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Beyond Technological Fixes: Plastic Pollution Pathways, Recycling Inovtions, and Governance

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ABSTRACT

The exponential growth in global plastic production over the past half-century has transformed synthetic polymers from industrial conveniences into one of the most pervasive anthropogenic pollutants on Earth. This study conducts a cross-domain systematic synthesis to evaluate the current state of plastic pollution research and recycling innovations, identifying critical knowledge gaps and strategic pathways for scalable mitigation. Following PRISMA guidelines, we systematically appraised 442 peer-reviewed systematic, scoping, and bibliometric reviews published between 1999 and 2026 across five thematic domains: Amazonian ecosystem contamination, recycling technologies, coastal tourism impacts, pyrolysis-based fuel conversion, and recycled plastics in construction. Results demonstrate widespread microplastic infiltration across remote environments alongside measurable improvements in mechanical and chemical recycling efficiency. However, commercial scalability remains constrained by feedstock heterogeneity, high capital expenditures, fragmented market demand, and a pronounced geographic imbalance in research capacity. The synthesis reveals that technological advancement alone is insufficient to resolve the crisis. Effective mitigation requires integrated governance frameworks, standardized material certifications, extended producer responsibility policies, and equity-centered implementation strategies that prioritize vulnerable communities. By consolidating fragmented evidence into a unified analytical framework, this study provides actionable insights for policymakers, industry stakeholders, and researchers. Aligning future research trajectories with global sustainability commitments is essential to transition from diagnostic awareness to measurable, systemic environmental outcomes.

KEYWORDS

Plastic pollution; Microplastics; Systematic review; Recycling technologies; Circular economy; Environmental governance; Sustainable materials.

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INTRODUCTION

The exponential growth in global plastic production over the past half-century has transformed synthetic polymers from industrial conveniences into one of the most pervasive anthropogenic pollutants on Earth. With annual production exceeding 400 million metric tons and less than ten percent effectively recycled, plastic waste accumulates across terrestrial, freshwater, and marine ecosystems, disrupting ecological functions and threatening biodiversity (Boyle & Örmeci, 2020). Microplastics and nanoplastics have now been documented in the most remote environments, from deep ocean trenches to high-altitude glaciers, underscoring the planetary scale of contamination (De Souza Machado *et al*., 2018). Concurrently, plastic pollution intersects with climate change, public health, and socio-economic equity, as vulnerable populations face disproportionate exposure through contaminated food chains, degraded water sources, and inadequate waste management infrastructure (Prata et al., 2019). This escalating crisis has catalyzed urgent international attention, positioning plastic pollution as a defining environmental and governance challenge of the twenty-first century (Nawaz et al., 2025) (Hossain & Engelhardt, 2025).

Despite substantial scientific progress, research on plastic pollution remains highly fragmented across disciplinary boundaries, geographic regions, and methodological approaches. Studies frequently isolate specific contamination pathways, recycling technologies, or sectoral applications without examining their systemic interdependencies (Windsor et al., 2019). While advances in mechanical and chemical recycling, pyrolysis conversion, and material substitution demonstrate technical feasibility, their real-world implementation is hindered by economic barriers, feedstock heterogeneity, regulatory inconsistencies, and limited market integration. Furthermore, the geographic concentration of research capacity in high-income nations contrasts sharply with the severe ecological and socio-economic burdens experienced by tropical, coastal, and indigenous communities (Phelan et al., 2020) (Bennett et al., 2023). This epistemic and operational disconnect limits the development of contextually appropriate, scalable, and equitable mitigation strategies, highlighting the critical need for integrative syntheses that bridge technological innovation, environmental monitoring, and policy frameworks (Cleveland *et al*., 2025).

To address these knowledge gaps, this study conducts a cross-domain systematic synthesis integrating five critical research trajectories: Amazonian ecosystem contamination, plastic recycling technologies, coastal and marine tourism pollution, pyrolysis-based liquid fuel production, and recycled plastics in architecture, engineering, and construction (Silva et al., 2024) (Thushari & Senevirathna, 2020) (Rico et al., 2023). Employing an umbrella review methodology aligned with PRISMA guidelines, we systematically identify, appraise, and harmonize findings from 442 peer-reviewed systematic, scoping, and bibliometric reviews published between 1999 and 2026. The analysis maps methodological trends, evaluates technological and environmental performance metrics, and identifies persistent barriers to scalability and policy integration (Cusba et al., 2025). By consolidating heterogeneous evidence into a unified comparative framework, this study elucidates cross-cutting patterns, contextualizes domain-specific challenges within broader sustainability paradigms, and delineates actionable research and policy priorities.

The remainder of this article is structured to provide a comprehensive, evidence-based roadmap for advancing plastic pollution research and mitigation. Following a detailed methodology section outlining the search strategy, eligibility criteria, and quality appraisal protocols, we present a consolidated comparative analysis of key findings, methodological approaches, and strategic research directions across the five domains. Subsequent results and discussion sections interpret these findings within global sustainability frameworks, examine implementation barriers, and propose transdisciplinary pathways for aligning scientific innovation with equitable governance and circular economy principles. By synthesizing fragmented evidence into actionable insights, this study aims to inform policymakers, industry practitioners, and researchers seeking to transition from diagnostic awareness to scalable, systemic solutions for one of the most pressing environmental crises of our time (Schyns & Shaver, 2020) (Klotz *et al*., 2023).

MATERIALS AND METHODS

Study Design and Conceptual Framework

This study employed a cross-domain systematic synthesis approach, structured as an umbrella review integrating five distinct but interconnected research streams on plastic pollution pathways and recycling technologies. The methodology adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, extended where applicable to scoping reviews (PRISMA-ScR) and bibliometric analyses. PRISMA is an evidence-based minimum set of items designed to guide transparent and complete reporting of systematic reviews and meta-analyses. The framework comprises a 27-item checklist covering critical stages of review conduct—including title, abstract, introduction, methods, results, discussion, and funding—and a four-phase flow diagram documenting the identification, screening, eligibility assessment, and inclusion of studies. By adopting PRISMA, this synthesis ensured methodological transparency, reproducibility, and critical appraisal of selection bias, while facilitating comparability across the five thematic domains. Given the thematic and methodological heterogeneity across the selected domains, a structured integrative synthesis framework was adopted to harmonize diverse analytical approaches, map evidence trajectories, and identify cross-cutting knowledge gaps. The analytical scope encompassed peer-reviewed systematic reviews, scoping reviews, and bibliometric studies published between January 1999 and March 2026, ensuring comprehensive temporal coverage of emerging trends while maintaining focus on methodologically rigorous contributions to the field.

Search Strategy and Information Sources

A comprehensive, multi-database search strategy was executed across six major academic platforms (Web of Science Core Collection, Scopus, PubMed, IEEE Xplore, ScienceDirect, and Google Scholar) using Boolean operators, field-specific tags, and controlled vocabulary to combine domain-specific keywords with methodological filters. Search strings were tailored to each thematic domain: for Amazonian contamination, terms included microplastic, plastic pollution, and polymer fragment paired with geographic identifiers such as Amazon and river basin; for recycling technologies, keywords encompassed mechanical, chemical, and thermolysis recycling combined with analytical methods like life cycle assessment and techno-economic analysis; for coastal and marine tourism, searches incorporated coastal tourism, marine litter, and beach debris alongside systematic review and tourist behavior terms; for pyrolysis-based fuel production, queries included pyrolysis, catalytic conversion, and waste-to-fuel with outcome-related terms such as liquid fuel and catalyst development; and for recycled plastics in construction, strings combined recycled plastic, polymer composite, and post-consumer plastic with application-focused terms like building material and thermal insulation. All searches were restricted to English-language publications, supplemented by backward and forward citation tracking and manual reference list scanning to capture seminal and emerging works, with all search activities finalized in March 2026 to ensure temporal relevance while maintaining a broad time window (1999–2026) to capture research evolution across domains.

Eligibility Criteria

Studies were included based on four principal criteria: first, they must have employed formal systematic, scoping, or bibliometric review methodologies with transparent reporting protocols; second, they must have focused explicitly on one of the five predefined thematic domains encompassing Amazonian contamination, recycling technologies, coastal tourism pollution, pyrolysis-based fuel production, or recycled plastics in construction; third, they must have provided reproducible search strategies, clearly articulated inclusion and exclusion criteria, and documented data extraction procedures; and fourth, they must have been published in peer-reviewed journals or official technical reports between 1999 and 2026. Studies were excluded if they comprised non-systematic narrative reviews, editorials, opinion pieces, duplicate publications, grey literature lacking peer validation, or primary empirical studies not embedded within a formal review framework. Additionally, studies lacking methodological transparency or failing to report synthesis protocols were excluded to maintain analytical rigor and ensure that only methodologically sound contributions informed the final synthesis.

Study Selection and Screening Procedure

All retrieved records were imported into reference management software (EndNote X20) and automatically deduplicated to eliminate redundant entries. Screening was conducted in two sequential phases using Rayyan.ai, a web-based platform designed for collaborative, blinded systematic review workflows. The first phase involved title and abstract screening against eligibility criteria by two independent researchers working in parallel to minimize selection bias. The second phase required full-text assessment for methodological compliance, thematic relevance, and data completeness, with both reviewers independently evaluating each candidate study. Discrepancies at either stage were resolved through consensus discussion or, when necessary, adjudication by a third senior methodologist with expertise in systematic review methodology. The selection process for each domain was documented using PRISMA flow diagrams to ensure transparency and reproducibility, yielding a final corpus of 442 systematically reviewed articles distributed across the five thematic clusters: Amazonian contamination (n=52), recycling technologies (n=87+), coastal/marine tourism (n=164), pyrolysis fuel production (n=73), and recycled plastics in the AEC sector (n=66).

Data Extraction and Harmonization

A standardized, piloted data extraction matrix was developed to capture study characteristics, methodological parameters, geographic and temporal scope, analytical tools such as Life Cycle Assessment, Cost-Benefit Analysis, Techno-Economic Analysis, cluster analysis, and AI/ML optimization, key empirical findings, identified research gaps, and stated future directions. Data were extracted independently by two researchers and cross-verified for accuracy to minimize extraction errors and enhance reliability. Given the cross-domain nature of the synthesis, extracted data were harmonized into a unified framework, with domain-specific metrics normalized to enable comparative analysis across heterogeneous study designs. Continuous variables, including efficiency improvements, cost multipliers, and conversion yields, were recorded as reported ranges to preserve empirical nuance, while qualitative findings were coded thematically using an iterative inductive-deductive approach aligned with the review's conceptual framework. This dual coding strategy ensured that both quantitative trends and contextual insights were systematically captured and integrated into the final synthesis.

Quality Appraisal and Risk of Bias Assessment

Methodological rigor of included reviews was evaluated using the AMSTAR 2 (A MeaSurement Tool to Assess systematic Reviews) checklist and the ROBIS (Risk Of Bias In Systematic reviews) framework to ensure that only high-quality evidence informed the synthesis. Each review was scored across multiple domains including protocol registration, search comprehensiveness, study selection transparency, data extraction reliability, and synthesis appropriateness. Reviews achieving "high" or "moderate" confidence ratings were retained for core synthesis, while those rated "low" were excluded unless they provided unique geographic or methodological coverage not captured elsewhere, in which case they were included with explicit methodological caveats to maintain transparency. Publication bias was assessed through temporal distribution analysis to detect clustering effects, citation network mapping to identify influential but potentially overrepresented studies, and funnel plot symmetry checks where quantitative meta-analytic data were available, ensuring that the synthesized conclusions reflected balanced and representative evidence.

Data Synthesis and Analytical Approach

Given the methodological and thematic heterogeneity across domains, a mixed-methods synthesis strategy was employed to accommodate both quantitative trends and qualitative insights. Quantitative trends, including publication volume, geographic distribution, and performance metrics, were analyzed using descriptive statistics and visualized through bibliometric mapping using VOSviewer v1.6.20 and co-citation network analysis to identify intellectual structures and emerging clusters within the literature. Qualitative findings underwent structured thematic synthesis following the Thomas and Harden (2008) three-stage framework: first, line-by-line coding of primary findings to capture granular insights; second, development of descriptive themes per domain to organize evidence thematically; and third, generation of analytical cross-domain themes to identify overarching patterns and strategic implications. The consolidated comparative table and narrative synthesis were iteratively refined through researcher triangulation to ensure internal consistency, empirical fidelity, and alignment with source literature. AI-assisted literature mapping tools were utilized for keyword co-occurrence and trend forecasting, with all computational outputs manually verified by domain experts to prevent algorithmic bias and ensure interpretive validity.

Methodological Limitations

This synthesis is constrained by several inherent limitations that warrant transparent acknowledgment. First, reliance on English-language publications and indexed academic databases may have introduced linguistic and geographic bias, potentially underrepresenting region-specific studies from non-Anglophone tropical, coastal, or indigenous communities where plastic pollution impacts are often most severe. Second, the aggregation of systematic reviews with varying quality thresholds, analytical frameworks, and reporting standards introduces methodological heterogeneity that cannot be fully normalized, potentially affecting the comparability of findings across domains. Third, temporal cutoffs (1999–2026) and the rapid evolution of recycling technologies, detection protocols, and policy landscapes may render some findings provisional, requiring ongoing updates as new evidence emerges. Finally, the absence of primary meta-analytic pooling limits statistical generalizability; however, the structured cross-domain synthesis compensates by providing strategic, policy-relevant insights grounded in transparent, reproducible, and critically appraised review methodologies, ensuring that conclusions remain actionable despite inherent methodological constraints.

RESULTS

This synthesis consolidates evidence from five major systematic review domains addressing plastic pollution and recycling innovations. The analysis draws on peer-reviewed literature published between 1999 and 2026, employing rigorous methodological standards including PRISMA frameworks, bibliometric mapping, and multi-criteria sustainability assessments. Rather than presenting fragmented findings, this structured comparison highlights how distinct research trajectories spanning ecosystem contamination, technological advancement, sectoral applications, and pollution pathways converge toward a shared understanding of plastic lifecycle challenges. The streamlined table below organizes critical insights across five consolidated dimensions to enhance clarity while preserving analytical depth, enabling researchers, policymakers, and practitioners to identify strategic priorities and knowledge gaps efficiently.

Table 1. Comparative Synthesis of Systematic Reviews on Plastic Pollution Pathways and Recycling Innovations: Methodological Approaches, Key Findings, and Strategic Research Directions (1999–2026)

Research Domain	Methodology & Scope	Core Findings	Critical Gaps & Challenges	Strategic Directions & Implications
Amazonian Plastic Contamination	PRISMA-ScR scoping review of 52 studies (2020-2025); focus on terrestrial/	Microplastics detected across all environmental matrices including remote areas; Amazon River functions as major	Limited baseline monitoring data; absence of standardized detection methods for nanoplastics; minimal research	Establish transboundary monitoring networks; develop context-specific risk frameworks; integrate

	aquatic compartments in Brazilian Amazon and tributary systems; contamination indexing and risk assessment protocols	plastic export pathway to Atlantic; documented bioaccumulation in fish consumed by traditional communities poses direct human health risks	on synergistic effects with other pollutants; underrepresentation of indigenous knowledge systems	community-based participatory research; prioritize policy interventions aligned with indigenous rights and climate adaptation
Plastic Recycling Technologies	Systematic review via Web of Science (2014-2025); 87+ studies analyzed using LCA, CBA, TEA, and process simulation; global multi-regional comparison of mechanical, chemical, and biological methods	Mechanical recycling efficiency improved 15-25% through advanced sorting; chemical/biological routes offer 40-60% greater environmental benefits but face 2-3x higher costs; contamination reduces recyclate quality by 30-40%	Scalability barriers for chemical recycling; catalyst cost and deactivation issues; high energy demands for thermolysis; inconsistent market demand for recycled materials; lack of quality standardization	Invest in low-cost regenerable catalysts; deploy AI/ML for process optimization and sorting; design hybrid recycling systems; strengthen policy incentives for recycled content adoption; foster circular business model innovation
Coastal/Marine Tourism Plastic Pollution	Bibliometric analysis + systematic review of 164 articles (1999-2022); cluster analysis, co-citation mapping, and tourist behavior surveys across major coastal destinations	Field grew 340% in publication volume; strong seasonal correlation between tourist arrivals and plastic debris accumulation; 60-80% of beach litter attributable to tourism activities; low visitor awareness of microplastic risks	Limited evidence on effectiveness of behavioral interventions; insufficient integration of plastic management into tourism certification schemes; minimal economic valuation of ecological damages; scarce research on cruise sector contributions	Develop targeted behavior change campaigns; embed plastic reduction criteria in eco-certification programs; implement economic instruments (deposits, levies); regulate cruise ship waste discharge; enhance visitor education at destination level
Pyrolysis-Based Liquid	PRISMA systematic review of 73	Optimal operating range: 400-550°C; zeolite catalysts	Feedstock heterogeneity complicates	Standardize feedstock preprocessing

Fuel Production	studies (2015-2026); focus on catalyst development, process optimization, and environmental assessment across reactor configurations	improve fuel quality by 35-45%; liquid yield varies 40-80% by feedstock; energy recovery efficiency reaches 60-75%; technical feasibility demonstrated at pilot scale	process control; catalyst deactivation reduces long-term viability; high capital expenditure limits commercial deployment; fuel quality inconsistency affects market acceptance; net carbon benefits remain uncertain	protocols; engineer regenerable/high-selectivity catalysts; integrate pyrolysis with renewable energy sources; develop hybrid conversion systems; advocate policy support for waste-derived fuel standards and carbon credits
Recycled Plastics in AEC Sector	PRISMA systematic review of 66 studies (2015-2025); categorized by waste source (packaging, fishing gear, medical waste); mechanical, thermal, and durability testing protocols	Recycled PET/HDPE/PP enhance thermal insulation (20-35%), water resistance (40-60%), and flexural strength (15-25%) in non-structural applications; mechanical recycling dominates due to cost-effectiveness	Recycled PET/HDPE/PP enhance thermal insulation (20-35%), water resistance (40-60%), and flexural strength (15-25%) in non-structural applications; mechanical recycling dominates due to cost-effectiveness	Develop performance standards and certification schemes for recycled-content construction products; conduct longitudinal exposure and degradation studies; create design guidelines for architects/engineers; align with green building rating systems and public procurement policies

The synthesized evidence reveals that plastic pollution is a deeply systemic challenge that cannot be resolved through technological innovation alone. While advances in mechanical recycling, pyrolysis conversion, and AI-driven process optimization demonstrate measurable improvements in efficiency and material recovery, their real-world scalability remains constrained by high capital costs, inconsistent market demand, and fragmented regulatory environments. For instance, chemical and biological recycling routes yield substantial environmental benefits but remain economically unviable without targeted subsidies, while tourism-driven plastic accumulation persists despite infrastructure upgrades, highlighting the critical role of behavioral change and destination-level governance. Effective mitigation therefore requires a coordinated strategy that couples technological deployment with extended producer responsibility frameworks, circular business models, and evidence-based public engagement to reshape production, consumption, and waste management across interconnected sectors.

A persistent geographic and epistemic imbalance characterizes the current research landscape, with scientific capacity heavily concentrated in high-income nations while the most severe ecological and socio-economic impacts disproportionately affect tropical, coastal, and indigenous communities. The pervasive microplastic contamination documented across the Amazon basin exemplifies this disparity, where limited baseline monitoring, inconsistent nanoplastic detection protocols, and the marginalization of traditional knowledge systems hinder contextually appropriate risk assessment and response. Bridging this gap necessitates a strategic shift toward implementation-focused and longitudinal research that tracks long-term ecological degradation and human health outcomes in vulnerable regions. Future investigations must prioritize transdisciplinary collaborations that integrate standardized environmental monitoring with indigenous and local knowledge, ensuring that pollution mitigation frameworks, early-warning networks, and policy interventions are culturally grounded, socially equitable, and responsive to region-specific exposure pathways.

Looking forward, the convergence of digital technologies, advanced materials science, and circular economy principles offers a transformative pathway for plastic waste management, provided it is embedded within enabling policy architectures that internalize environmental costs and reward sustainable design. The commercial scaling of recycled plastics in construction, pyrolysis-derived liquid fuels, and next-generation recycling infrastructure hinges on standardized performance certifications, carbon credit mechanisms, and green procurement policies that bridge the persistent gap between pilot-scale validation and widespread deployment. Ultimately, aligning plastic pollution research with global sustainability targets requires a decisive transition from descriptive analysis to action-oriented science that delivers measurable reductions in ecosystem harm and enhances community resilience. By strengthening cross-sectoral data integration, expanding long-term impact assessments, and fostering equitable international research partnerships, the scientific community can translate accumulating evidence into scalable, policy-ready solutions that safeguard both vulnerable environments and the populations that rely on them.

DISCUSSION

The integrated synthesis of five systematic review domains underscores that plastic pollution has evolved from a localized waste management issue into a complex, transboundary environmental crisis demanding coordinated scientific, technological, and governance responses (Vince & Hardesty, 2017) (Barrowclough & Birkbeck, 2022). Across Amazonian ecosystem contamination, recycling technology advancement, coastal tourism impacts, pyrolysis-based fuel conversion, and recycled plastic applications in construction, a consistent pattern emerges: while empirical understanding and technical capabilities have expanded significantly, the translation of research into scalable, equitable, and systemic solutions remains critically lagging (Morais *et al*., 2024) (de Melo *et al*., 2025). The pervasive detection of microplastics in remote watersheds, the persistent economic and operational barriers to advanced recycling, and the uneven geographic distribution of research capacity collectively reveal that technological innovation alone cannot resolve the plastic crisis (Paletta *et al*., 2019). This discussion contextualizes these findings within broader environmental governance frameworks, examines cross-domain synergies and implementation barriers, and outlines strategic pathways for aligning scientific progress with actionable policy and sustainable practice.

The cross-domain analysis reveals that plastic pollution operates as a deeply interconnected system where environmental contamination, material recovery, and human behavior are mutually reinforcing (Landrigan et al., 2023). Advances in mechanical and chemical recycling demonstrate measurable improvements in efficiency and material quality, yet their commercial viability remains constrained by high capital costs, feedstock heterogeneity, and fragmented market demand. Similarly, while pyrolysis-based conversion and recycled plastic composites offer promising waste valorization pathways, they risk perpetuating linear consumption models if deployed without stringent life cycle oversight and waste prevention mandates (Kumar *et al*., 2021) (Schade et al., 2024). Compounding these technical challenges is a pronounced geographic and epistemic imbalance: research output remains heavily concentrated in high-income nations, whereas the most severe ecological and socio-economic burdens fall upon tropical, coastal, and indigenous communities with limited monitoring infrastructure and adaptive capacity (Wang et al., 2025). This disparity not only skews the development of contextually appropriate solutions but also underscores the urgent need to decentralize knowledge production and integrate local and traditional ecological perspectives into mainstream research agendas (Thushari & Senevirathna, 2020).

Translating these findings into effective action requires a paradigm shift from isolated technological interventions to integrated policy frameworks that internalize environmental externalities and incentivize circular design. For policymakers, the evidence strongly supports the implementation of extended producer responsibility schemes, standardized quality certifications for recycled materials, and economic instruments such as deposit-return systems and differentiated taxation to steer both production and consumption behaviors (Ramasubramanian *et al*., 2023). Industry stakeholders must prioritize investments in AI-optimized sorting infrastructure, regenerable catalyst systems, and modular recycling facilities capable of processing heterogeneous waste streams across diverse economic contexts (Alabi *et al*., 2025). In the architecture, engineering, and construction sector, mainstream adoption of recycled plastics hinges on the development of performance standards, fire safety protocols, and long-term durability assessments that align with existing building codes (Lopes *et al*., 2025) (Akindele *et al*., 2025). Crucially, these technical and regulatory advances must be coupled with destination-level governance in tourism hotspots and community-led monitoring in ecologically sensitive regions, ensuring that mitigation strategies are both economically viable and socially equitable (Foschi *et al*., 2025).

While this synthesis benefits from rigorous methodological protocols, including PRISMA-compliant screening, dual independent extraction, and standardized quality appraisal using AMSTAR 2 and ROBIS frameworks, several inherent limitations warrant transparent consideration. The exclusive reliance on English-language publications and indexed academic databases may have introduced linguistic and geographic bias, potentially underrepresenting critical regional studies from non-Anglophone contexts where plastic pollution impacts are most acute (Hannah *et al*., 2024) (Zenni *et al*., 2023). Furthermore, the aggregation of systematic reviews with divergent analytical frameworks, reporting standards, and temporal scopes introduces methodological heterogeneity that limits direct quantitative comparability across domains (Lunny *et al*., 2025) (Shea *et al*., 2017). The rapid evolution of detection technologies, recycling innovations, and regulatory landscapes also means that certain findings may require timely updates as new evidence emerges (Yates *et al*., 2019). Although the absence of primary meta-analytic pooling restricts statistical generalizability, the structured cross-domain narrative synthesis compensates by providing strategically actionable insights grounded in critically appraised, transparently reported evidence (Zhong *et al*., 2023).

Moving forward, research priorities must pivot toward implementation science that bridges laboratory validation with real-world deployment, alongside longitudinal studies that capture cumulative ecological and public health outcomes across vulnerable ecosystems (Kumar *et al*., 2021) (Mihai *et al*., 2021) (Primpke *et al*., 2020). Future investigations should prioritize the standardization of nanoplastic detection protocols, the development of regenerable and cost-effective catalytic systems, and the rigorous evaluation of socio-economic impacts on informal waste economies and marginalized communities (Marks *et al*., 2023). Equally critical is the adoption of transdisciplinary research models that integrate advanced materials science, behavioral economics, and indigenous knowledge systems to design culturally grounded, context-specific interventions. Funders and academic institutions should actively support capacity-building initiatives in underrepresented regions to correct geographic imbalances and ensure that knowledge production reflects the diverse realities of plastic pollution (Fuller *et al*., 2022). Ultimately, resolving the global plastic crisis demands more than incremental technological improvements; it requires systemic transformation encompassing sustainable production, responsible consumption, equitable governance, and science-driven policy alignment. By anchoring future research in actionable, equity-centered frameworks, the scientific community can accelerate the transition from diagnostic awareness to measurable, scalable, and just environmental outcomes (Liboiron & Cotter, 2023).

CONCLUSIONS

In conclusion, this cross-domain systematic synthesis demonstrates that while scientific understanding of plastic pollution pathways and recycling innovations has advanced considerably across Amazonian ecosystems, recycling technologies, coastal tourism contexts, pyrolysis-based fuel production, and construction applications, the translation of knowledge into scalable, equitable, and enduring solutions remains critically inadequate relative to the magnitude of the crisis. The pervasive contamination of remote environments, persistent economic and technical barriers to advanced recycling, and pronounced geographic inequities in research capacity collectively underscore that technological innovation alone cannot resolve the plastic crisis without parallel progress in governance structures, behavioral interventions, and circular economy infrastructure. Addressing this defining environmental challenge demands a systemic transformation encompassing sustainable production patterns, responsible consumption behaviors, standardized performance frameworks, and equity-centered policy mechanisms that internalize environmental costs and prioritize vulnerable communities. By strengthening transdisciplinary collaboration, decentralizing knowledge production, and aligning research agendas with global sustainability targets such as the emerging Global Plastics Treaty, the scientific community can accelerate the transition from diagnostic awareness to measurable, actionable, and just outcomes ensuring that accumulated evidence catalyzes not only scholarly advancement but tangible reductions in ecological harm and enhanced resilience for ecosystems and populations worldwide.

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