on ecosystem structure; chemical interactions with environmental processes; biological community responses; ecosystem service implications; emerging threats from environmental stressors.

Study Selection

The first search named seven studies (n=7), of which five met the inclusion criteria. Studies were evaluated based on their relevance to ecosystem impacts and methodological quality. The following inclusion/exclusion decisions were made:

Included Studies (n=5):

1. Zhang et al. (2021) - Life-cycle environmental impact assessment of wet wipes
2. Bodor et al. (2024) - Microplastic impacts on soil ecosystems
3. Douglas et al. (2024) - Impacts on seagrass meadows
4. Shams et al. (2021) - COVID-19 related plastic pollution
5. Barrett et al. (2024) - Macroplastic impacts in freshwater systems

Excluded Studies (n=2):

1. Ervik et al. (2024) - Educational focus rather than ecosystem impacts
2. Drielsma et al. (2022) - Focus on modeling methods rather than plastic pollution

The included studies stand for diverse ecosystem types and pollution categories, providing comprehensive coverage of emerging threats.

Data Extraction

Data extraction was conducted systematically using a standardized form to capture key information from each study. The following tables present the extracted data from the reviewed articles. Table 1-A shows that quality scores range from 1-5, where five shows highest quality based on methodological rigor, direct relevance to emerging threats, and strength of ecosystem impact analysis.

Table 1-A
Overview of Included Studies (2021-2024)

Study ID	Authors	Year	Journal	Database	Quality Score
PP2025_001	Zhang et al.	2021	Resources, Conservation & Recycling	Science Direct	4
PP2025_004	Bodor et al.	2024	Ecotoxicology and Environmental Safety	Science Direct	5
PP2025_005	Douglas et al.	2024	Journal of Marine Science and Engineering	MDPI	5
PP2025_006	Shams et al.	2021	Environmental Advances	Science Direct	4
PP2025_007	Barrett et al.	2024	Environments	MDPI	5

Study selection, Table 1-B, was based on relevance to ecosystem impacts and methodological quality. Excluded studies focused on educational aspects or modeling methods rather than direct plastic pollution impacts.

Table 1-B
Study Selection Details (2021-2024)

Study Type	Number	Database Source	Quality Range
Included Studies	5	Science Direct (3), MDPI (2)	4-5
Excluded Studies	2	Science Direct (2)	3

Total Reviewed	7	Science Direct (5), MDPI (2)	3-5

Quality Assessment

Each study was evaluated using a 5-point quality assessment scale, with scores assigned based on the following criteria: methodological rigor, direct relevance to emerging threats, quality of ecosystem impact analysis, and quantitative assessment strength.

Quality Scores of Included Studies:

1. Bodor et al. (2024) - Score: 5/5 (Direct analysis of emerging threats to terrestrial ecosystems)
2. Douglas et al. (2024) - Score: 5/5 (Direct assessment of ecosystem impacts)
3. Barrett et al. (2024) - Score: 5/5 (Quantitative analysis of ecosystem impacts)
4. Zhang et al. (2021) - Score: 4/5 (Direct assessment of emerging pollution sources)
5. Shams et al. (2021) - Score: 4/5 (Addresses emerging threat patterns)

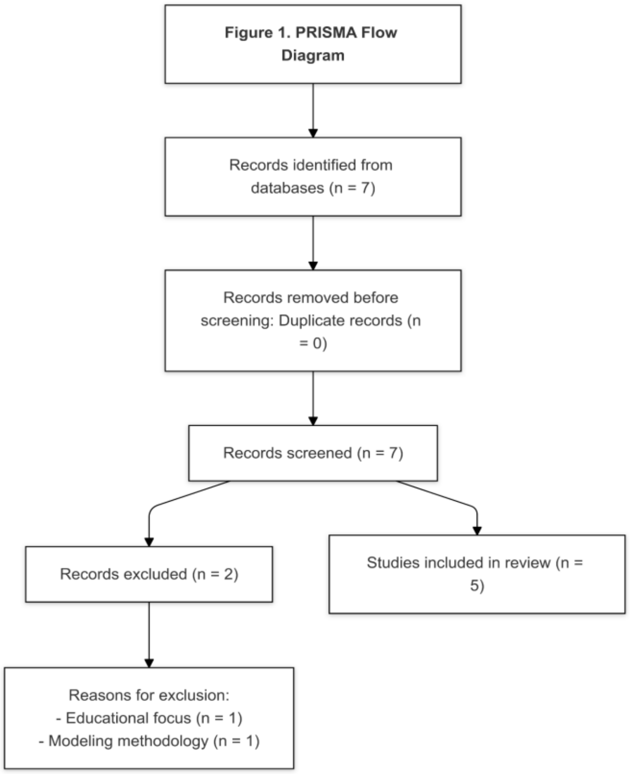
The three highest-rated studies (scoring 5/5) focused on terrestrial microplastic pollution, seagrass meadow impacts, and freshwater macroplastic contamination, respectively.

Results Framework

Search Results and Study Selection

The systematic search process, illustrated in the PRISMA flow diagram (Figure 1), found seven potentially relevant studies from the selected databases. After applying the inclusion and exclusion criteria, five studies met the full eligibility requirements for this review. Two studies were excluded: one focused primarily on educational aspects rather than ecosystem impacts, and another emphasized modeling method without direct relevance to plastic pollution impacts.

Figure 1
PRISMA Diagram



Quality Assessment and Study Characteristics

The quality assessment of the studies included revealed a consistently high level of methodological rigor across the selected research. Quality scores range from 1-5, where five shows highest quality. Three studies achieved the highest quality score (5/5), being excellence in method and direct relevance to emerging threats:

1. **Terrestrial Ecosystem Research**: Bodor et al. (2024) provided a comprehensive analysis of microplastic impacts on soil ecosystems, employing robust methodological approaches and presenting clear empirical evidence.
2. **Marine Ecosystem Analysis**: Douglas et al. (2024) delivered an in-depth assessment of plastic pollution impacts on seagrass meadows, with particular attention to ecosystem services in Southeast Asia.
3. **Freshwater Systems Study**: Barrett et al. (2024) contributed a detailed quantitative analysis of macroplastic impacts in freshwater basins, offering valuable insights into this understudied ecosystem type.

Two other studies scored 4/5, proving good methodological quality while addressing unique aspects of plastic pollution:

1. Life-cycle assessment: Zhang et al. (2021) provided valuable life-cycle assessment data on specific pollution sources, focusing on wet wipes as an emerging environmental concern.
2. COVID-19 impact: Shams et al. (2021) offered prompt insights into the relationship between the COVID-19 pandemic and plastic pollution patterns, highlighting novel threat patterns in environmental systems.

Thematic Analysis of Findings

Analysis of the included studies revealed distinct patterns of plastic pollution impacts across different environmental compartments. The selected studies provide comprehensive coverage across three major environmental compartments: terrestrial ecosystems (soil systems), marine environments (seagrass meadows), and freshwater systems (headwater basins). This distribution ensures a holistic understanding of plastic pollution impacts across different environmental contexts, while two studies offer cross-cutting perspectives through life-cycle assessment and pandemic-related impacts.

The following detailed analysis presents key findings organized by ecosystem type, beginning with terrestrial impacts (Bodor et al., 2024), followed by marine impacts (Douglas et al., 2024), and freshwater impacts (Barrett et al., 2024). The analysis concludes with examination of two cross-cutting studies: Zhang et al. 's (2021) life-cycle assessment of emerging pollution sources and Shams et al.'s (2021) analysis of pandemic-related plastic pollution patterns.

Terrestrial Impacts (Bodor et al., 2024)

In the terrestrial environment, Bodor et al. (2024) named several critical impacts of microplastic pollution (MP) on soil ecosystems with a large-scale in-depth study into the contamination consequences. Their studies showed that microplastics have been interacting with the soil through agroecosystems, causing effects on terrestrial ecosystems, being transported, and changing the physical, chemical, and biological soil components.

The study revealed that microplastic contamination significantly affects soil physical properties. Specifically, Table 2 summarizes the characteristics and potential soil impacts of various petroleum-based and bio-based plastics, as reported by Wolter et al. (2022). The table highlights the differences in biodegradability between conventional plastics and bioplastics, as well as their wide-ranging applications that can contribute to their entry and accumulation in soils. The potential soil impacts listed suggest that non-biodegradable plastics may persist and alter soil structure and properties, while biodegradable plastics, though less persistent, may still influence soils through their biodegradation products. The information presented in this table underscores the need for further research to understand the fate and effects of different plastic types in soils under various conditions, as well as the importance of considering soil impacts in regulations and product innovation. Bodor et al. (2024) cite these findings in their comprehensive review of the impacts and ecological risks of microplastic pollution in terrestrial environments.

Table 2

Characteristics and Potential Soil Impacts of Petroleum-Based and Bio-Based Plastics

Plastic Category	Polymer Types	Biodegradability	Key Applications	Potential Soil Impacts
Petroleum-based	PE, PP, PS, PVC, PET, PUR	Not biodegradable	Packaging, disposable items, textiles, agricultural films	Persist and accumulate in soils; may alter soil structure and properties
Petroleum-based (biodegradable)	PBAT, PCL	Biodegradable	Packaging, compostable bags, disposable tableware, agriculture	Less likely to persist; biodegradation products may influence soil properties
Bio-based	bio-PE, bio-PET	Not biodegradable	Same as petroleum-based PE and PET	Like petroleum-based counterparts
Bio-based (biodegradable)	PHAs, PLA, PBS	Biodegradable	Packaging, disposable items, agricultural films, biomedical products	Degrade faster than non-biodegradable plastics; degradation rate varies with soil conditions

Source: Adapted and modified from Wolter et al. (2022), as cited in Bodor et al. (2024)

Significant effects occur in the soil based on its physical properties through MP accumulation. These include bulk density, size and distribution of water-stable aggregates, porosity, infiltration, retention, and evaporation of water dynamics. According to Baho et al. (2021) and Iqbal et al. (2021), alterations in soil physical properties are not uniform and are related to different elements, including soil type, climatic conditions, and MPs characteristics (abundance, parental material, and shape) (as cited in Bodor et al., 2024). This analysis finds out the MPs present in the soil and proposes that the consequences are related to their physical features. The modification is not considered uniform because of different factors, such as soil type, climate, and MPs configuration. Regarding microplastics, they are qualified by quantity or concentration in each area or sample, material/type from which the microplastics were derived (like polyethylene, polypropylene), and physical form or geometry of the microplastic particles (like spherical, fibrous, irregular). Findings about soil structure considered different types of soil: soil aggregates, soil porosity, soil bulk density, and soil moisture. According to Wang et al. (2022b) and Yadav et al. (2022), soil aggregates represent particles of varying sizes ranging from 2 to 200 µm in diameter, determine soil structure, pore size, and stability, thereby regulating water flow (and hence nutrient distribution), soil aeration, erosion susceptibility, and soil microbial activity. Notably, MPs are often incorporated into soil aggregates, and a study by Zhang and Liu (2018) found that 72% of plastic particles were associated with soil aggregates, while only 28% were dispersed (as cited in Bodor et al., 2024). Soil porosity manages the stream and aeration of water, allowing the impact on the distribution of microorganisms (aerobic and anaerobic), as well as transpiration and nutrients by plants. Larger pores like macropores>30 µm can drain water quickly, but smaller pores like micropores<30 µm can hold water in the soil (Mbachu et al., 2021). Water quality, porosity, plant root, and fertility are affected through soil bulk density. Soil moisture content is an important element that affects the bioavailability of nutrients and pollutants through management of survival and reproduction of soil-dwelling organisms and plants (Wang et al., 2022b) (Bodor et al., 2024). The alteration in soil properties through MPs accumulation led to consequences, such as: modifying soil structure and aggregate formation (Wang et al., 2022b; Iqbal et al., 2021); impacting soil porosity depending on the MPs' shape (Wang et al., 2022b); reducing soil bulk density while increasing porosity (Wang et al., 2022b); and disrupting the soil moisture system, resulting in imbalances (Wang et al., 2022b) (as cited in Bodor et al., 2024).

As we already know, physical alterations occurred in soil properties. The research also documented substantial effects on soil chemical properties. The presence of microplastics has caused chemical impacts on soil contents, such as carbon (C), nutrients, and pH, among others. MPs are primarily composed of carbon and can potentially serve as a source of C for the soil ecosystem, but most plastics are inert and exhibit limited or no decomposition, resulting in long-term storage and accumulation of C in the soil (Qiu et al., 2022; Zhang et al., 2021). Dissolved organic matter (DOM) plays a crucial role in soil biogeochemical cycles, and the presence of MPs can disrupt these processes (Ren et al., 2022; Wang et al., 2022b). Different types of MPs have varying effects on dissolved organic carbon (DOC) and soil organic matter (SOM) (Ren et al., 2022; Dong et al., 2021). The research has found that the MPs contained in the soil can obstruct biogeochemical cycles, allowing the circulation of inorganic macronutrients such as nitrogen and phosphorus and contaminants. According to Ren et al. (2022) and Wang et al. (2022b), certain microorganisms can degrade plastics and utilize their monomers and degradation products as organic C sources, particularly in the case of bioplastics, being able to increase the amount of dissolved organic carbon (DOC) in environments heavily contaminated with MPs. Most plastics have little or no nitrogen (N) and phosphorus (P) (Bouaicha et al., 2022), and they only affect inorganic nutrient levels through indirect mechanisms (Iqbal et al., 2021). The effects of different types of MPs on soil N and P levels vary, with both negative and positive impacts reported (Wang et al., 2022b; Xu et al., 2020; Yin et al., 2023; Yan et al., 2021). MPs can also influence the circulation of soil nutrients through their effects on microbial activity and soil enzyme activities (Zhang et al., 2021; Wang et al., 2022b). Though the impact of MPs on soil N and P can vary, there are studies that found insignificant effects. The ageing process of MPs can lead to their involvement in the adsorption, transportation, and desorption of contaminants from various external sources (Dissanayake et al., 2022a; Sajjad et al., 2022; Zhang et al., 2021). Aged MPs help the binding of organic compounds and heavy metals through various mechanisms (Ren et al., 2022), and the release of substances from aged MPs can have detrimental effects on soil ecosystem functions (Zhang et al., 2021). Finally, according to some studies, certain MPs can increase soil pH; however, the presence of MPs in soil is not considered fully understood (as cited in Bodor et al., 2024). Soil pH is a critical abiotic factor that finds various soil properties and processes (Wang et al., 2022b). The impact of MPs on soil pH has shown conflicting results, with examples of both increasing and decreasing effects (Yang et al., 2021; Qi et al., 2020; Lozano et al., 2021b; Zhao et al., 2021; Dong et al., 2021; Li et al., 2021b; Boots et al., 2019). The effects of MPs on soil pH can be influenced by various factors, such as the type, abundance, size, and shape of MPs, as well as soil type, fertilization history, and the duration of the experiment (Wang et al., 2022b) (as cited in Bodor et al., 2024).

Beyond physical alterations and chemical impacts that occurred in soil, the research documented substantial effects on biological communities. According to Kauer et al. (2022), the presence of microplastics impacts biodiversity, altering soil quality and health. MPs not only function as contaminants within the soil ecosystem by accumulating in the food chain through uptake or ingestion, adsorbing secondary contaminants, or containing harmful additives but they also have a direct impact on soil-dwelling organisms by altering their habitat (as cited in Bodor et al., 2024). The study found that MPs can affect terrestrial vegetation by altering soil physical parameters and enzyme activities, promoting, or hindering plant growth and development. Smaller plastic particles, particularly nanoplastics, can enter plant tissues through various mechanisms and trigger physiological and biochemical responses, potentially leading to the accumulation of MPs in edible plant parts (as cited in Bodor et al., 2024). The research also documented the effects of MPs on soil fauna, with micro- and mesofauna serving as potential entry points for MPs into the terrestrial food web. Terrestrial organisms showed dose-dependent responses: earthworm (*Lumbricus terrestris*) growth and survival declined significantly at PE-MP concentrations of 28%, 45%, and 60%, while springtail (*Folsomia candida*) growth and reproduction were inhibited at just 0.1% PVC-MPs (Bodor et al., 2024). Ingestion of MPs by soil fauna can cause physical or biochemical damage and lead to changes in survival rates, reproduction, and behavior (as cited in Bodor et al., 2024). Microplastics bioaccumulate through terrestrial food webs, with earthworms holding approximately 13× the soil concentrations, chicken manure 105×, and chicken gizzards 5× (Bodor et al., 2024). Furthermore, the study highlighted the impact of MPs on soil microbiota, as MPs can directly affect soil-dwelling microorganisms by providing novel habitats and indirectly by altering the environmental characteristics of the soil matrix. Changes in microbial community composition and functions can have far-reaching consequences for ecosystem functions, such as nutrient cycling and organic matter decomposition (as cited in Bodor et al., 2024).

The long-term implications of these impacts suggest that MPs can act directly or indirectly on soil and can produce modifications in its physicochemical and biological characteristics. The research reveals several effects of MPs on soil; however, there are still uncertainties and knowledge gaps about the precise impacts caused by MPs. This raises concerns about the size of plastic pollution on ecosystems, considering the degradation of both natural and agroecosystems. Further research is necessary to develop and apply methods for obtaining more comprehensive and correct results, preferably involving diverse soil types, polymer types, and test organisms. Standardized experimental designs and methods for extracting and quantifying MPs from environmental samples are also crucial to help future assessment, management, and comparison of the damage they cause.

Marine Impacts (Douglas et al., 2024)

Plastics are found everywhere in the environment (LIM, 2021), can be classified as macroplastic (>20 mm), mesoplastic (5–10 mm), and microplastic (<5 mm) (Barnes, 2009). In marine ecosystems, Douglas et al. (2024) focused on the effects of plastic pollution on seagrass meadows in Southeast Asia, revealing multiple levels of ecosystem disruption. Because plastics may break down to smaller sizes, it is difficult to remove them in the marine environment (Pawar, 2016) (Douglas et al., 2024).

The study documented direct physical effects on seagrass communities. Plastic pollution reduced seagrass respiration by 30-50% at microplastic concentrations of 1,000 mg/L, with rhizome length decreasing by 50% in the presence of plastic bags and leaf density declining by 26% under micro/nanoplastic exposure (Douglas et al., 2024). These effects were documented alongside climatic, environmental, and anthropogenic impacts (Litsi-Mizan et al., 2013; Zhou, 2023). These effects were particularly pronounced in overfishing, habitat degradation, pollution, and climatic change (Unsworth et al., 2018).

The table below presents a comprehensive analysis of marine plastic pollution's impacts on seagrass ecosystem services in Southeast Asia, derived from a systematic review by Douglas et al. (2024). By categorizing ecosystem services across provisioning, regulating, and cultural domains, the research reveals the multifaceted consequences of marine plastic pollution on these critical marine habitats. The analysis shows that marine plastic pollution poses significant risks to seagrass ecosystems, with most services experiencing negative impacts, particularly in regulating functions such as climate regulation and coastal protection. The varying evidence strengths highlight both the complexity of these ecosystem interactions and the urgent need for continued research and conservation efforts in Southeast Asian marine environments. Table 3 was adapted from Douglas et al. (2024) systematic literature review on marine plastic pollution impacts in Southeast Asia. Evidence strength based on literature abundance (Low = 1-5 articles, Medium = 6-10 articles, High = 11+ articles).

Table 3
Marine Plastic Pollution Impacts on Seagrass Ecosystem Services in Southeast Asia

ES Section	Ecosystem Service	Impact of Marine Plastic Pollution	Evidence Strength
Provisioning	Food provision	Negative impacts through reduced growth (26% fewer leaves per shoot) and habitat degradation	High
	Genetic material provision	Potential disruption through altered microbial communities (65.8% increase in diversity, including disease-causing taxa)	Low

Regulating	Water purification	Mixed effects: positive (trapping of MPP via egagropiles) and negative (reduced physiological functioning)	High
	Climate regulation	Negative impacts through reduced photosynthesis (30-50% reduction in dark respiration under high microplastic concentrations)	High
	Coastal protection	Decreased sediment stability due to reduced rhizome growth (50% reduction in rhizome length with plastic bags)	High
	Life cycle maintenance	Conflicting effects on decomposition (64.1% increase with masks; 36% decrease with high MPP levels)	High
Cultural	Recreation/tourism	Potential degradation of marine ecosystem aesthetics	Low
	Cognitive	Potential reduction in research and educational value	Low
	Symbolic/sacred	Limited evidence of impacts on cultural ecosystem values	Low

Source: Adapted from Douglas et al. (2024)

Microplastic contamination was pervasive, with 80% of seagrass biota, 75% of seagrass blades, and 27.6% of associated macroinvertebrates having plastic particles (Douglas et al., 2024). Various impacts of marine plastic pollution (MPP) on seagrass ecosystems were found, with most reflecting negative effects. These impacts included reduced growth metrics, such as the leaves per shoot and rhizome length, and variations in the rate of decomposition and nutrient cycling (Douglas et al., 2024). The research linked these impacts to seagrass-derived ecosystem services (ES), finding that all ES from the analytical framework were affected negatively, besides water purification and life cycle maintenance, for which the results showed both positive and negative effects (Douglas et al., 2024).

The study highlighted that seagrass meadows provide multiple ecosystem services, with climate regulation, life cycle maintenance, and water purification being the most reported (Douglas et al., 2024). Chemical analysis detected DEHT concentrations of 1.121-9.19 mg/kg in seagrass tissues, while BPA concentrations in Malaysian waters ranged from 1.32 to 1,890.51 ng/L (mean 59.01 ng/L)—well above the 300 ng/L growth retardation threshold (Douglas et al., 2024). These services vary depending on multiple factors, including the general present or the size or condition of the plant (Douglas et al., 2024). Notably, the research found that while some ecosystem services are easily quantifiable, such as climate and water quality regulation, others stay challenging to measure, including intangible relationships between people and seagrass (Douglas et al., 2024).

A critical finding was the risk assessment using Pollution Load Index (PLI) assessments, which classified all five Southeast Asian countries as 'extremely high' (threshold >30), with Vietnam scoring 7,173.75, Thailand 5,629.08, Malaysia 1,250.00, Indonesia 640.49, and Singapore 521.11 (Douglas et al., 2024). This assessment underscores the potential comprehensive threat to seagrass ecosystem services, suggesting significant implications for marine environmental health.

Freshwater Impacts (Barrett et al., 2024)

Barrett et al. (2024) offered crucial insights into macroplastic pollution in freshwater systems, highlighting distinct patterns of accumulation and impact in Richland Creek, a small, heavily forested watershed in western North Carolina, USA.

Plastic debris abundance showed a clear downstream gradient, increasing 4-5-fold from forested headwaters (Site 1: 1.10 items/m) to urbanized reaches (Sites 6-7: 4.52-5.72 items/m) (Barrett et al., 2024), particularly in areas draining from urban development. These distributions were influenced by several environmental factors, including channel morphology and riparian vegetation density, following patterns like those saw in other riverine systems (Gasperi et al., 2014; Blettler et al., 2017). The accumulation patterns were significantly affected by watershed development, with about 80% of marine plastics originating from rivers draining urban areas (Honorato-Zimmer et al., 2021).

Ecological impacts in freshwater systems manifested through physical and chemical effects on aquatic and riparian biota (Wagner et al., 2014; Eerkes-Medrano et al., 2015). Fragmentation rates were highest for foams (93%) and films (86%), with over two-thirds (67%) of all collected items showing evidence of breakdown from their original form (Barrett et al., 2024). This fragmentation contributed to microplastic formation, adding to the 22% of produced plastics that are released into the environment globally (Schmidt et al., 2017). The predominance of films and synthetic fabrics highlighted the significant contribution of domestic sources to freshwater plastic pollution (as cited in Barrett et al., 2024).

Life-cycle Assessment Impacts (Zhang et al., 2021)

This research provides crucial evidence for understanding how seemingly small consumer products can have significant cumulative environmental impacts across their lifecycle. The findings underscore the importance of considering both production and end-of-life environmental consequences when designing everyday products.

Zhang et al. (2021) precisely quantified that in China, the amount of plastic used in wet wipes reached 0.41 million tons in 2019, being 5.1 times the plastic weight consumed in non-degradable express tape and 4.6 times that of non-degradable disposable straws. Their research revealed that over 90% of wet wipes hold plastic, with the mainstream products composed of 30% viscose fiber and 70% polyester fiber.

The lifecycle assessment by Zhang et al. (2021) showed that viscose fiber production and polyester fiber production stages dominate the sources of environmental impacts, contributing 80.1%-99.8% of total emissions. Specifically, they found that polyester fiber production contributes most significantly to Human Toxicity (HT), Photochemical Oxidant Formation (POF), and Global Warming Potential (GWP) indicators, with HT accounting for 75% of the total risk. Meanwhile, viscose fiber production contributes 98% to Freshwater Eutrophication (FE) due to pesticides and fertilizers used in tree planting.

The study proved that bio-based wet wipes showed significantly lower environmental impacts, with the weighted comprehensive environmental impact index of degradable wet wipes (100% viscose fiber) being 38% lower than that of plastic wet wipes (100% polyester fiber). These life cycle assessment results should be interpreted with caution when comparing across studies, as LCA methodologies employ different system boundaries, functional units, and impact categories; the Zhang et al. (2021) study used a functional unit of one wet wipe piece with cradle-to-grave boundaries, which may not be directly comparable to other plastic product assessments using different scopes. However, Zhang et al. (2021) noted important trade-offs: while bio-based wipes have obvious advantages in resource consumption and toxicity risk indicators, being 60% lower than petroleum-based wipes, they may cause significant water pollution with 120 times higher risk of eutrophication than petroleum-based wipes.

Zhang et al. (2021) concluded that their findings support policy measures recommending that the Chinese government should list plastic-containing wet wipes as prohibited and restricted products, encouraging the use of bio-based fibers to replace petroleum-based alternatives. They emphasized that addressing this issue requires both material substitution and behavioral change, highlighting the importance of improving production equipment selling and waste fiber capture capacity.

Pandemic-Related Impacts (Shams et al., 2021)

This comprehensive analysis by Shams et al. (2021) is particularly valuable as it provides one of the first systematic assessments of COVID-19's impact on global plastic pollution patterns. Their work proved crucial baseline data for understanding how pandemic responses can create long-lasting environmental impacts, particularly through increased plastic pollution and compromised waste management systems. Their findings suggest that the environmental implications of pandemic response measures will continue to manifest long after the immediate health crisis subsides.

Plastics generated during the COVID-19 pandemic have become ubiquitous environmental contaminants (Shams et al., 2021), with their fundamental properties as polymeric materials consisting of long carbon chains being well-documented (Jakubowicz, 2003a). These materials are classified as macro (>25mm), meso (5-25 mm), and micro (<5 mm) plastics, with their widespread use attributed to their excellent physicochemical properties and economic viability (Geyer et al., 2017; Silva et al., 2020). In global environments, Shams et al. (2021) focused on the unprecedented surge in plastic pollution during the pandemic, revealing multiple levels of environmental system disruption. Because plastics eventually break down into micro & nanoscopic bits due to physical, chemical, or biological actions in the environment (Da Costa et al., 2016; Dantas et al., 2012; Lambert et al., 2014), their removal becomes increasingly challenging.

The study documented direct impacts across environmental systems and their cascading effects, including atmospheric, marine, and terrestrial impacts (Shams et al., 2021). These effects were particularly pronounced in waste management disruption (Klemeš et al., 2020), with medical facilities experiencing unprecedented challenges in waste handling (Yu et al., 2020). The pandemic dramatically altered plastic consumption patterns, with Kahlert and Bening (2020) documenting significant increases in PPE usage and associated recycling challenges.

Medical plastic waste in the United States increased six-fold during the first two months of the pandemic, rising from 1.48 million tons (2018 baseline) to an estimated 8.85 million tons (2020), with associated greenhouse gas emissions increasing by 67.42 million metric tons CO_2-equivalent—equivalent to adding 14.3 million cars to the road for one year (Shams et al., 2021). COVID-19 significantly affected plastic pollution across environmental systems in 2020. Bondaroff and Cooke (2020) reported that 1.56 billion masks contributed to 5,159-6,878 tons of marine pollution. Medical waste increased dramatically from 40 to 240 tons per day (Shams et al., 2021). The recycling rate declined from 12% to approximately 4.25% (Shams et al., 2021). According to Prata et al. (2020), waste generation included monthly use of 129 billion face masks and sixty-five billion gloves worldwide.

The study highlighted that the pandemic created multiple plastic pollution pathways, with medical waste generation being particularly problematic. The World Bank warned about this unprecedented increase in single-use plastics (Bengali, 2020), while regional studies documented specific challenges in medical waste management (Klemeš et al., 2020; Rhee, 2020).

A critical finding was the risk assessment, which revealed that plastic pollution during the pandemic would increase GHG emissions in incineration facilities and endanger marine species through improper disposal into oceans and lands (Shams et al., 2021). This comprehensive analysis, supported by numerous researchers, underscores the potential threat to environmental health, suggesting significant implications for long-term ecological stability.

This analysis shows how the COVID-19 pandemic has created a complex web of environmental challenges related to plastic pollution, with impacts documented across multiple environmental systems and supported by extensive research from various experts in the field. The findings highlight the need for improved waste management systems and environmental protection measures, particularly during global health crises. Table 4 summarizes the key quantitative findings across all five studies, organized by ecosystem type.

Table 4

Quantitative Findings Across Marine, Terrestrial, and Freshwater Ecosystems

Ecosystem Type	Study	Key Quantitative Findings	Effect Magnitude
MARINE (Seagrass)	Douglas et al., 2024	Microplastic concentration in sediments	17.90–24,805.41 items/kg (mean 5,378.98 ± 9,735.17)
		Biota contamination rate	80% of seagrass biota; 75% of blades; 27.6% of macroinvertebrates
		Seagrass respiration reduction	−30 to −50% at 1,000 mg/L MPs
		Rhizome length reduction	−50% with plastic bag exposure
		Leaf density reduction	−26% with micro/nanoplastic exposure
		Pollution Load Index (regional)	1,893.26 ("extremely high"; all 5 countries >640)
		Economic value at risk	>$100 billion annually ($28,916/ha/yr)
		Annual decline rate	10% (SEA) vs. 7% (global average)
TERRESTRIAL (Soil)	Bodor et al., 2024	Plastic loading (terrestrial vs. marine)	4–23× higher in terrestrial environments
		Agricultural MP input (sewage sludge)	Europe: 63,000–430,000 tonnes/yr; N. America: 44,000–300,000 tonnes/yr
		Dominant soil polymers	PP: 50.51%; PE: 43.43%
		Biodegradation rates	PE: 0.1–0.4% over 800 days; PVC: 0% over 35 years
		Earthworm growth/survival effects	Significant decline at 28%, 45%, 60% PE-MPs
		Springtail reproduction inhibition	0.1% PVC-MPs threshold
		Food web bioaccumulation	Earthworms: 13×; chicken manure: 105×; gizzard: 5× soil levels
		Plant contamination	Up to 233 particles/kg in edible species
		Soil process mediation affected	80–90% of microbial processes affected

FRESHWATER	Barrett et al., 2024	Riparian zone debris density	~5 items per linear meter (range: 0.4–5.7)
		Urban-rural gradient	4–5× increase from forested to developed areas
		Fragmentation rates	Foams: 93%; films: 86%; overall: >67%
		Size distribution	<5 cm: ~50%; <10 cm: ~75% of items
		Dominant materials (by count)	Films: 43%; hard plastic: 24%; foams: 13%
		Functional origin	Shopping bags: 30%; food wrappers: 10%
		Microplastic production potential	>400 MPs from all materials except new foam
		Water column MP composition	~90% fibers (shape mismatch with macroplastic sources)
LCA (Product)	Zhang et al., 2021	Wet wipe plastic consumption (China 2019)	0.41 million tons (65% of spun lace fabric; >90% polyester)
		COVID-19 usage increase	+41% in Q1 epidemic period
		Bio-based vs. petroleum impact	Overall: 38% lower; but freshwater eutrophication: 120× higher
		Production stage contribution	Fiber production: 80.1–99.8% of total environmental impact
		Human toxicity source	Polyester: 75%; Viscose: 98% of eutrophication
PANDEMIC (Global)	Shams et al., 2021	Plastic production increase	396 million tons (2018) → 698 million tons (2020 est.)
		Global PPE monthly need	129 billion masks + 65 billion gloves
		Medical waste increase (USA)	6-fold in first 2 months; 1.48 → 8.85 million tons
		GHG emissions increase (USA)	+67.42 million metric tons CO_2-eq (= 14.3 million cars/year)
		Marine plastic increase	+30% projected vs. 2019; 1.56 billion masks in oceans
		Recycling reduction (USA)	8.5% → 4.25% (−50%)
		Medical waste by country (tons/day)	Wuhan: 40→240; Bangladesh: 483; Philippines: 280; Bangkok: +210

Conclusion

The systematic review of emerging plastic pollution threats to ecosystem sustainability reveals several critical patterns and implications across terrestrial, marine, and freshwater environments. The analysis of high-quality studies from 2021-2024 proves both ecosystem-specific impacts and interconnected challenges that transcend environmental boundaries.

Our analysis reveals three major patterns in emerging plastic pollution threats. The studies analyzed employed diverse methodological approaches—including field sampling (Douglas et al., 2024; Barrett et al., 2024), life cycle assessment (Zhang et al., 2021), laboratory soil analysis (Bodor et al., 2024), and pandemic waste estimation (Shams et al., 2021)—reflecting the multifaceted nature of plastic pollution research across different ecosystem types.

Plastic pollution runs as an interconnected, cross-ecosystem threat with clear transmission pathways among environmental compartments. Terrestrial environments serve as the primary receptor, receiving 4-23 times more plastic annually than marine waters (Bodor et al., 2024), through agricultural applications (mulch films, biosolids), atmospheric deposition, and improper waste disposal. These terrestrial sources later feed freshwater systems through runoff, erosion, and direct discharge; Barrett et al. (2024) documented this gradient with plastic debris increasing 4-5-fold as streams transitioned from forested headwater through urban areas. Freshwater systems then function as conduits to marine environments, with an estimated 80% of oceanic plastics originating from riverine sources (Shams et al., 2021). Within each compartment, macroplastics undergo physical, chemical, and biological degradation into microplastics (Barrett et al., 2024), which later bioaccumulate through food webs—observed at magnifications of 13-105× in terrestrial systems (Bodor et al., 2024) and affecting 80% of marine seagrass biota (Douglas et al., 2024). The COVID-19 pandemic dramatically accelerated this entire system, introducing an estimated 698 million tons of plastic in 2020 alone—a 76% increase over pre-pandemic projections (Shams et al., 2021)—with medical waste standing for a novel, high-volume pathway into all three ecosystem types. Table 5 illustrates the size of plastic transmission pathways across ecosystem boundaries.

Table 5
Cross-Ecosystem Transmission Pathways and Magnitudes

Pathway	Size	Source	Receiving System	Impact
Terrestrial → Freshwater	4–5× increase through urban gradient	Barrett et al., 2024	Riparian zones	0.4 → 5.7 items/m
Terrestrial Loading	4–23× higher than marine	Bodor et al., 2024	Soil systems	Up to 7% contamination

Freshwater → Marine	~80% of marine plastic	Shams et al., 2021; Barrett et al., 2024	Oceanic systems	Via riverine transport
Agricultural Input	63,000–430,000 tonnes/yr (Europe)	Bodor et al., 2024	Terrestrial soils	2–3× annual increase
Atmospheric Deposition	~100 particles/m²/day	Barrett et al., 2024	All systems	Cross-ecosystem contamination
Food Web Bioaccumulation	13–105× magnification	Bodor et al., 2024	Terrestrial organisms	Chicken manure: 105× soil
Food Web Bioaccumulation	80% contamination rate	Douglas et al., 2024	Marine organisms	Seagrass biota
Macroplastic → Microplastic	>400 MPs per item	Barrett et al., 2024	All systems	Size reduction via degradation
Pandemic Surge	+76% over baseline	Shams et al., 2021	All systems	396 → 698 million tons/yr

First, microplastic contamination appears as a universal concern across all studied ecosystems, though its manifestations differ significantly by environment. In terrestrial systems, Bodor et al. (2024) documented how microplastics alter fundamental soil properties, affecting everything from bulk density to water retention dynamics. The study revealed that 72% of plastic particles become incorporated into soil aggregates, suggesting deep integration into soil structure. In marine environments, Douglas et al. (2024) showed similar systemic disruptions in seagrass meadows, with impacts extending to essential ecosystem services like carbon sequestration and coastal protection. This parallel suggests that microplastic pollution's capacity to alter fundamental ecosystem properties extends across environmental boundaries, creating a concerning pattern of systemic disruption.

Second, the review names a clear trend in the cascading nature of plastic pollution impacts across all studied environments. The economic and ecological stakes of plastic pollution are large (Table 6).

Table 6
Ecosystem Service Impacts and Economic Valuation

Ecosystem	Service Category	Impact Magnitude	Economic Value at Risk	Source
Marine (Seagrass)	All 9 ES categories	Negative impact across all	>$100 billion/yr ($28,916/ha/yr)	Douglas et al., 2024

Marine (Seagrass)	Carbon sequestration	Respiration: −30 to −50%	Included in valuation above	Douglas et al., 2024
Marine (Seagrass)	Habitat provision	90% meadow reduction (disease)	Included in valuation above	Douglas et al., 2024
Marine (Seagrass)	Predicted extinction	By 2060 (SEA region)	Total loss of $100B/yr value	Douglas et al., 2024
Terrestrial (Soil)	Nutrient cycling	80–90% of processes affected	Not quantified	Bodor et al., 2024
Terrestrial (Soil)	Agricultural productivity	Crop contamination: 233 MPs/kg	Not quantified	Bodor et al., 2024
Freshwater	Water quality/aesthetics	>67% items fragmented	Not quantified	Barrett et al., 2024
Global (Climate)	GHG regulation	+67.42 million tons CO_2-eq (USA alone)	Climate change costs	Shams et al., 2021

In terrestrial systems, Bodor et al. (2024) showed how microplastic soil contamination triggers a sequence of interconnected effects: physical alterations in soil structure led to changes in nutrient availability, which in turn affected microbial communities and impacted plant growth and soil fauna. The research showed that these changes affect critical processes like organic matter decomposition and nutrient cycling. Similarly, in marine environments, Douglas et al. (2024) documented how plastic pollution creates interconnected disruptions across seagrass ecosystem services, finding that impacts cascade from direct physical effects on seagrass growth to broader implications for coastal protection and climate regulation. Barrett et al. further supported these patterns (2024) freshwater research, which showed how plastic accumulation patterns intensify from upstream to downstream locations, with urban development amplifying these effects.

Third, our analysis reveals emerging evidence of novel threat pathways associated with global events and changing consumption patterns. The assessment by Shams et al. (2021) of COVID-19-related plastic pollution exemplifies how global events can rapidly introduce new pollution patterns and amplify existing threats. Their documentation of dramatic increases in medical waste (from 40 to 240 tons per day) and the addition of 1.56 billion masks to marine environments proves the rapid emergence of new pollution sources. This finding, combined with Zhang et al.'s (2021) life-cycle assessment of wet wipes, reveals critical insights into product-specific pollution patterns that demand targeted policy responses.

Zhang et al.'s (2021) comprehensive lifecycle analysis provides particularly valuable guidance for environmental management frameworks. Their quantification of wet wipes consuming 0.41 million tons of plastic in China alone during 2019, standing for 5.1 times the plastic weight of non-degradable express packaging, illustrates how seemingly minor consumer products can generate substantial environmental burdens. More significantly, their finding that production stages dominate environmental impacts (contributing 80.1%-99.8% of total emissions) shows that effective pollution prevention must target manufacturing processes rather than focusing solely on end-of-life management. This production-stage dominance suggests that policy interventions addressing fiber choice, manufacturing efficiency, and production waste capture could yield far greater environmental benefits than traditional waste management approaches alone.

These findings have significant implications for environmental management and policy development. The universal presence of microplastic contamination across ecosystems suggests the need for integrated management approaches that consider cross-ecosystem impacts. The documented cascading effects show that traditional single-focus mitigation strategies may be insufficient, as impacts ripple across ecological boundaries and processes.

The emergence of novel threat pathways, particularly those associated with global events like the COVID-19 pandemic, highlights the need for more adaptive and responsive environmental management frameworks. Such frameworks must incorporate several key elements: rapid assessment protocols capable of evaluating emerging pollution sources within months rather than years; flexible regulatory mechanisms that can quickly restrict problematic products without lengthy legislative processes; coordinated response systems linking public health agencies, environmental regulators, and waste management authorities; and predictive modeling capabilities that can anticipate pollution surges from global events such as pandemics, natural disasters, or economic disruptions.

Furthermore, adaptive management frameworks should prove pre-positioned response capabilities, including emergency waste processing capacity, alternative material supply chains for essential products, and communication systems to rapidly give new environmental threats to relevant stakeholders. The COVID-19 experience shows that environmental agencies need protocols for collaborating with health authorities during crises to balance immediate health needs with long-term environmental protection.

Limitations

An independent researcher conducted this exploratory systematic review, which is subject to various methodological limitations that should be transparently showed. First, the search strategy was limited to two databases (ScienceDirect and MDPI), which may have excluded relevant studies indexed in other repositories such as Web of Science, Scopus, or PubMed. This database selection was driven by resource constraints inherent to independent research; however, it enabled focused analysis of high-quality, open-access literature published in peer-reviewed journals. While this approach may have limited the breadth of literature captured, the selected databases provided sufficient coverage of recent research (2021-2024) across the three targeted ecosystem types.

Second, the review's evidentiary base consists of five studies, which some might consider a modest sample size for systematic review. This limitation reflects the focused scope of the review on *emerging* threats rather than the entirety of plastic pollution research. The inclusion criteria prioritized recent, high-quality empirical studies that directly addressed ecosystem-level impacts across different environmental compartments. The five included studies stand for distinct ecosystem types (terrestrial, marine, freshwater) and research approaches (field sampling, life cycle assessment, pandemic impact analysis), providing complementary rather than redundant evidence. Nonetheless, the limited sample size means that findings should be interpreted as indicative of emerging patterns rather than definitive conclusions about all plastic pollution impacts.

Third, screening and data extraction were conducted by a single reviewer without independent verification or adjudication protocols. This single-reviewer approach is a recognized limitation in systematic review method, as it introduces potential for subjective bias in study selection and data interpretation. In traditional research settings, multiple independent reviewers with consensus-building mechanisms would strengthen methodological rigor. However, the single-reviewer approach enabled detailed, consistent analysis using standardized extraction forms and explicit inclusion/exclusion criteria, with all decisions documented transparently in the PRISMA flow diagram and selection rationale.

Fourth, the quality assessment employed a 5-point rubric developed specifically for this review, without formal calibration procedures or inter-rater reliability testing. This approach lacks the validation that would come from established quality assessment tools such as GRADE or Newcastle-Ottawa Scale, and the absence of multiple raters means that quality scores reflect one researcher's judgments rather than consensus evaluation. The rubric criteria (methodological rigor, relevance to emerging threats, ecosystem impact analysis quality, quantitative assessment strength) were applied consistently across all studies; however, the scores should be interpreted as relative rankings within this review rather than absolute quality measures comparable across different systematic reviews.

Finally, the synthesis presents primarily qualitative interpretation of study findings, with limited meta-analytical quantification. The heterogeneity of methodological approaches across the included studies—ranging from laboratory soil analysis to field-based marine ecosystem assessment to life cycle modeling—precluded statistical pooling of effect sizes. While this methodological diversity enriched the breadth of ecosystem coverage, it meant that some findings stay descriptive rather than statistically aggregated.

These limitations are characteristic of exploration systematic reviews conducted by independent researchers using outside institutional research infrastructure. The constraints in database access, reviewer resources, and validation mechanisms do not invalidate the findings but do contextualize them as preliminary synthesis that highlights emerging patterns requiring further investigation through larger-scale, multi-reviewer systematic reviews with broader database coverage. Importantly, the review succeeds in its primary goal: finding and categorizing emerging plastic pollution threats across multiple ecosystem types through transparent, systematic analysis of recent high-quality research.

Despite the comprehensive nature of the analyzed studies, several knowledge gaps appear that require attention in future research. While individual ecosystem impacts are well-documented, there is limited understanding of cross-ecosystem interactions and cumulative effects. The rapid emergence of novel threat pathways suggests a need for more agile research frameworks that can quickly assess and respond to new pollution sources, including real-time monitoring systems and standardized rapid assessment protocols for emerging contaminants.

The evidence synthesized in this review shows that plastic pollution stands for a dynamic, evolving challenge requiring equally dynamic and integrated management responses. The interconnected nature of impacts across terrestrial, marine, and freshwater systems, combined with the rapid emergence of novel pollution sources, demands a fundamental shift from reactive, compartmentalized approaches toward initiative-taking, cross-ecosystem management strategies capable of expecting and rapidly responding to emerging threats.

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