

Research Trends on the Utilization of Industrial and Domestic Waste for Sustainable Pavement Materials

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Abstract

Introduction: The increase in industrial activities and urbanization has led to higher amounts of waste such as fly ash, slag, plastic waste, and construction debris, which may cause environmental problems. The utilization of these wastes in pavement construction offers a sustainable solution to reduce waste accumulation and the use of natural resources. **Objective:** This article aims to analyze research trends on the utilization of industrial and domestic waste as sustainable pavement materials. **Method:** This study employed a literature review of 15 scientific articles retrieved from Google Scholar, analyzed based on waste type, pavement type, technical performance parameters, and environmental aspects. **Results and Discussion:** The findings show that fly ash is the most studied waste material, followed by slag, plastic waste, and recycled concrete aggregate (RCA). Most studies focus on flexible asphalt pavements using parameters such as Marshall Stability, compressive strength, and CBR. Proper waste incorporation improves technical performance while reducing natural aggregate consumption and waste disposal. **Conclusion:** The use of industrial and domestic waste in pavement construction has strong potential to support sustainable infrastructure development, although more integrated technical and environmental evaluation is still needed.

Introduction

The rapid growth of industrial activities and urbanization in recent years has significantly increased the generation of industrial and domestic solid waste, including fly ash, steel slag, plastic waste (PET, PE, PP), and construction debris such as recycled concrete aggregate (RCA). If not properly managed, these waste materials may impose substantial environmental burdens, including soil and water contamination as well as increased greenhouse gas emissions resulting from landfill disposal. At the same time, the high consumption of raw materials particularly natural aggregates further exacerbates the environmental footprint of the construction sector. In this context, integrating waste streams into pavement materials is increasingly viewed as a sustainable solution to simultaneously reduce landfill burdens and decrease dependence on virgin aggregates (Medina et al., 2023).

Despite these potential benefits, the implementation of waste-based pavement systems remains limited, and only a small proportion of studies comprehensively follow ISO-based environmental impact assessment standards. Consequently, more specific and standardized guidelines are still required to evaluate environmental performance in road construction projects (Medina et al., 2023). The incorporation of waste materials into pavement construction aligns with the principles of the circular economy, whereby waste streams are diverted from disposal systems and transformed into value-added inputs in asphalt or concrete mixtures. This approach contributes to carbon footprint reduction in the construction industry and supports the conservation of natural resources (Romadhon & Garside, 2020).

The use of recycled materials such as recycled concrete aggregate (RCA) provides not only technical advantages across various pavement layers including subgrade, subbase, and surface courses but also potential energy savings and reductions in harmful emissions compared to conventional aggregate extraction (Romadhon & Garside, 2020). Furthermore, sustainable pavement designs that integrate recycled asphalt pavement (RAP) with high-performance waste materials such as rubber powder and steel slag have demonstrated enhanced deformation resistance and reduced life-cycle energy consumption and emissions relative to conventional pavement systems (Zhao & Yang, 2024). Environmental considerations have become increasingly central in pavement engineering research. For example, the use of plastic waste as an asphalt modifier has been reported to improve the mechanical properties of asphalt mixtures while simultaneously addressing the growing global challenge of plastic waste management (Hafidz et al., 2025). Similarly, soil stabilization using industrial by-products can replace conventional chemical stabilizers, thereby reducing environmental impacts and supporting sustainable development objectives. However, attention must be given to potential environmental risks, such as the release of hazardous residues during field applications.

Although numerous studies have examined waste utilization in pavement construction, the literature remains fragmented, particularly in studies that concurrently evaluate technical performance and ISO-aligned environmental impacts across multiple waste streams and pavement applications. Key gaps also include limited long-term field performance evidence and the absence of standardized design frameworks that integrate structural performance, safety considerations, and environmental sustainability. Therefore, this review sets measurable objectives to (1) classify the literature by waste type (e.g., fly ash, steel slag, plastics, RCA, RAP/rubber) and by pavement application (e.g., subgrade stabilization, base/subbase layers, asphalt mixtures, concrete pavements),

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(2) synthesize reported technical parameters (e.g., strength, stiffness, rutting/fatigue resistance, durability) alongside environmental parameters (e.g., carbon footprint, energy use, emissions, leaching/toxicity indicators) using comparable assessment approaches, and (3) identify research trends and future priorities to support the implementation of environmentally sustainable road infrastructure.

Method

This study employed a literature review approach to analyze research trends related to the utilization of industrial and domestic waste as sustainable pavement materials. The review was conducted through a systematic process of identification, screening, and in-depth analysis of scientific publications relevant to the research topic. Google Scholar was selected as the primary database due to its broad coverage of national and international peer-reviewed publications. To ensure the quality and relevance of the selected studies, specific inclusion criteria were applied. The articles had to (1) be published in national or international scientific journals, (2) address the utilization of industrial or domestic waste in pavement construction, and (3) present technical performance data, mechanical analysis, or environmental impact assessments related to pavement applications. Studies that did not provide sufficient technical or environmental evaluation were excluded from the analysis.

The literature selection process was conducted in three stages. The first stage involved identifying potentially relevant articles based on title relevance to the research topic. The second stage consisted of abstract screening to confirm alignment with the focus on waste utilization in pavement systems. The third stage involved full-text review to verify compliance with the predefined inclusion criteria. Based on this selection procedure, 15 eligible articles were identified and subjected to comprehensive analysis.

Data analysis was conducted using a descriptive and thematic classification approach. The selected articles were categorized according to (1) type of waste material, (2) type of pavement application, (3) technical performance parameters evaluated, and (4) environmental aspects discussed. Waste types identified in the literature included fly ash, steel slag, plastic waste, recycled concrete aggregate (RCA), and combinations of multiple waste materials. Pavement applications were classified into flexible pavement, rigid pavement, and subgrade stabilization. The technical parameters analyzed included Marshall Stability, compressive strength, California Bearing Ratio (CBR), permeability, and volumetric properties of mixtures. Environmental considerations included waste reduction potential, substitution of natural materials, and indications of environmental impact reduction. The results of this classification were subsequently synthesized to identify dominant research patterns, emerging trends, and existing research gaps that require further investigation in the development of sustainable pavement systems.

Result and Discussion

Trends in Types of Waste Materials Investigated

The utilization of industrial and domestic waste as alternative materials for pavement construction has shown significant development in recent years. Based on the classification of the 15 articles analyzed in this study, several dominant waste types were identified, including fly ash, industrial slag, plastic/styrofoam waste, recycled concrete aggregate (RCA), and combinations of multiple waste materials (multi-waste systems). The quantitative distribution of the analyzed waste types is presented in Table 1.

Table 1
Distribution of Articles by Waste Type

Waste Type	Number of Articles	Percentage (%)
Fly ash	4	27
Slag (steel/nickel/industrial slag)	3	20
Plastic / Styrofoam	3	20
Recycled concrete / construction waste	2	13
Multi-waste (combination of several wastes)	3	20
Total	15	100

As shown in Table 1, fly ash represents the most frequently investigated waste material, accounting for 27% of the reviewed studies. This dominance indicates that fly ash remains one of the most relevant industrial by-products in the development of sustainable pavement systems. It is commonly utilized as a filler substitute or soil stabilization agent due to its pozzolanic properties, which contribute to improved compressive strength and mixture stability. Medina et al. (2023) emphasized that fly ash continues to be a primary focus in pavement waste utilization studies because of its ability to enhance mechanical characteristics while reducing the demand for cement and natural aggregates.

Industrial slag accounts for 20% of the analyzed studies. Steel slag, in particular, is widely used as a coarse aggregate replacement in both asphalt and concrete mixtures. Several studies have reported that slag exhibits good abrasion resistance and enhances mixture stability as well as resistance to permanent deformation. However, Plati et al. (2024) highlighted the importance of evaluating heavy metal leaching potential and volumetric stability to ensure long-term environmental safety.

Plastic and styrofoam waste also represent 20% of the reviewed articles, indicating growing attention to domestic waste management within the road construction sector. Plastic waste is typically used as a bitumen modifier through either wet or dry processes, and has been reported to improve rutting resistance and enhance the viscoelastic properties of asphalt mixtures at elevated temperatures. You et al. (2022) observed a significant increase in experimental studies on plastic-modified asphalt in response to the global accumulation of plastic waste.

Recycled concrete aggregate (RCA) accounts for 13% of the analyzed studies. RCA is generally applied as an alternative aggregate in subbase layers or rigid concrete pavements. Its utilization supports circular economy principles by reducing natural aggregate extraction and diverting construction waste from landfills. Nevertheless, technical challenges such as relatively high water absorption and variability in material quality remain critical considerations for practical implementation.

Overall, the distribution of investigated waste types suggests that current research is still dominated by relatively homogeneous and industrially controlled waste materials, such as fly ash and slag. However, the increasing attention to plastic waste and multi-waste approaches indicates a gradual shift toward integrating both technical performance and environmental considerations in sustainable pavement development.

Distribution of Pavement Types Investigated

In addition to variations in waste types, the analyzed studies also demonstrate differences in the types of pavement systems investigated. Flexible pavement systems

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based on asphalt mixtures represent the dominant focus in the reviewed articles, followed by rigid pavement (concrete-based systems), subgrade stabilization, and porous (pervious) pavement applications. The distribution of pavement types is presented in Table 2

Table 2
Distribution by Pavement Type

Pavement Type	Number of Articles	Percentage (%)
Flexible pavement (asphalt)	8	53
Rigid pavement (concrete)	4	27
Subgrade stabilization	2	13
Porous / pervious pavement	1	7
Total	15	100

The dominance of flexible pavement research indicates that most studies emphasize asphalt concrete as the primary medium for incorporating waste materials. This preference is largely attributed to the flexible nature of bitumen, which can be readily modified with various waste materials to improve technical performance, including mixture stability, rutting resistance, and fatigue durability. Mashaan et al. (2025) confirmed that mining by-products such as slag and fly ash can be effectively incorporated into asphalt concrete mixtures to enhance mechanical and rheological properties while simultaneously reducing industrial waste accumulation.

Rigid pavement systems, typically based on concrete, appear in several studies as alternative applications for waste materials such as recycled concrete aggregate (RCA) or demolition debris. The incorporation of RCA in rigid pavement construction demonstrates potential for reducing construction waste volume and decreasing the consumption of virgin aggregates. Technical challenges such as variability in material quality and relatively high water absorption remain critical considerations and often require pre-treatment processes to ensure consistent performance. Despite these challenges, the utilization of construction waste aligns strongly with circular economy principles.

Several studies also investigated subgrade stabilization using waste materials, particularly fly ash and slag, to improve soil bearing capacity under traffic loading. The addition of such materials has been shown to enhance the California Bearing Ratio (CBR), which is a key parameter in pavement structural design. Although fewer articles focus on this category compared to asphalt or concrete applications, subgrade stabilization represents an important strategy for integrating waste materials across different pavement layers. Porous pavement systems, although represented by only one analyzed article, have begun to receive attention in the context of environmentally friendly pavement development. Their ability to facilitate water infiltration and reduce surface runoff aligns with sustainable urban drainage concepts and long-term stormwater management strategies. Overall, the distribution of pavement types indicates that research on waste utilization in road construction remains concentrated on flexible asphalt systems, likely due to their adaptability and ease of laboratory modification. Meanwhile, rigid pavement and subgrade stabilization applications demonstrate promising potential but have received comparatively less research attention.

Technical Performance Parameters Analyzed

The effectiveness of waste utilization in pavement materials is generally evaluated through various technical performance parameters. These parameters are used to ensure that mixtures containing waste materials comply with design standards and are capable of sustaining traffic loads over a specified service life. The distribution of performance parameters examined in the analyzed articles is presented in Table 3.

Table 3
Distribution of Technical Performance Parameters

Test Parameter	Number of Articles
Marshall Stability	6
Compressive Strength	4
California Bearing Ratio (CBR)	2
Permeability	2
Volumetric Properties (VIM, VMA, MQ)	4

As shown in Table 3, Marshall Stability is the most frequently applied parameter, particularly in studies focusing on flexible asphalt pavements. Marshall Stability serves as a primary indicator for assessing resistance to permanent deformation (rutting) and the structural integrity of asphalt mixtures. You et al. (2022) reported that the incorporation of plastic waste as a bitumen modifier can enhance Marshall Stability values when applied at optimal proportions. This finding reinforces the role of Marshall testing as a standard evaluation method in asphalt mixture design.

Similarly, Mashaan et al. (2025) demonstrated that the incorporation of industrial waste materials such as slag and fly ash into asphalt concrete mixtures improves mechanical performance, including stability and fatigue resistance. The continued dominance of Marshall-based evaluation reflects its relatively simple procedure and widespread standardization, making it a preferred approach in preliminary assessments of waste-modified asphalt mixtures. Compressive strength is the primary parameter used to evaluate the performance of concrete incorporating waste materials. Zhang et al. (2023) found that partial replacement of cement with fly ash or other industrial by-products can enhance concrete strength at later curing ages due to pozzolanic reactions, although early-age strength reductions may occur. They emphasized the importance of testing compressive strength at 7, 14, and 28 days to obtain a comprehensive understanding of strength development.

The California Bearing Ratio (CBR) is commonly employed to assess improvements in subgrade bearing capacity following treatment with waste materials. Ahmed (2024) reported that the addition of fly ash in specific proportions significantly increases CBR values by promoting stronger interparticle bonding within the soil matrix. Enhanced CBR values contribute directly to improved pavement structural design and potential optimization of layer thickness. Permeability testing is particularly relevant in porous pavement research aimed at supporting sustainable drainage systems. Nguyen (2021) noted that the permeability of porous mixtures is influenced by void structure and aggregate composition, and that the incorporation of certain waste materials may either enhance or reduce infiltration capacity. Therefore, permeability testing should be combined with durability evaluation to ensure long-term functional performance.

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Although mechanical performance parameters dominate the reviewed studies, Medina et al. (2023) argued that evaluating waste utilization in pavement construction should not be limited to mechanical aspects alone. A Life Cycle Assessment (LCA) approach is necessary to comprehensively quantify environmental impacts, including potential reductions in carbon emissions and energy consumption resulting from waste material substitution.

Technical and Environmental Impacts of Waste Utilization

The utilization of waste materials in pavement construction generates not only technical performance improvements but also broader environmental implications. To provide a systematic overview of these contributions, the key findings from the reviewed articles are summarized in Table 4.

Table 4
Technical and Environmental Impacts of Waste Utilization

Waste Type	Main Technical Impact	Environmental Impact
Fly ash	Improves compressive strength and mixture stability	Reduces consumption of new cement and natural aggregates
Slag	Enhances stability and deformation resistance	Reduces accumulation of industrial waste
Plastic / Styrofoam	Improves rutting resistance	Reduces plastic waste volume
Recycled Concrete	Serves as alternative aggregate with adequate strength	Reduces construction waste
Multi-waste	Combined composition enhances performance	Strengthens circular economy principles

Barbhuiya et al. (2025) reported that the incorporation of waste materials such as fly ash, slag, recycled concrete aggregate (RCA), and bio-based fillers can improve mechanical performance while providing functional equivalence to conventional materials in asphalt and concrete mixtures. However, the effectiveness of these materials depends strongly on their proportion and mixing methodology. The adoption of low-carbon material technologies may reduce the environmental burden associated with natural resource extraction while maintaining the structural strength required for pavement surface applications.

Senarathne (2025) demonstrated that integrating recycled aggregates and recycled plastics into pavement systems can significantly reduce global warming impacts, with estimated emission reductions of 40–60% compared to conventional pavement structures. Additionally, reductions in eutrophication potential were observed due to decreased reliance on virgin raw material production. These findings highlight the dual benefits of waste utilization in both technical performance and environmental sustainability. Fatmeriany (2025) found that the use of nickel waste in porous asphalt mixtures improves material performance while contributing to environmental benefits through reduced industrial waste accumulation. However, the application of heavy industrial by-products such as nickel slag requires careful environmental risk management, particularly regarding heavy metal leaching and stabilization, to prevent adverse impacts on soil and surface water systems.

Similarly, Razak (2025) reported that the incorporation of LDPE plastic waste in asphalt mixtures enhances stability while simultaneously mitigating plastic pollution. The reuse of post-consumer plastic increases the added value of waste materials and reduces dependence on primary asphalt resources, thereby contributing to long-term environmental pollution reduction. Despite the positive findings reported across many studies, several limitations remain. Salehi et al. (2025) emphasized that although Life Cycle Assessment (LCA) approaches frequently demonstrate reductions in Global Warming Potential (GWP), many assessments still overlook critical phases such as transportation, pre-treatment processes, and end-of-life disposal. As a result, the overall environmental impact may not be fully captured. This limitation underscores the need for more comprehensive research frameworks that integrate technical performance evaluation with holistic environmental assessment.

Conclusion

The findings of this review justify the author's argument that industrial and domestic waste can serve as viable alternative materials in pavement construction, supported by a clear upward research trend over the past five years. The dominance of fly ash in the reviewed literature reinforces the rationale for prioritizing this material, as its pozzolanic properties and broad availability make it one of the most practical waste streams for sustainable pavement innovation. The concentration of studies on flexible asphalt pavements further supports the author's position that asphalt systems currently provide the most adaptable platform for waste incorporation, allowing modifications to be tested efficiently through widely accepted mechanical indicators such as Marshall Stability, compressive strength, and CBR

While many studies report improvements in mixture stability, strength, and resistance to permanent deformation, the evidence base remains limited in terms of comprehensive environmental verification. The relatively small number of studies that integrate performance outcomes with Life Cycle Assessment (LCA) or environmental risk screening—particularly heavy metal leaching—supports the author's justification for calling attention to the gap between laboratory performance claims and full sustainability evaluation. Therefore, the author's recommendation for future research is well founded: long-term field validation, environmental risk assessment, and integrated frameworks that combine technical, environmental, and economic dimensions are necessary to move waste-based pavement systems from promising laboratory concepts into credible and scalable sustainable infrastructure solutions

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