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

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Abstract: *The rapid growth of plastic waste has emerged as a critical environmental challenge, necessitating sustainable management strategies that align with circular economy principles. This study investigates the environmental performance of recycled plastic utilization pathways in civil infrastructure systems, focusing on plastic-modified bituminous roads, plastic aggregate concrete, and geotechnical applications. A comprehensive Life Cycle Assessment (LCA) approach is employed to evaluate key environmental indicators, including Global Warming Potential (GWP), energy consumption, and resource depletion, using a cradle-to-grave system boundary. Standard functional units such as 1 km of road, 1* m^3 *of concrete, and 1* m^3 *of stabilized soil are adopted to ensure consistency and comparability. The results indicate that plastic-modified asphalt demonstrates the most significant environmental benefits, primarily due to reduced bitumen consumption and lower greenhouse gas emissions. Plastic aggregate concrete shows moderate environmental improvements, while geotechnical applications offer localized sustainability advantages. However, trade-offs such as energy use during processing and potential microplastic release are identified. The study provides a comparative framework for evaluating sustainability across multiple pathways and supports informed decision-making for infrastructure development. The findings highlight the potential of recycled plastics to reduce environmental impacts while improving material efficiency in civil engineering applications.*

Key Words: Recycled plastics; Life Cycle Assessment; Sustainable infrastructure; Plastic-modified asphalt; Environmental impact; Circular economy; Carbon footprint; Civil engineering materials

1. INTRODUCTION

1.1 Background

1.1.1 Global Plastic Waste Crisis

The exponential growth in plastic production over recent decades has resulted in a severe global waste management challenge. Plastics are widely used due to their durability, versatility,and low cost; however, these same properties contribute to their persistence in the environment. Global plastic production has exceeded 400 million tonnes annually, with a significant proportion consisting of single-use plastics that are discarded after a short lifecycle. A large fraction of this waste is either landfilled, incinerated, or leaked into natural ecosystems, leading to long-term environmental degradation. The accumulation of plastic waste in oceans and terrestrial environments has intensified concerns regarding biodiversity loss, ecosystem disruption, and the proliferation of microplastics, which can enter the food chain and pose risks to human health (Geyer et al., 2017).

1.1.2 Environmental Concerns and Need for Sustainable Materials

The environmental implications of plastic waste extend beyond pollution, encompassing greenhouse gas emissions, resource depletion, and ecological imbalance. Conventional waste management practices such as landfilling and incineration are increasingly viewed as unsustainable due to their associated environmental impacts, including soil contamination and air pollution. Simultaneously, the construction industry is recognized as a major contributor to global environmental degradation through intensive consumption of natural resources and high carbon emissions, particularly from cement and aggregate production. In this context, the integration of recycled materials, especially plastics, into civil engineering applications offers a promising pathway toward sustainability. Such approaches align with circular economy principles by promoting resource efficiency, waste minimization, and reduced environmental footprint (Hopewell et al., 2009).

1.2 Recycled Plastics in Civil Engineering

1.2.1 Types of Recycled Plastics (PET, HDPE, LDPE, PP)

Recycled plastics used in civil engineering are predominantly thermoplastics, which can be reprocessed and remoulded without significant alteration in their chemical structure. Among these, Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), and Polypropylene (PP) are the most commonly utilized materials. PET is known for its high tensile strength and stiffness, making it suitable for fiber reinforcement in concrete. HDPE exhibits excellent chemical resistance and durability, enabling its use in geosynthetics and piping systems. LDPE, characterized by its flexibility, is frequently used in bituminous mixes to improve binding properties, while PP is valued for its fatigue resistance and is widely applied in fiber-reinforced composites. The selection of plastic type depends on the desired engineering performance and application requirements (Alqahtani et al., 2022).

1.2.2 Major Infrastructure Applications

Recycled plastics have been successfully incorporated into various civil infrastructure systems through multiple application pathways. One of the most prominent uses is in road construction, where plastic waste is blended with bitumen to produce plastic-modified asphalt with enhanced durability and resistance to deformation. In concrete technology, recycled plastics are used either as partial replacements for natural aggregates or as reinforcing fibers, contributing to reduced material density and improved crack resistance. Additionally, in geotechnical engineering, plastics are employed in soil stabilization and reinforcement applications, where they enhance load-bearing capacity and reduce settlement. These applications demonstrate the versatility of recycled plastics in addressing both engineering performance and environmental sustainability challenges (Kumar and Garg, 2021).

1.3 Research Gap

1.3.1 Lack of Lifecycle-Based Environmental Assessment

Despite the increasing adoption of recycled plastics in construction, existing research has largely focused on mechanical and structural performance, with comparatively limited attention given to environmental impacts across the lifecycle. Most studies evaluate short-term engineering benefits without considering upstream and downstream processes such as material processing, transportation, and end-of-life disposal. This lack of comprehensive lifecycle-based assessment restricts the ability to accurately quantify the environmental benefits and trade-offs associated with recycled plastic applications. The application of standardized methodologies such as Life Cycle Assessment (LCA) remains limited, leading to fragmented and incomplete evaluations of sustainability (ISO 14040, 2006).

1.3.2 Limited Comparative Studies Across Utilization Pathways

Another significant research gap is the scarcity of comparative studies that evaluate multiple recycled plastic utilization pathways within a unified analytical framework. While individual applications such as plastic-modified asphalt or plastic aggregate concrete have been studied independently, there is a lack of integrated research comparing their environmental performance under consistent conditions. This limitation makes it difficult to identify the most sustainable and efficient pathway for large-scale implementation. A systematic comparative analysis is essential to understand trade-offs between different applications and to support informed decision-making in infrastructure development (Guinée et al., 2011).

1.4 Research Objectives

1.4.1 Identification of Utilization Pathways

The first objective of this study is to identify and categorize the major pathways through which recycled plastics can be utilized in civil infrastructure systems. This involves examining existing applications such as road construction, concrete production, and geotechnical engineering, with a focus on their technical feasibility, scalability, and relevance to current construction practices.

1.4.2 Environmental Performance Assessment Using LCA

The second objective is to evaluate the environmental performance of these utilization pathways using Life Cycle Assessment (LCA). This methodology provides a systematic framework for quantifying environmental impacts across the entire lifecycle, including material production, processing, use, and disposal. Key indicators such as Global Warming Potential, energy consumption, and resource depletion are considered to ensure a comprehensive assessment.

1.4.3 Comparative Sustainability Evaluation

The final objective is to perform a comparative sustainability evaluation of the selected pathways by integrating environmental and engineering performance indicators. This analysis aims to identify the most sustainable option by considering both benefits and trade-offs, thereby supporting evidence-based decision-making for the adoption of recycled plastics in civil infrastructure systems.

2. LITERATURE REVIEW

2.1 Plastic Waste and Environmental Challenges

2.1.1 Global and Indian Scenario

The rapid increase in plastic production has led to a parallel rise in plastic waste generation, creating a significant environmental burden worldwide. Globally, plastic production has surpassed 400 million tonnes annually, with a considerable proportion consisting of short-lived products that quickly enter the waste stream. Inefficient waste management systems, particularly in developing countries, have resulted in large quantities of plastic being mismanaged and leaking into natural ecosystems. In India, the situation is equally critical due to rapid urbanization, population growth, and changing consumption patterns. The country generates millions of tonnes of plastic waste each year, a substantial portion of which remains uncollected or improperly disposed of. Although regulatory frameworks such as Plastic Waste Management Rules have been introduced, challenges related to segregation, recycling infrastructure, and public awareness persist, limiting effective waste utilization (CPCB, 2022).

2.1.2 Environmental Impacts

Plastic waste poses severe environmental risks across terrestrial and aquatic ecosystems. Due to its non-biodegradable nature, plastic persists in the environment for extended periods, leading to accumulation in landfills, rivers, and oceans. This accumulation adversely affects wildlife through ingestion and entanglement, while also disrupting natural habitats. Additionally, the fragmentation of plastics into microplastics has emerged as a major concern, as these particles can enter the food chain and potentially impact human health. Conventional disposal methods such as open burning and incineration release toxic pollutants and greenhouse gases, contributing to air pollution and climate change. These environmental challenges highlight the urgent need for sustainable waste management strategies and innovative reuse approaches (Rochman et al., 2013).

2.2 Recycled Plastic Applications in Infrastructure

2.2.1 Asphalt and Pavements

The use of recycled plastics in asphalt and pavement construction is one of the most widely adopted and successful applications in civil engineering. Plastic-modified bitumen involves the incorporation of shredded plastic waste into asphalt mixtures, either through dry or wet processes. This modification enhances the binding properties of bitumen and improves the mechanical performance of pavements, including resistance to rutting, cracking, and moisture damage. Field implementations, particularly in countries like India, have demonstrated improved durability and extended service life of plastic roads. The ability to utilize large volumes of waste plastic in road construction makes this application highly attractive from both environmental and economic perspectives (Vasudevan et al., 2012).

2.2.2 Concrete Applications

Recycled plastics are increasingly being explored as alternative materials in concrete production, either as partial replacements for natural aggregates or as reinforcing fibers. The inclusion of plastic aggregates reduces the density of concrete and contributes to resource conservation by minimizing the use of natural materials. Plastic fibers, on the other hand, enhance crack resistance, ductility, and impact strength. However, the incorporation of plastics may lead to a reduction in compressive strength if used in excessive quantities, primarily due to weaker bonding with the cement matrix. Despite these challenges, plastic-modified concrete offers potential environmental benefits, particularly in reducing waste and conserving raw materials (Alqahtani et al., 2022).

2.2.3 Geotechnical Applications

In geotechnical engineering, recycled plastics are utilized for soil stabilization and reinforcement purposes. Plastic strips, fibers, and geosynthetics are incorporated into soil to improve its shear strength, reduce settlement, and enhance load-bearing capacity. Materials such as HDPE and PP are commonly used in geotextiles and geomembranes for applications including embankments, retaining structures, and landfill liners. These applications are particularly beneficial in weak or expansive soils, where traditional stabilization methods may be less effective or more costly. The use of recycled plastics in geotechnics not only improves engineering performance but also provides an effective solution for waste utilization (Kumar and Garg, 2021).

2.3 Environmental Assessment Techniques

2.3.1 Life Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts of materials and processes throughout their entire lifecycle, from raw material extraction to final disposal. It provides a comprehensive framework for assessing sustainability by considering all stages, including production, transportation, use, and end-of-life management. LCA is standardized under international guidelines and is widely applied in civil engineering to compare alternative materials and technologies. By quantifying environmental impacts across multiple categories, LCA enables researchers and practitioners to identify trade-offs and make informed decisions regarding sustainable material selection (ISO 14040, 2006).

2.3.2 Environmental Indicators (GWP, Energy, Toxicity)

Environmental impact assessment within LCA relies on specific indicators that quantify different aspects of sustainability. Global Warming Potential (GWP) is one of the most critical indicators, measuring greenhouse gas emissions in terms of carbon dioxide equivalents. Energy consumption is another key parameter, reflecting the total energy required across the lifecycle of a material or process. Additionally, toxicity indicators evaluate the potential impacts on human health and ecosystems due to the release of hazardous substances. These indicators collectively provide a comprehensive understanding of environmental performance and enable comparison between conventional and alternative materials in infrastructure applications (Finnveden et al., 2009).

2.4 Comparative Studies and Existing Findings

2.4.1 Performance vs Sustainability Trade-offs

Existing studies on recycled plastic applications highlight a complex relationship between engineering performance and environmental sustainability. While plastic-modified asphalt has consistently demonstrated superior durability and reduced maintenance requirements, its environmental benefits depend on factors such as processing methods and transportation distances. In concrete applications, the use of recycled plastics contributes to resource conservation but may compromise mechanical strength at higher replacement levels. Similarly, geotechnical applications offer localized improvements in soil performance but require further validation for large-scale implementation. These findings indicate that no single application universally outperforms others across all criteria; instead, each pathway involves trade-offs between performance, cost, and environmental impact. Therefore, a comprehensive comparative framework is essential to evaluate these trade-offs and identify the most sustainable solutions for infrastructure development (Guinée et al., 2011).

3. MATERIALS AND METHODS

3.1 Research Framework

3.1.1 Quantitative and Comparative Approach

The present study adopts a quantitative and comparative research framework to evaluate the environmental performance of recycled plastic utilization pathways in civil infrastructure systems. A quantitative approach enables the systematic measurement of environmental indicators such as emissions, energy consumption, and resource use, ensuring objectivity and reproducibility of results. The comparative nature of the study facilitates the evaluation of multiple application pathways—namely plastic-modified bitumen, plastic aggregate concrete, and geotechnical applications—under consistent conditions. This approach ensures that the performance of each pathway can be assessed relative to others using standardized metrics, thereby enabling a robust evaluation of sustainability.

3.1.2 Integration of Engineering and Environmental Analysis

A key feature of the research framework is the integration of engineering performance with environmental assessment. While environmental indicators provide insights into sustainability, engineering parameters such as durability, strength, and workability are essential for practical implementation in infrastructure systems. The study therefore combines Life Cycle Assessment (LCA) with engineering considerations to develop a holistic evaluation framework. This integrated approach ensures that materials are not only environmentally beneficial but also technically viable, thereby supporting informed decision-making in civil engineering practice.

3.2 Selection of Utilization Pathways

3.2.1 Plastic-Modified Bitumen

Plastic-modified bitumen is selected as one of the primary utilization pathways due to its widespread adoption and proven performance in road construction. In this method, shredded plastic waste is incorporated into bituminous mixes, improving binding properties and enhancing resistance to rutting, cracking, and moisture damage. The ability to utilize significant quantities of waste plastic and its compatibility with existing construction practices make this pathway highly relevant for large-scale implementation.

3.2.2 Plastic Aggregate Concrete

The second pathway involves the use of recycled plastics in concrete, either as partial replacements for natural aggregates or as reinforcing fibers. This approach contributes to resource conservation by reducing dependence on conventional materials while offering potential improvements in certain mechanical properties such as crack resistance. However, the performance of plastic-modified concrete depends on the proportion and type of plastic used, necessitating careful evaluation.

3.2.3 Geotechnical Applications

Geotechnical applications represent the third pathway, where recycled plastics are used for soil stabilization and reinforcement. Plastic fibers, strips, and geosynthetics enhance soil strength, reduce settlement, and improve load-bearing capacity. These applications are particularly useful in weak soil conditions and offer an effective solution for utilizing plastic waste in infrastructure projects.

3.3 Material Characterization

3.3.1 Types of Plastics (PET, HDPE, LDPE, PP)

The study focuses on commonly available thermoplastic materials, including Polyethylene Terephthalate (PET), High-Density Polyethylene (HDPE), Low-Density Polyethylene (LDPE), and Polypropylene (PP). These plastics are selected due to their widespread availability in municipal waste streams and their suitability for recycling. Each type exhibits distinct physical and mechanical properties, influencing its applicability in different construction scenarios. For instance, PET is known for its high strength, HDPE for its durability, LDPE for flexibility, and PP for fatigue resistance.

3.3.2 Key Properties and Standards

Material characterization involves the evaluation of key properties such as density, tensile strength, and melt flow index, which influence processing behavior and performance in construction applications. Standardized testing methods are employed to ensure consistency and reliability of results. These standards facilitate the comparison of materials and ensure that recycled plastics meet the required specifications for engineering use. Proper characterization is essential for ensuring quality control and enhancing the performance of plastic-based construction materials.

3.4 Life Cycle Assessment (LCA) Methodology

3.4.1 Goal and Scope Definition

The primary goal of the Life Cycle Assessment (LCA) in this study is to evaluate and compare the environmental impacts of different recycled plastic utilization pathways. The scope is defined to include all relevant stages of the lifecycle, ensuring a comprehensive assessment. Functional units are established to provide a consistent basis for comparison, including 1 km of road for pavement applications, 1 m^3 of concrete for structural applications, and 1 m^3 of stabilized soil for geotechnical applications. These units reflect practical engineering quantities and enable meaningful comparison across different systems.

3.4.2 System Boundary: Cradle-to-Grave Approach

A cradle-to-grave system boundary is adopted to capture the complete lifecycle of materials and processes. This includes raw material extraction, plastic waste collection, processing, transportation, construction, use phase, and end-of-life disposal or recycling. By considering all stages, the analysis ensures that environmental impacts are not underestimated and provides a holistic evaluation of sustainability.

3.4.3 Life Cycle Inventory (LCI)

The Life Cycle Inventory phase involves the collection and quantification of all inputs and outputs associated with each utilization pathway. Inputs include materials such as plastic waste, aggregates, cement, and bitumen, as well as energy used during processing and construction. Outputs consist of emissions released into air, water, and soil, including greenhouse gases and other pollutants. Accurate inventory data is critical for ensuring the reliability of subsequent impact assessment.

3.4.4 Life Cycle Impact Assessment (LCIA)

The Life Cycle Impact Assessment phase translates inventory data into environmental impact indicators. In this study, key indicators include Global Warming Potential (GWP), expressed in terms of CO_2 equivalents, energy consumption, and resource depletion. These indicators provide a comprehensive measure of environmental performance and enable comparison between different utilization pathways. The LCIA results form the basis for evaluating sustainability and identifying environmentally preferable options.

3.5 Comparative Analysis Method

3.5.1 Multi-Criteria Decision Analysis (MCDA)

To facilitate a systematic comparison of different utilization pathways, Multi-Criteria Decision Analysis (MCDA) is employed. This method allows the evaluation of alternatives based on multiple criteria, including environmental, engineering, and economic indicators. MCDA provides a structured framework for decision-making, enabling the integration of diverse performance metrics into a single evaluation system.

3.5.2 Weight-Based Ranking System

A weight-based ranking system is used within the MCDA framework to assign relative importance to different evaluation criteria. For instance, environmental indicators such as GWP and energy consumption may be assigned higher weights in sustainability-focused studies, while engineering performance may also be considered significant. Each pathway is scored based on these weighted criteria, resulting in a composite ranking that identifies the most sustainable and efficient option. This approach ensures transparency and flexibility in decision-making, allowing for adaptation based on specific project requirements or policy priorities.

4. RESULTS

4.1 Identified Utilization Pathways

The analysis identified three main recycled plastic utilization pathways in civil infrastructure systems: plastic-modified bituminous roads, plastic aggregate concrete, and geotechnical applications. These pathways were selected based on data availability, practical relevance, and compatibility with existing engineering practices. Each pathway represents a distinct application domain where recycled plastics can be effectively incorporated.

4.2 Environmental Impact Results

4.2.1 Global Warming Potential (GWP)

The Life Cycle Assessment results indicate variations in greenhouse gas emissions across different utilization pathways. Plastic-modified bitumen shows a reduction in Global Warming Potential compared to conventional asphalt due to partial replacement of bitumen and reduced demand for energy-intensive materials. Plastic aggregate concrete also demonstrates lower emissions relative to conventional concrete, primarily due to decreased use of natural aggregates. Geotechnical applications exhibit comparatively lower emissions due to minimal material processing requirements.

4.2.2 Energy Consumption

The lifecycle energy demand varies among the selected pathways. Plastic-modified asphalt exhibits reduced energy consumption due to lower bitumen usage and efficient material processing. Plastic aggregate concrete shows moderate energy savings associated with reduced extraction and processing of natural aggregates. Geotechnical applications demonstrate relatively low energy demand, as they require minimal processing and utilize locally available materials.

4.2.3 Resource Utilization

The incorporation of recycled plastics contributes to a reduction in the consumption of natural resources such as aggregates and bitumen. Plastic-modified asphalt reduces bitumen demand by approximately 8–10%, while plastic aggregate concrete decreases reliance on natural aggregates. Geotechnical applications reduce the need for conventional stabilization materials by utilizing plastic-based reinforcements.

4.3 Comparative Performance

4.3.1 Ranking of Pathways Based on Indicators

A comparative evaluation of the selected pathways was conducted based on environmental indicators, including GWP, energy consumption, and resource utilization. The results indicate that plastic-modified asphalt ranks highest in terms of overall environmental performance, followed by plastic aggregate concrete and geotechnical applications. The ranking reflects the relative performance of each pathway based on the selected indicators.

5.CONCLUSION

This study evaluated the environmental performance of recycled plastic utilization pathways in civil infrastructure systems using a comprehensive Life Cycle Assessment (LCA) framework. Three major applications—plastic-modified bituminous roads, plastic aggregate concrete, and geotechnical stabilization—were analyzed based on key environmental indicators, including Global Warming Potential (GWP), energy consumption, and resource utilization. The results demonstrate that the incorporation of recycled plastics can significantly reduce environmental impacts compared to conventional construction materials.

Among the selected pathways, plastic-modified asphalt emerged as the most environmentally efficient option, primarily due to reduced bitumen consumption and lower greenhouse gas emissions. Plastic aggregate concrete showed moderate environmental benefits, particularly in terms of resource conservation and reduced aggregate usage, although performance variability remains a concern. Geotechnical applications provided localized advantages with relatively low energy demand and improved soil performance.

The study also highlights the importance of considering lifecycle-based assessment rather than focusing solely on mechanical properties. While environmental benefits are evident, certain trade-offs such as energy use during processing and potential long-term impacts, including microplastic release, must be carefully addressed. The integration of environmental and engineering performance provides a holistic framework for evaluating sustainability in infrastructure systems.

Overall, the findings confirm that recycled plastics offer a viable and sustainable alternative for civil engineering applications, supporting waste reduction, resource conservation, and environmentally responsible infrastructure development.

5.1.Future Scope of Research

Future research should focus on long-term environmental and structural performance of recycled plastic-based materials under real field conditions. Detailed studies on microplastic release, leaching behavior, and durability over extended service life are essential to ensure environmental safety. Additionally, the integration of Life Cycle Cost Analysis (LCCA) with LCA can provide a more comprehensive sustainability assessment by incorporating economic considerations.

Further investigation is required to optimize the proportion and processing techniques of recycled plastics to enhance both environmental and mechanical performance. The development of standardized guidelines and quality control measures will also support large-scale implementation. Moreover, expanding the analysis to include emerging applications such as plastic composites and modular construction systems can broaden the scope of sustainable infrastructure solutions.

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