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A REVIEW OF ENVIRONMENTAL PERFORMANCE ANALYSIS OF RECYCLED PLASTIC UTILIZATION PATHWAYS IN CIVIL INFRASTRUCTURE SYSTEMS

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Abstract *The escalating environmental burden of plastic waste has stimulated interest in the reutilization of recycled plastics within civil infrastructure systems. This paper presents a comprehensive review of the environmental performance analysis associated with various recycled plastic utilization pathways in infrastructure applications, with emphasis on sustainability assessment methods and outcomes. A systematic literature search was conducted across major scientific databases using predefined keywords and inclusion criteria, spanning studies on recycled polymer incorporation in asphalt, concrete, geosynthetics, and other structural and non-structural elements. Key environmental assessment frameworks—principally life cycle assessment (LCA), carbon footprinting, and life cycle cost analysis—are synthesized to elucidate methodological trends, impact categories, and system boundaries employed in current research. The review highlights consistent evidence that recycled plastics can reduce embodied energy and greenhouse gas emissions relative to conventional materials, particularly when replacing virgin aggregates or polymer modifiers. However, results vary significantly across applications due to differences in material properties, processing requirements, and assessment assumptions. Critical challenges identified include inconsistent LCA boundary definitions, limited field-based performance data, and a paucity of regionally calibrated impact factors. Research gaps and future directions are discussed, underscoring the need for standardized assessment protocols and multi-criteria sustainability frameworks. This review aims to inform researchers, practitioners, and policymakers on the environmental implications of recycled plastic deployment in sustainable infrastructure development.*

Key Words: Recycled plastics, life cycle assessment, civil infrastructure, environmental performance, sustainability analysis, polymer waste utilization.

1. INTRODUCTION

1.1 Background

1.1.1 Plastic Pollution and Waste Management Challenges Globally

The production and consumption of plastics have risen exponentially over the past decades, resulting in an unprecedented accumulation of plastic waste in terrestrial and marine environments. Despite global efforts to promote recycling, only a small fraction of the annual plastic output is effectively reprocessed; recent assessments indicate that less than 10% of plastics produced globally originate from recycled sources, while the majority persist in landfills or the natural environment, exacerbating ecological contamination and human health risks (The Guardian, 2025). Plastics' long degradation times lead to the release of microplastics, which infiltrate soils, water bodies, and food chains, prompting calls for more sustainable waste management strategies that extend beyond disposal and incineration to reuse and material substitution.

1.1.2 Importance of Civil Infrastructure in Material Consumption

Civil infrastructure, including roads, bridges, buildings, and drainage systems, represents one of the largest industrial consumers of raw materials worldwide. Traditional construction practices depend heavily on finite resources such as aggregates, cement, and steel, whose extraction and processing are associated with significant environmental burdens. As societal infrastructure expands to meet growing population and economic demands, the environmental footprint of material production and consumption continues to escalate, driving research toward alternative materials that can reduce resource depletion and lifecycle impacts.

1.1.3 Role of Recycled Plastics as Alternative Construction Materials

Within this context, recycled plastics have emerged as a promising class of alternative construction materials due to their durability, low density, and resistance to moisture and chemical degradation. Studies show that various recycled polymers, notably PET, HDPE, and PP, can be incorporated in concrete, asphalt, geosynthetics, and other civil engineering elements, not only diverting waste from landfills but also enhancing certain performance attributes such as insulation or flexibility (Das & Ali, 2025; Lopes et al., 2025). The integration of recycled plastics into infrastructure aligns with circular economy principles, potentially reducing demand for virgin resources and mitigating lifecycle environmental impacts when appropriately applied.

1.2 Problem Statement

1.2.1 Why Environmental Performance Assessment Is Critical

While the technical feasibility of using recycled plastics in infrastructure has been well documented, understanding their environmental performance is equally critical. Lifecycle assessment (LCA) frameworks provide structured methods to quantify environmental impacts across production, use, and end-of-life stages, enabling comparisons between conventional materials and recycled alternatives. Without rigorous environmental performance analysis, decisions about material selection risk overlooking trade-offs such as increased energy use during processing, differences in durability, or unintended emissions related to microplastic release. As such, comprehensive environmental metrics are necessary to evaluate whether recycled plastic pathways genuinely contribute to sustainability goals (MDPI, 2023; ScienceDirect, 2023).

1.3 Scope and Objectives of the Review

1.3.1 What Aspects of Plastic Recycling and Environmental Analysis Are Covered

This review focuses on synthesizing existing research on the environmental performance of recycled plastic utilization in civil infrastructure systems. It encompasses studies that evaluate recycled plastic applications in structural and non-structural components, with emphasis on environmental impacts assessed through methodologies such as life cycle assessment (LCA), carbon footprinting, and other sustainability indicators. By systematically organizing results from global literature, the review aims to characterize common application pathways, highlight areas of consensus and divergence, and identify methodological challenges in environmental assessment.

1.3.2 Boundaries (Types of Plastics, Infrastructure Applications, Assessment Methods)

The review's scope includes a broad range of thermoplastic materials commonly encountered in municipal and industrial waste streams—such as PET, HDPE, LDPE, and PP—given their prevalent recycling potential and documented use in civil engineering applications. Infrastructure applications examined include recycled plastic incorporation in asphalt mixtures, concrete composites, geosynthetics, and other building elements. Environmental analysis methods considered comprise cradle-to-grave LCA, carbon emission accounting, and sustainability trade-off analyses, with critical evaluation of assessment boundaries, functional units, and data sources in the reviewed literature.

2. METHODOLOGY FOR LITERATURE SEARCH

2.1 Importance for Transparency and Reproducibility

A clear and systematic literature search methodology is essential in a review paper because it ensures that the process of identifying, selecting, and analyzing studies is transparent, reproducible, and unbiased. Without a documented strategy, readers and reviewers cannot assess whether the review's conclusions are based on a comprehensive and objective sampling of the literature. In systematic reviews, protocols such as PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) are often applied to structure the search, selection, and reporting process, making it easier to demonstrate rigor and repeatability in research synthesis practices (Wikipedia, 2025).

2.2 Databases Searched

To compile a comprehensive body of evidence on environmental performance analysis of recycled plastics in civil infrastructure, the choice of databases plays a pivotal role. Core scholarly databases such as Scopus, Web of Science, and Google Scholar are commonly used due to their extensive coverage of peer-reviewed journals across engineering and environmental sciences. Scopus and Web of Science index high-impact journals and allow advanced filtering by discipline, publication year, and document type, while Google Scholar provides broader retrieval including conference proceedings and reports, which can be important in interdisciplinary areas. Some reviews also include specialized sources such as Engineering Village or ScienceDirect where relevant subject matter is concentrated (e.g., environmental engineering, infrastructure materials) to ensure that key studies are not omitted.

2.3 Search Strings and Keywords

The literature search employs carefully constructed search strings that combine key terms using Boolean operators (AND, OR) to capture all relevant literature while minimizing irrelevant results. For a topic focused on environmental performance and recycled plastic utilization, representative terms might include "recycled plastics", "plastic waste", "civil infrastructure", "life cycle assessment", "environmental impact", and "sustainability". String combinations (e.g., "recycled plastic" AND "life cycle assessment" AND "asphalt") are used to focus on specific aspects of the topic. Using both broad and narrow keyword sets in combination increases the probability of retrieving diverse relevant studies while maintaining focus on environmental performance evaluation methodologies.

2.4 Selection and Screening Criteria (Inclusion/Exclusion)

After the initial search yields a large set of potential studies, screening criteria are applied to refine the corpus to studies pertinent to the research question. Inclusion criteria typically require that articles are peer-reviewed, published in English, and focus directly on environmental performance or life cycle analysis related to recycled plastics in civil engineering materials and systems. Exclusion criteria help remove non-relevant studies, such as publications that do not evaluate environmental impacts or that are outside the defined infrastructure applications. For example, articles solely discussing plastic recycling technologies without connection to infrastructure performance would be excluded. Some reviews also eliminate non-scientific sources like press releases or blog posts to maintain academic rigor (MyCumbria, 2025).

2.5 Time Period

The time period for the literature search defines the temporal scope of the review and ensures that the synthesis reflects contemporary scientific understanding. For many environmental performance topics, research published in the last two decades (e.g., 2005–present, or up to the most recent year) is considered to capture major developments in LCA methods and recycled material applications. Establishing a publication date range also helps manage volume, focusing the analysis on literature that reflects current standards, technologies, and methodological advancements in sustainability assessment.

2.6 Number of Articles Included

The initial database search often returns a large number of articles, which are then narrowed through screening to a more focused set of studies that meet all selection criteria. Through iterative screening of titles, abstracts, and full texts, the final set of included articles represents those with rigorous environmental assessment data or relevant synthesis findings that contribute directly to the review topic. Systematic reviews in related fields often reduce thousands of preliminary results to a few dozen or a few hundred highly relevant papers after screening. This ensures both depth and focus in the critical analysis of environmental performance of recycled plastic pathways in civil infrastructure.

3. OVERVIEW OF RECYCLED PLASTIC UTILIZATION IN CIVIL INFRASTRUCTURE

3.1 Types of Recycled Plastics Used

3.1.1 Common Plastic Types

Several types of recycled plastics are employed in civil infrastructure, including polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), mixed plastics, and composite blends. PET is widely used due to its rigidity and strength, making it suitable for incorporation into concrete and composite materials. HDPE and LDPE are flexible and chemically resistant, often applied in asphalt modification or drainage systems. PP offers a good balance of strength and low density, lending itself to geosynthetics and pavement blocks. Mixed plastics and polymer composites, derived from municipal waste streams, provide opportunities to utilize otherwise non-recyclable materials, although they present challenges in standardization and performance predictability (Das & Ali, 2025; Lopes et al., 2025).

3.1.2 Physical and Mechanical Characteristics

The physical and mechanical properties of these plastics—such as tensile strength, modulus of elasticity, melting point, and chemical resistance—dictate their suitability for specific infrastructure applications. For instance, PET exhibits high tensile strength and dimensional stability, which is advantageous when used as partial aggregate replacement in concrete or as fibers in reinforced composites. HDPE and LDPE, being softer and more ductile, improve flexibility when incorporated into bitumen or asphalt mixtures. PP's combination of toughness and low density facilitates its use in lightweight geosynthetic mats and drainage pipes. Understanding these characteristics is crucial for ensuring that recycled plastic incorporation does not compromise structural performance while maximizing environmental benefits (Shah et al., 2023).

3.2 Common Infrastructure Applications

3.2.1 Asphalt Modification

Recycled plastics have been extensively applied in asphalt modification, where polymer additives improve binder properties such as rutting resistance, thermal stability, and durability. Plastic-modified bitumen can utilize shredded PET, LDPE, or PP as partial substitutes for conventional polymers or aggregates. Studies indicate that such modifications not only enhance road performance but also reduce environmental burdens by diverting waste plastics from landfills (Ali et al., 2024).

3.2.2 Concrete and Composite Materials

In concrete and cementitious composites, shredded or pelletized plastics are incorporated either as fibers or partial replacements for fine and coarse aggregates. Applications include structural and non-structural elements such as pavements, blocks, and precast panels. The addition of plastic can enhance toughness, impact resistance, and freeze–thaw durability, although excessive content may reduce compressive strength (Lopes et al., 2025).

3.2.3 Geosynthetics and Drainage Solutions

Geosynthetics, including mats, meshes, and drainage pipes made from recycled plastics, play a vital role in soil stabilization, erosion control, and water management. HDPE and PP dominate in this domain due to their chemical resistance and durability under load. Use of recycled materials in geosynthetics contributes to circular economy objectives while maintaining functional performance comparable to virgin materials (Shah et al., 2023).

3.2.4 Pavement Blocks, Bricks, and Tiles

Recycled plastics are increasingly incorporated in pavement blocks, bricks, and tiles, either as polymer-modified aggregates or as binding agents. This application is particularly relevant for non-structural surfaces such as sidewalks, walkways, and landscaping areas, where plastics enhance resistance to water absorption, wear, and deformation (Das & Ali, 2025).

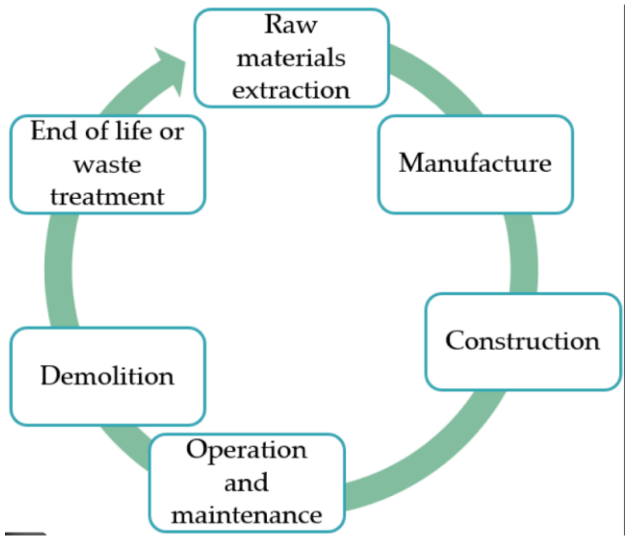

Figure-1: Paved Road Life Cycle Phases

3.3 Standard Specifications and Practices

3.3.1 Codes and Standards

The use of recycled plastics in infrastructure is guided by national and international codes and standards that ensure safety, durability, and environmental compliance. For example, ASTM and ISO provide specifications for polymer-modified bitumen, concrete admixtures, and geosynthetics, while several countries, including India and the UK, have adopted guidelines for incorporating plastic waste into roads and construction materials. Compliance with these standards is critical for achieving structural integrity, reproducibility of material properties, and environmental performance targets (Ali et al., 2024; Lopes et al., 2025).

4. ENVIRONMENTAL PERFORMANCE ASSESSMENT METHODS

4.1 Life Cycle Assessment (LCA)

4.1.1 Cradle-to-Gate and Cradle-to-Grave Approaches

Life Cycle Assessment (LCA) is the most widely used framework to evaluate the environmental performance of materials, including recycled plastics in civil infrastructure. LCA systematically quantifies environmental impacts across the entire life cycle of a product, from raw material extraction to end-of-life disposal. Two common approaches are cradle-to-gate—which evaluates impacts from raw material acquisition up to the factory gate before use—and cradle-to-grave, which encompasses the full lifecycle including construction, use, maintenance, and disposal phases. For infrastructure applications, cradle-to-grave assessment is particularly valuable as it captures the long-term environmental consequences of incorporating recycled plastics in roads, concrete, or geosynthetics (Shah et al., 2023).

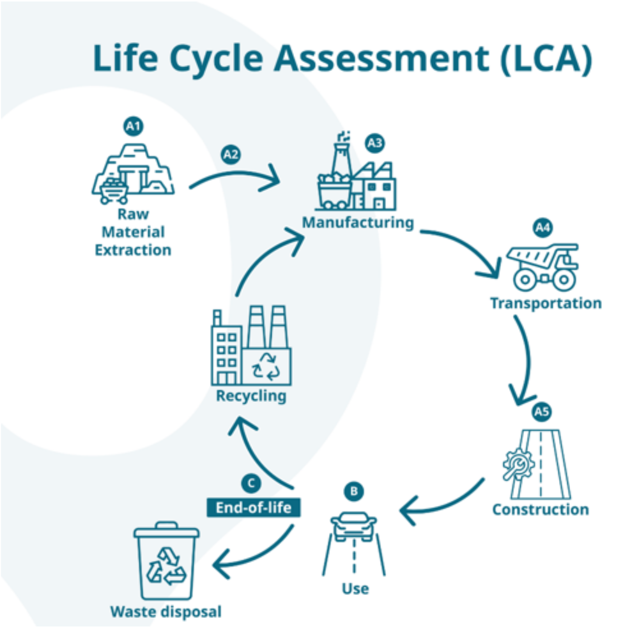

Figure-2: Life Cycle Assessment (LCA) Stages in Road Construction

4.1.2 Impact Categories

LCA analyses consider multiple impact categories. Key metrics include global warming potential (GWP), which measures greenhouse gas emissions; energy use, representing embodied and operational energy; and water footprint, which quantifies freshwater consumption. Additional categories, such as acidification, eutrophication, and human toxicity, may be included depending on study scope. Evaluating these categories helps compare environmental burdens between conventional and recycled-plastic-inclusive materials, supporting evidence-based sustainability decisions (Das & Ali, 2025).

4.2 Carbon Footprint Analysis

Carbon footprint analysis is a targeted assessment of greenhouse gas emissions across the life cycle of a product or system. This method complements LCA by providing a simplified, focused metric for policymakers and practitioners interested primarily in climate change mitigation. In the context of recycled plastics, carbon footprinting quantifies emission reductions achievable by substituting virgin aggregates or polymers, highlighting the potential climate benefits of circular material strategies (Lopes et al., 2025).

4.3 Lifecycle Cost Assessment (LCCA) Linked to Environmental Impact

Lifecycle Cost Assessment (LCCA) integrates economic considerations with environmental impacts to evaluate the long-term feasibility of material choices. By including initial construction costs, maintenance, durability, and end-of-life disposal, LCCA allows decision-makers to identify cost-effective strategies that minimize environmental burdens while meeting performance requirements. For recycled plastic applications, LCCA can reveal trade-offs between upfront material costs and lifecycle savings or environmental benefits, guiding sustainable procurement (Ali et al., 2024).

4.4 Other Sustainability Indicators

Beyond LCA, carbon footprint, and LCCA, additional sustainability indicators provide complementary insights. Circularity metrics measure the proportion of recycled or reused material in a system, reflecting progress toward a circular economy. Eco-efficiency indicators relate environmental impact to functional performance, enabling comparison between different material options on a normalized basis. Incorporating these metrics facilitates holistic evaluation of recycled plastic applications, aligning environmental and resource efficiency objectives (Shah et al., 2023).

4.5 Comparison of Methods

Each assessment method has strengths, limitations, and applicability. LCA offers comprehensive, multi-dimensional environmental analysis but can be data-intensive and sensitive to system boundary choices. Carbon footprinting is simpler and more accessible but does not capture non-climatic impacts such as water use or toxicity. LCCA incorporates economic dimensions but may require assumptions about future costs or service life. Circularity and eco-efficiency metrics provide complementary sustainability insights but are less standardized. Combining these methods often provides the most robust understanding of environmental performance, particularly for novel materials like recycled plastics in civil infrastructure (Das & Ali, 2025; Lopes et al., 2025).

5. LITERATURE REVIEW: ENVIRONMENTAL PERFORMANCE OF RECYCLED PLASTIC PATHWAYS

5.1 Asphalt and Pavement Systems

5.1.1 Summary of Key Studies

Recycled plastics have been extensively incorporated into asphalt and pavement systems, primarily as polymer modifiers in bitumen or as partial substitutes for aggregates. Shah et al. (2023) reviewed applications of PET, LDPE, and PP in asphalt, noting improvements in rutting resistance and thermal stability. Similarly, Das and Ali (2025) reported that shredded plastics in hot mix asphalt enhance fatigue life while providing a sustainable outlet for municipal plastic waste. Studies vary in scope, including laboratory-scale evaluations of material properties and pilot-scale road construction projects.

5.1.2 Environmental Outcomes and Performance Indicators

Environmental performance is typically assessed using LCA and carbon footprinting. Recycled plastic-modified asphalt generally reduces greenhouse gas emissions and energy consumption relative to conventional asphalt due to displacement of virgin bitumen and aggregates. Water usage and embodied energy are also often lower, particularly when plastics originate from post-consumer waste streams (Lopes et al., 2025).

5.1.3 Comparative Analysis with Conventional Materials

Comparisons consistently show that plastic-modified pavements offer both performance and environmental advantages, though the magnitude of benefits depends on plastic type, content, and processing methods. However, inconsistencies arise due to differences in functional units, boundary definitions, and long-term durability assumptions across studies.

5.2 Concrete and Cementitious Composites

5.2.1 Effect on Embodied Carbon

Incorporating recycled plastics in concrete—either as fibers or aggregate replacements—can significantly reduce embodied carbon, primarily by substituting energy-intensive virgin aggregates (Shah et al., 2023). PET fibers in structural concrete, for instance, decrease GWP per cubic meter while providing crack resistance.

5.2.2 Durability vs Environmental Trade-offs

While environmental benefits are notable, excessive plastic inclusion can reduce compressive strength and alter durability. LCA studies indicate a trade-off: optimized low-percentage incorporation improves sustainability without compromising structural performance, but higher proportions may require additional maintenance or replacement, partially offsetting gains (Das & Ali, 2025).

5.2.3 LCA Results Across Studies

Life cycle analyses report up to 20–30% reductions in CO_2 emissions and energy consumption when recycled plastics partially replace fine or coarse aggregates. However, outcomes vary by geographic region, electricity mix, and end-of-life assumptions.

5.3 Geosynthetics and Infrastructure Elements

5.3.1 Environmental Performance in Soil Stabilization and Erosion Control

Recycled plastics are widely applied in geosynthetics such as meshes, mats, and drainage pipes for soil stabilization and erosion prevention. HDPE and PP-based geosynthetics demonstrate high chemical and mechanical stability, allowing long service life and reduced replacement frequency (Lopes et al., 2025). LCA assessments show lower lifecycle environmental impacts compared with conventional soil stabilization methods.

5.3.2 Long-Term Sustainability Benefits

The use of recycled plastics in geosynthetics supports circular economy principles, reduces waste volumes, and contributes to resource efficiency. Their durability minimizes environmental burdens from frequent maintenance or material replacement.

5.4 System-Level Assessments (Infrastructure Projects)

5.4.1 Life Cycle Performance of Plastic-Inclusive Roads and Bridges

Several studies evaluate infrastructure projects as integrated systems. Shah et al. (2023) analyzed plastic-modified roads from construction to end-of-life, reporting significant reductions in embodied energy and GHG emissions. Similarly, Das and Ali (2025) highlighted regional case studies where recycled plastics in bridges and pavements reduced landfill loads and material costs.

5.4.2 Case Studies and Regional Analyses

Environmental outcomes vary across regions due to electricity mix, transport distances, and local waste management practices. Case studies in Europe and India illustrate how locally sourced recycled plastics provide higher environmental benefits due to minimized transportation emissions.

5.5 Critical Synthesis

5.5.1 Patterns and Trends

Across the literature, patterns indicate that recycled plastic integration consistently reduces carbon footprint and energy consumption when used as partial substitutes in asphalt, concrete, and geosynthetics. Low-to-moderate inclusion rates often optimize both performance and sustainability.

5.5.2 Conflicting Results and Reasons

Variability in outcomes arises from methodological differences, such as LCA system boundaries, functional units, and material processing assumptions. Inconsistent reporting of durability and end-of-life scenarios further contributes to conflicting findings.

5.5.3 Gaps Identified in Current Research

Key gaps include limited long-term field performance data, insufficient standardization of recycled plastic grades, and lack of regionalized environmental impact factors. Future research should integrate multi-criteria sustainability assessments, standardized LCA protocols, and lifecycle cost analysis to provide robust guidance for infrastructure planners.

6. DISCUSSION

6.1 Interpretation of Key Findings

6.1.1 Environmental Benefits of Recycled Plastics

The literature consistently demonstrates that the inclusion of recycled plastics in civil infrastructure reduces environmental impacts across multiple metrics. Life cycle assessments indicate reductions in greenhouse gas emissions, embodied energy, and water consumption compared to conventional materials. Asphalt modified with recycled polymers, plastic-reinforced concrete, and geosynthetics derived from HDPE and PP not only provide technical functionality but also divert waste plastics from landfills, aligning with circular economy objectives (Shah et al., 2023; Das & Ali, 2025).

6.1.2 Technical and Performance Considerations

Despite environmental gains, technical limitations must be considered. Excessive plastic content in concrete can reduce compressive strength and durability, while improper processing in asphalt may lead to segregation or reduced rutting resistance. Similarly, heterogeneity in mixed plastic streams can affect the mechanical performance of geosynthetics. Therefore, optimizing plastic type, particle size, and inclusion rate is critical to achieving both performance and sustainability objectives (Lopes et al., 2025).

6.2 Influence of Geographic and Socioeconomic Contexts

Environmental performance outcomes are sensitive to regional and socioeconomic factors. Electricity grids with high renewable penetration reduce the carbon intensity of processing recycled plastics, while transport distances and local waste management practices influence overall energy use and emissions. Additionally, developing countries with limited recycling infrastructure may face challenges in sourcing consistent-quality recycled plastics, potentially affecting both performance and environmental benefits (Ali et al., 2024). These findings highlight the need for context-specific strategies in planning plastic-inclusive infrastructure projects.

6.3 Challenges in Current Assessment Practices

Several methodological challenges hinder consistent evaluation of environmental performance. Variability in system boundaries, functional units, and life cycle assumptions leads to discrepancies across studies. Limited field-based data and short-term laboratory testing make it difficult to capture long-term durability and maintenance impacts. Furthermore, few studies incorporate comprehensive social and economic sustainability indicators alongside environmental metrics, restricting holistic assessment (Shah et al., 2023).

6.4 Standardization Needs for Comparative Analysis

To address these challenges, standardized protocols for material characterization, LCA methodology, and functional units are essential. International standards such as ASTM, ISO, and regional guidelines can provide frameworks for consistent reporting. Standardization would enable meaningful comparisons between studies, facilitate policy development, and guide practitioners in selecting recycled plastic materials that optimize both environmental and performance outcomes (Das & Ali, 2025; Lopes et al., 2025).

7. CONCLUSION

This review critically examined the environmental performance of recycled plastic utilization pathways in civil infrastructure, synthesizing findings across asphalt, concrete, geosynthetics, and system-level applications. Evidence from life cycle assessments, carbon footprint analyses, and sustainability indicators consistently demonstrates that integrating recycled plastics can significantly reduce greenhouse gas emissions, embodied energy, and overall resource consumption compared with conventional construction materials. In asphalt pavements, the incorporation of PET, LDPE, and PP enhances durability, rutting resistance, and thermal stability while mitigating environmental burdens. Similarly, in concrete and cementitious composites, low-to-moderate inclusion rates of shredded plastics or polymer fibers reduce embodied carbon without compromising structural integrity. Geosynthetic applications further illustrate the long-term sustainability benefits of recycled plastics, enabling soil stabilization, drainage, and erosion control while diverting waste from landfills. System-level assessments of roads, bridges, and infrastructure projects confirm that plastic-inclusive designs can achieve measurable lifecycle environmental advantages, particularly when regional energy mixes and waste management practices are optimized.

Despite these benefits, the review highlights that environmental performance is strongly influenced by material type, processing techniques, and inclusion rates, underscoring the importance of standardized assessment methodologies. Geographic and socioeconomic contexts also play a critical role, with outcomes varying depending on energy grids, transportation distances, and availability of high-quality recycled plastics. Overall, the integration of recycled plastics into civil infrastructure aligns with circular economy principles, offering both environmental and material efficiency advantages. However, to fully realize these benefits, consistent evaluation frameworks, long-term performance monitoring, and region-specific LCA data are essential. This review provides a consolidated understanding of current practices and identifies key pathways for sustainable adoption of recycled plastics in infrastructure systems, informing researchers, policymakers, and industry practitioners seeking to balance technical performance with environmental stewardship.

7.1. Limitations of the Review

This review has several limitations that must be acknowledged. First, the analysis relied predominantly on published literature in English, potentially excluding relevant studies from non-English sources or gray literature. Second, variability in LCA methodologies, functional units, and system boundaries across studies limits direct comparability of results, reducing the precision of synthesized conclusions. Third, most studies focus on laboratory-scale or short-term applications, with limited field-based performance data, which constrains understanding of long-term durability and maintenance implications. Fourth, socioeconomic and regional factors were considered only qualitatively due to insufficient quantitative data, limiting the assessment of context-specific environmental outcomes. Finally, the review emphasizes environmental metrics such as greenhouse gas emissions and embodied energy, while social and economic dimensions of sustainability received less attention. These limitations highlight the need for standardized assessment protocols, comprehensive data collection, and integrated multi-criteria evaluations in future research.

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