Sustainable Road Construction: Utilizing Industrial By-Products for Environmental and Structural Benefits: A Review

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ABSTRACT

Sustainable Road construction is a critical focus in mitigating environmental impacts caused by traditional materials like cement, aggregates, and bitumen. The use of industrial by-products such as fly ash, recycled plastics, and agricultural residues not only reduces carbon footprints but also enhances the mechanical properties of pavements. Research highlights the success of these materials in improving strength, durability, and load-bearing capacity while addressing environmental concerns. Life Cycle Assessment (LCA) and Building Information Modeling (BIM) tools are vital in optimizing sustainable practices in road infrastructure. This approach contributes to environmental sustainability and circular economy principles, ensuring long-term infrastructure resilience.

Keywords: *Sustainable Construction, Industrial By-Products, Life Cycle Assessment (LCA), Circular Economy.*

I. INTRODUCTION

Sustainable development has become a central focus in modern infrastructure planning due to the increasing environmental challenges associated with rapid urbanization, industrialization, and population growth. The construction sector, particularly road infrastructure, is one of the largest consumers of natural resources and a major contributor to environmental degradation, including greenhouse gas (GHG) emissions, energy consumption, and depletion of non-renewable materials. Traditional road construction practices rely heavily on virgin aggregates, bitumen, and cement, all of which have high carbon footprints and significant ecological impacts. In recent years, there has been a growing emphasis on incorporating sustainable materials and practices into pavement engineering to minimize these adverse effects. One promising approach is the utilization of industrial by-products and waste materials such as fly ash, ground granulated blast furnace slag (GGBS), crumb rubber, recycled plastics, and agricultural residues. These materials not only reduce the environmental burden associated with waste disposal but also contribute to resource conservation and circular economy principles. According to Nandhini and Karthikeyan (2022), the incorporation of industrial by-products in construction can significantly reduce carbon dioxide emissions associated with cement production while improving the mechanical and durability properties of concrete. Similarly, Praticò et al. (2020) highlighted that the use of recycled materials in asphalt mixtures can lower energy consumption and environmental impacts, particularly when combined with warm mix asphalt technologies. These developments underscore the importance of transitioning toward sustainable road construction practices that integrate environmental, economic, and technical considerations.

The application of industrial by-products in road construction has shown promising results in enhancing both structural performance and sustainability. Various studies have demonstrated that materials such as fly ash, glass fiber, and GGBS can be effectively used in base and subbase layers of pavements to improve strength characteristics and load-bearing capacity. For instance, Kedar et al. (2024) employed Response

Surface Methodology (RSM) to optimize the composition of industrial waste materials and reported significant improvements in unconfined compressive strength (UCS) and California Bearing Ratio (CBR), making them suitable for heavy traffic conditions. Additionally, Olugbenga (2019) demonstrated that partial replacement of natural aggregates with aluminum slag and crushed ceramic tiles resulted in satisfactory Marshall stability values, indicating their suitability for asphalt concrete production. Beyond mechanical performance, the incorporation of innovative materials such as biomass-derived activated carbon has further enhanced the durability and resistance of construction materials. Al Khaldi and Mourad (2025) reported that the addition of biomass activated carbon to sulfur concrete improved compressive strength, reduced voids, and enhanced moisture resistance, thereby extending the lifespan of pavement structures. Furthermore, the use of recycled aggregates and industrial waste materials has been identified as a viable solution to address the challenges of resource scarcity and environmental pollution caused by excessive waste generation (BAŞYİĞİT et al., 2021). These findings collectively highlight the dual benefits of using industrial by-products in road construction—improving engineering performance while promoting environmental sustainability.

In addition to material innovation, the adoption of advanced analytical tools and sustainability assessment frameworks has played a crucial role in evaluating the environmental impacts of road construction practices. Life Cycle Assessment (LCA) has emerged as a widely used methodology for quantifying the environmental footprint of pavement materials and construction processes across their entire lifecycle, from raw material extraction to end-of-life disposal. Movilla-Quesada et al. (2021) utilized LCA to analyze greenhouse gas emissions from asphalt mixtures modified with recycled materials and found that certain by-products, such as copper slag and cellulose ash, could significantly reduce emissions compared to conventional materials. Similarly, Shokri et al. (2024) emphasized the importance of integrating low-carbon energy sources, such as green hydrogen and renewable electricity, into asphalt production to achieve substantial reductions in global warming potential. Moreover, the integration of Building Information Modeling (BIM) with sustainability assessment frameworks has enabled more comprehensive and data-driven decision-making in infrastructure development. Patel and Ruparathna (2023) developed a BIM-based life cycle sustainability assessment framework that facilitates the comparison of different construction methods based on environmental, economic, and social criteria, thereby supporting the selection of optimal solutions aligned with sustainable development goals. The growing adoption of such tools reflects a shift toward holistic and multidisciplinary approaches in road construction, where sustainability is evaluated not only in terms of material selection but also through lifecycle performance and resource efficiency. Despite these advancements, challenges such as lack of standardization, variability in material properties, and limited large-scale implementation remain significant barriers. Therefore, continued research and innovation are essential to fully realize the potential of industrial by-products in achieving sustainable and resilient road infrastructure systems.

II. RESEARCH BACKGROUND

Al Khaldi and Mourad (2025) investigated the enhancement of sulfur concrete (SC), which was acknowledged for its sustainability and chemical resistance but was limited by mechanical strength and thermal durability, through the incorporation of biomass-derived activated carbon (BAC) obtained from corn husk and cob. They examined replacements of 1 %, 3 %, 5 %, and 7 % of carbide lime by weight with BAC, which was synthesized via pyrolysis at 400 °C and characterized by high porosity (91 % in cob-derived and 74.5 % in husk-derived) and a particle size of 100–200 µm. Their study reported that mechanical testing indicated a 23.9 % increase in compressive strength at 7 % BAC replacement, reaching 52 MPa, which surpassed previous SC formulations (25–43 MPa). SEM/EDX analyses suggested that

BAC contributed to microstructural densification, void reduction, and improved sulfur–aggregate adhesion. Durability tests under 12 wet/dry cycles demonstrated that BAC-modified SC exhibited negligible cracking and less than 2 % mass fluctuation, highlighting enhanced moisture resistance. They concluded that the integration of agricultural waste-derived BAC not only improved SC's structural performance but also promoted circular economy principles by utilizing industrial and agricultural by-products, positioning BAC-SC as a viable, high-performance alternative for harsh environments.

Kedar et al. (2024) investigated the sustainable utilization of fly ash, glass fiber, and ground granulated blast furnace slag (GGBS) as stabilizing agents in the base and subbase layers of flexible pavements. They employed Design Expert 13 software and Response Surface Methodology (RSM) to identify optimal mixture proportions satisfying technical specifications. Their analysis revealed that a composition of 88% fly ash, 3% glass fiber, and 9% GGBS achieved an Unconfined Compressive Strength (UCS) exceeding 3 MPa at 28 days, making it suitable for subbase layers, whereas a blend of 83% fly ash, 5% glass fiber, and 12% GGBS attained UCS values up to 6.76 MPa, appropriate for base layers. Modified Compaction, UCS, and California Bearing Ratio (CBR) tests, complemented by ANOVA, were conducted to validate the statistical methodology. Notably, mixtures with higher glass fiber content exhibited substantial improvements in UCS and CBR, with the 88–3–9 blend recording a CBR of 67.20%, well above the 30% minimum required for heavy-traffic pavements, highlighting the potential of industrial waste materials to enhance mechanical performance and sustainability in pavement construction.

Shokri et al., (2024, May) investigated approaches to reducing Greenhouse Gas (GHG) emissions and promoting sustainable practices within the energy sector, noting the strong consensus on aligning with the Sustainable Development Goals (SDGs), particularly SDG 12 and SDG 13, which referenced the 2015 Paris Agreement and emphasized limiting global warming to 1.5 ℃ while advocating sustainable production and consumption. They highlighted that meeting global energy demand necessitated large-scale infrastructure and storage, with hydrogen emerging as a promising sustainable energy carrier and the establishment of global hydrogen networks being critical for a rapid transition. The study employed life-cycle analyses (LCAs) following ISO 14040/44 standards to assess road pavements using Crumb Rubber (CR) and Electric Arc Furnace (EAF) slag, alongside alternative fuels for asphalt production. Their results indicated that although fossil fuels remained economically advantageous, the adoption of greener alternatives such as green hydrogen and green electricity could substantially reduce Global Warming Potential (GWP) by up to 70%, emphasizing the significance of low-impact fuels in sustainable asphalt production and road construction.

Peluso (2023) examined the coffee by-product market, highlighting its transformative potential within the coffee industry by turning previously overlooked resources into economic value through sustainable practices. The study emphasized the multifaceted opportunities and financial benefits derived from the utilization, processing, and commercialization of coffee by-products across diverse industries. It was noted that coffee by-products, once considered waste, were repurposed for energy production, including biofuel generation from coffee grounds and biomass energy from coffee husks, thereby reducing operational costs and enhancing financial resilience. The research also indicated that the food and beverage sector leveraged coffee cherry pulp and cascara for functional foods and nutraceuticals, capitalizing on their antioxidant and nutritional properties. Additionally, coffee silverskin was identified as a sustainable material for energy-efficient construction and niche artisanal products, while biochar derived from coffee cherry pulp contributed to improved soil health in agriculture. Peluso concluded that the coffee by-product market embodied a convergence of sustainability, innovation, and economic growth, offering significant opportunities for coffee-producing regions and stakeholders aligned with circular economy principles.

Patel and Ruparathna (2023) investigated sustainable road construction practices, noting that a substantial portion of federal and regional infrastructure budgets was allocated to building, maintaining, repairing, and replacing road infrastructure. They highlighted that despite the potential of sustainable practices to support national development goals, progress had been constrained by limited expertise, information, and resources. The authors argued that the advent of Building Information Modeling (BIM) offered enhanced access to functional and physical data on construction materials, which had been largely overlooked in existing literature for life cycle sustainability evaluation of road construction techniques. They proposed a methodological framework based on life cycle thinking to evaluate road infrastructure and compare the sustainability performance of alternative pavement construction methods. A BIM-based visual program was developed to automate the framework, which was demonstrated by assessing three construction methods for a collector road. Their findings suggested that geomembrane roads provided the best sustainability performance according to the triple bottom line, and the framework, along with the BIM tool, was expected to aid infrastructure managers in selecting construction methods aligned with United Nations Sustainable Development Goals.

Nandhini and Karthikeyan (2022) investigated the use of industrial waste products as sustainable alternatives to cement in self-compacting concrete. They reported that the annual generation of industrial waste had exceeded 1000 million tons, causing significant environmental hazards, including soil pollution. The authors emphasized that incorporating such waste into concrete could mitigate these negative impacts by reducing the high cement content, which is associated with large carbon dioxide emissions. Their review analyzed the chemical and physical properties of various industrial by-products, including fly ash, ground granulated blast furnace slag, metakaolin, microsilica, and nanosilica, to evaluate their suitability as partial cement replacements. They further examined the effects of these materials on the fresh, strength, and durability characteristics of self-compacting concrete. The study highlighted both the potential benefits and the critical challenges of utilizing industrial waste products, presenting a comprehensive synthesis of existing literature toward the development of eco-friendly, sustainable concrete solutions.

Movilla-Quesada et al. (2021) investigated the production and construction stages of the life cycle analysis (LCA) of asphalt mixtures modified with industrial waste and by-products, focusing on the quantification of methane (CH4), carbon monoxide (CO), and carbon dioxide (CO2) emissions generated during these processes. They employed a laboratory-designed and calibrated gas measurement system using a microcontroller and MQ sensors to compare greenhouse gas (GHG) emissions from a conventional asphalt mix with those from waste-modified mixes, including polyethylene terephthalate (PET) and nylon fibres, as well as industrial by-products like copper slag and cellulose ash. The study revealed that polymer-modified mixes exhibited increased methane emissions—21% for PET and 14% for nylon—while mixtures incorporating copper slag and cellulose ash showed a 12% reduction. Moreover, replacing natural aggregates with these by-products reduced overall GHG emissions by 15% and shortened photochemical ozone formation. CO2 emissions were found to rise substantially for all mixes, notably 130% for PET and 53% for nylon, while CO emissions remained comparable across all mixtures, indicating the importance of both emission levels and atmospheric persistence in environmental assessments.

BAŞYİĞİT et al., (2021) examined migration as a process involving temporary or permanent relocation from an origin to a new place. They noted that historically, migration had been driven by factors such as natural disasters, religion, poverty, and wars, and had consequently contributed to urbanization and population growth. The authors highlighted that increases in population and irregular migration had led to resource scarcity, unplanned urbanization, and inadequacies in infrastructure delivery, including wastewater, drinking water, rainwater collection, electricity, and natural gas networks, while traffic congestion and waste generation had intensified. They argued that these developments had exacerbated environmental pollution and health problems in urban areas. The study further observed that, due to the negative environmental impacts, public awareness had increased, prompting efforts toward sustainable construction practices, recycling, and waste reuse. In this context, the authors evaluated prior research and outcomes related to the use of recycled aggregates as a potential solution to mitigate environmental pollution associated with the construction sector.

Praticò et al. (2020) investigated the potential of recycled and low-temperature materials as sustainable alternatives to traditional hot mix asphalts, emphasizing the limited research on their life-cycle impacts. They conducted a life cycle assessment (LCA) of various pavement technologies, including hot mix asphalt and warm mix asphalt incorporating recycled materials such as reclaimed asphalt pavements, crumb rubber, and waste plastics, following the ISO 14040 series. Different scenarios of pavement production, construction, and maintenance were analyzed and compared to a reference case using conventional materials. The study reported that material production accounted for the largest share (approximately 60–70%) of environmental impacts across all categories. It was further observed that the combined use of warm mix asphalts and recycled materials reduced energy consumption and environmental impacts by lowering virgin bitumen and aggregate use, decreasing primary energy demand, raw material consumption, and disposal impacts. The results suggested that LCA could effectively guide eco-design strategies in pavement engineering.

Olugbenga (2019) investigated the use of industrial waste products for asphalt concrete production in road construction. In the study, aggregates were partially replaced with aluminum slag (AS) and crushed ceramic tiles (CCT) at varying percentages of 10%, 20%, 30%, 40%, and 50% by weight. Physical tests were conducted on the aggregates, while flash and fire point tests, along with penetration tests, were performed on the bitumen. Marshall stability tests were also carried out on cylindrical asphalt concrete specimens. The study reported that the average aggregate impact value (AIV) and aggregate crushing value (ACV), recorded as 18.88 and 30.69 respectively, met the requirements for road surfacing. Furthermore, Marshall stability values of 10.84 kN, 4.27 kN, and 3.21 kN were obtained for 30%, 20%, and 50% partial replacements with AS, which were found suitable for heavy, medium, and light traffic according to Asphalt Institute design criteria. The findings suggested that incorporating AS and CCT could mitigate industrial waste while reducing pavement construction and maintenance costs.

III. KEY FINDINGS FROM STUDY

Author(s) & Year	Objective	Materials / By-Products Used	Methodology	Key Findings	Contribution to Sustainability
Al Khaldi & Mourad (2025)	Enhance performance of sulfur concrete using waste materials	Biomass Activated Carbon (BAC) from corn husk & cob	Mechanical tests, SEM/EDX, durability analysis	23.9% increase in compressive strength; improved durability and reduced cracking	Promotes circular economy by utilizing agricultural waste and improving material lifespan
Kedar et al. (2024)	Optimize industrial waste in pavement base and subbase layers	Fly ash, glass fiber, GGBS	Response Surface Methodology (RSM), ANOVA, UCS & CBR tests	UCS up to 6.76 MPa; CBR up to 67.2% suitable for heavy traffic	Reduces use of natural aggregates and improves pavement strength sustainably

Shokri et al. (2024)	Reduce GHG emissions in road construction	Crumb rubber, EAF slag, green hydrogen	Life Cycle Assessment (ISO 14040/44)	Up to 70% reduction in global warming potential using green fuels	Supports low-carbon construction and climate change mitigation
Peluso (2023)	Explore value of coffee industry by-products	Coffee husk, pulp, silverskin, biochar	Market and sustainability analysis	Waste reused in biofuel, construction, and agriculture	Enhances waste valorization and promotes circular economy
Patel & Ruparathna (2023)	Evaluate sustainability of road construction methods	Various materials analyzed via BIM	BIM-based Life Cycle Sustainability Assessment	Geomembrane roads showed best sustainability performance	Enables data-driven sustainable decision-making
Nandhini & Karthikeyan (2022)	Replace cement with industrial by-products	Fly ash, GGBS, metakaolin, microsilica	Literature review and material performance analysis	Reduced CO_2 emissions; improved strength and durability	Minimizes cement usage and environmental impact
Movilla-Quesada et al. (2021)	Assess environmental impact of modified asphalt	PET, nylon fibers, copper slag, cellulose ash	Gas emission measurement system, LCA	15% reduction in GHG with slag/ash; polymers increased emissions	Highlights eco-friendly alternatives and emission trade-offs
BAŞYİĞİT et al. (2021)	Analyze environmental effects of construction materials	Recycled aggregates	Review-based analysis	Recycling reduces pollution and resource scarcity	Encourages sustainable material reuse in infrastructure
Praticò et al. (2020)	Evaluate sustainable pavement technologies	RAP, crumb rubber, warm mix asphalt	Life Cycle Assessment (LCA)	60–70% environmental impact from material production; WMA reduces energy use	Supports eco-design and energy-efficient pavement construction
Olugbenga (2019)	Utilize industrial waste in asphalt concrete	Aluminum slag, crushed ceramic tiles	Marshall stability, AIV, ACV tests	Suitable for heavy to light traffic; adequate strength achieved	Reduces construction cost and industrial waste disposal

IV. CONCLUSION

The reviewed literature clearly establishes that sustainable road construction using industrial by-products is a highly effective and practical approach for addressing the environmental challenges associated with conventional pavement engineering. The increasing generation of industrial and agricultural waste, combined with the high environmental cost of traditional construction materials such as cement, bitumen, and natural aggregates, has created a strong need for alternative sustainable solutions. Studies consistently demonstrate that materials such as fly ash, ground granulated blast furnace slag (GGBS), crumb rubber, copper slag, recycled plastics, and biomass-derived materials can successfully replace or partially substitute conventional materials without compromising structural performance. Mechanical performance outcomes across multiple studies indicate that the incorporation of industrial by-products often leads to improved or comparable strength characteristics. For instance, optimized mixtures containing fly ash, glass fiber, and GGBS have shown enhanced unconfined compressive strength (UCS) and California Bearing Ratio (CBR), making them suitable for high-traffic pavement applications. Similarly, biomass-based additives such as activated carbon have demonstrated improvements in compressive strength, durability, and resistance to environmental degradation. These findings confirm that waste-derived materials can contribute positively to pavement performance when properly processed and proportioned. From an environmental perspective, the benefits are equally significant. Life Cycle Assessment (LCA) studies reveal that a large portion of environmental impact in road construction originates from material production stages. However, the use of recycled and industrial by-products significantly reduces greenhouse gas emissions, energy consumption, and resource depletion. In some cases, emission reductions of up to 70% have been reported when integrating cleaner energy sources and recycled materials. Additionally, waste valorization practices not only reduce landfill burden but also promote circular economy principles by transforming waste into valuable construction resources. Furthermore, the integration of advanced tools such as BIM and LCA frameworks has improved sustainability assessment by enabling multi-criteria decision-making. These tools allow engineers and policymakers to evaluate environmental, economic, and social impacts simultaneously, leading to more informed and sustainable infrastructure planning. Overall, the literature confirms that industrial by-product utilization is not only technically feasible but also environmentally and economically beneficial, making it a key strategy for future sustainable road infrastructure development.

V. FUTURE SCOPE

- **Standardization of Industrial By-Product Usage:** There is a strong need to develop standardized guidelines, specifications, and codes for the use of industrial by-products in road construction. Variability in waste material composition and performance currently limits large-scale adoption. Establishing uniform standards will ensure reliability, safety, and consistency in construction practices.
- **Large-Scale Field Implementation and Monitoring:** Most existing research is based on laboratory studies. Future work should focus on full-scale field applications and long-term performance monitoring of roads constructed with industrial by-products. This will help in understanding real-world durability, maintenance requirements, and performance under varying climatic and traffic conditions.
- **Integration with Smart Technologies:** Emerging technologies such as Artificial Intelligence (AI), Machine Learning (ML), Internet of Things (IoT), and advanced BIM systems should be integrated with sustainable pavement design. These technologies can optimize material selection, predict pavement deterioration, and improve maintenance planning, thereby enhancing overall efficiency.

- **Advanced Life Cycle Cost and Environmental Analysis:** Future studies should combine Life Cycle Assessment (LCA) with Life Cycle Cost Analysis (LCCA) to provide a more comprehensive evaluation of sustainability. This will help in balancing environmental benefits with economic feasibility, making sustainable solutions more attractive for large-scale adoption.
- **Development of Hybrid and Nanomodified Waste Materials:** Research should explore the combination of multiple waste materials and nanotechnology-based enhancements to improve mechanical and functional properties of pavement materials. Hybrid composites and nano-engineered waste materials may offer superior strength, durability, and environmental performance.
- **Policy Support and Circular Economy Integration:** Governments and regulatory bodies should promote policies that encourage industrial waste recycling in infrastructure projects. Strengthening the link between construction industry and circular economy models will ensure long-term sustainability and reduced environmental impact.

REFERENCES

1. Al Khaldi, V., & Mourad, A. H. I. (2025). Black magic for concrete: Using biomass and industrial by-products to create innovative sustainable construction materials. *Case Studies in Construction Materials*, *22*, e04674.
2. Kedar, H. N., Aware, R., Repale, G., Pankaj, T., & Sangale, P. (2024). Optimizing industrial waste in road construction: a response surface methodology approach. *Journal of Building Pathology and Rehabilitation*, *9*(1), 59.
3. Shokri, M., Mankaa, R. N., & Traverso, M. (2024, May). Toward Sustainability–Life Cycle Perspective in Green Hydrogen and By-Products Material in Asphalt Production: A Case Study for Road Pavement. In *International Symposium on Pavement, Roadway, and Bridge Life Cycle Assessment* (pp. 318-333). Cham: Springer Nature Switzerland.
4. Peluso, M. (2023, August). Coffee by-products: economic opportunities for sustainability and innovation in the coffee industry. In *Proceedings* (Vol. 89, No. 1, p. 6). MDPI.
5. Patel, K., & Ruparathna, R. (2023). Life cycle sustainability assessment of road infrastructure: a building information modeling-(BIM) based approach. *International Journal of Construction Management*, *23*(11), 1837-1846.
6. Nandhini, K., & Karthikeyan, J. (2022). A review on sustainable production of self-compacting concrete utilizing industrial by-products as cementitious materials. *Innovative Infrastructure Solutions*, *7*(3), 199.
7. Movilla-Quesada, D., Lagos-Varas, M., Raposeiras, A. C., Muñoz-Cáceres, O., Andrés-Valeri, V. C., & Aguilar-Vidal, C. (2021). Analysis of greenhouse gas emissions and the environmental impact of the production of asphalt mixes modified with recycled materials. *Sustainability*, *13*(14), 8081.
8. BAŞYİĞİT, C., Alkayıs, M., & Kartli, M. (2021). Environmental effects of utilization of sustainable building materials. *Heritage and Sustainable Development*, *3*(1).
9. Praticò, F. G., Giunta, M., Mistretta, M., & Gulotta, T. M. (2020). Energy and environmental life cycle assessment of sustainable pavement materials and technologies for urban roads. *Sustainability*, *12*(2), 704.
10. Olugbenga, O. J. (2019). Utilization of industrial waste products in the production of asphalt concrete for road construction. *Slovak Journal of Civil Engineering*, *27*(4), 11-17.