

# Decarbonizing Pavement Construction: Review of Sustainable Asphalt Mix Technologies

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**Abstract.** The road construction industry contributes significantly to global greenhouse gas (GHG) emissions due to energy-intensive processes in asphalt production. This review examines sustainable asphalt mix technologies—specifically Hot Mix Asphalt (HMA), Warm Mix Asphalt (WMA), Reclaimed Asphalt Pavement (RAP), and bio-based binders—with a focus on their role in decarbonizing pavement construction. Through a synthesis of peer-reviewed studies and life cycle assessment (LCA) analyses, the paper highlights that WMA can reduce energy consumption and CO<sub>2</sub> emissions by 20–40% compared to HMA, while RAP utilization further enhances circularity and resource efficiency. Bio-asphalts, derived from renewable feedstocks such as lignin or waste cooking oil, show potential to replace fossil-based bitumen partially. The findings suggest that integrating WMA, RAP, and bio-binders within construction practices can significantly lower the carbon footprint, contributing to net-zero emission goals and sustainable infrastructure development.

**Keywords:** Sustainable Asphalt, Warm Mix Asphalt, Reclaimed Asphalt Pavement, Bio-binder, Life Cycle Assessment, Carbon Reduction.

## 1. Introduction

The global construction industry, and particularly pavement construction, plays a vital role in supporting economic development and connectivity. However, it also represents one of the most energy-intensive and carbon-emitting sectors worldwide. According to Hasan, Islam, and Napiah (2021), asphalt pavement production—especially Hot Mix Asphalt (HMA)—accounts for up to 39% of total energy consumption within the construction sector due to its high production temperatures ranging between 150°C and 180°C. This energy demand translates directly into significant greenhouse gas (GHG) emissions, with HMA plants emitting large amounts of CO<sub>2</sub>, SO<sub>2</sub>, and volatile organic compounds (VOCs) (Yang, Wang, & Liu, 2020).

As nations work toward net-zero carbon targets, the decarbonization of pavement construction has become a strategic priority within sustainable infrastructure frameworks (United Nations, 2023). The asphalt industry, in particular, is undergoing a technological

transformation to address environmental challenges through energy-efficient and resource-conserving practices (Rubio, Martínez, Baena, & Moreno, 2012).

Several innovations have emerged to improve the sustainability performance of asphalt mixtures. Warm Mix Asphalt (WMA) technology, for instance, reduces production and compaction temperatures by 20–40°C through foaming or chemical additives, leading to 20–35% lower fuel use and up to 40% reduction in CO<sub>2</sub> emissions (D'Angelo et al., 2008; Rubab & Hamid, 2019). Meanwhile, Reclaimed Asphalt Pavement (RAP) promotes circular economy principles by reusing existing pavement materials, thus reducing the demand for virgin aggregates and bitumen (Zaumanis & Mallick, 2015). Additionally, bio-asphalt binders, derived from renewable sources such as lignin, waste cooking oil, and algae, provide a sustainable alternative to petroleum-based bitumen, reducing dependence on fossil resources and minimizing life cycle impacts (Wang, Chen, & Zhang, 2022).

These technologies collectively represent a paradigm shift toward low-carbon, resource-efficient, and circular pavement systems. However, the degree of sustainability improvement varies based on material composition, climatic conditions, and construction practices (Caputo et al., 2019). Therefore, it is essential to assess these technologies not only from an environmental perspective but also through economic, technical, and social dimensions to determine their readiness for large-scale implementation.

The aim of this paper is to conduct a comprehensive review of sustainable asphalt mix technologies—including HMA, WMA, RAP, and bio-asphalt—using comparative sustainability assessments and life cycle analysis (LCA). The goal is to identify how these technologies contribute to decarbonization and to evaluate their potential in advancing global sustainable infrastructure development.

## **2. Technological Overview**

### **2.1 Hot Mix Asphalt (HMA)**

Beyond fly ash and steel slag, recent studies demonstrate that agricultural by-products like rice husk ash (RHA) can also substitute cementitious or aggregate components in concrete, achieving comparable strength while reducing embodied carbon. Rahman, Das, and Hossain (2025) reported that RHA-modified concrete achieved lower CO<sub>2</sub> emissions and acidification potential than steel-slag-based mixes, highlighting RHA's superior environmental performance in life-cycle terms. Hot Mix Asphalt (HMA) has been the traditional method for road construction for more than half a century. It is produced at mixing temperatures between 150°C and 180°C, ensuring full coating of aggregates and proper compaction of the mixture (Hasan, Islam, & Napiah, 2021). However, this high-temperature process requires intensive fuel use, resulting in significant emissions of CO<sub>2</sub>, NO<sub>x</sub>, and volatile organic compounds (VOCs) (Yang, Wang, & Liu, 2020). Because HMA production depends heavily on fossil fuels, it contributes substantially to the carbon footprint of the pavement industry. Consequently, the search for low-temperature, energy-efficient alternatives has intensified as part of global efforts to reduce greenhouse gas (GHG) emissions in construction.

### **2.2 Warm Mix Asphalt (WMA)**

Warm Mix Asphalt (WMA) is a next-generation technology developed to reduce the high energy demand of conventional asphalt production. WMA allows aggregate coating and compaction at 20–40°C lower temperatures by using techniques such as water foaming, organic wax additives, or chemical surfactants (Rubab & Hamid, 2019; D'Angelo et al., 2008). Lowering production temperatures can decrease fuel consumption by 20–35% and

reduce GHG emissions by up to 40% (Rubio, Martínez, Baena, & Moreno, 2012). Beyond environmental advantages, WMA improves workability, compaction, and worker safety, since reduced fumes and heat exposure make paving operations more comfortable and less hazardous (Sánchez-Garrido, Vega-Zamanillo, & Calzada-Pérez, 2021). Beyond cementitious systems, similar sustainability advantages have been reported in the pavement sector. Das, Rahman, and Hossain (2025) found that Warm Mix Asphalt (WMA) technologies lowered energy consumption by 20–75% and CO<sub>2</sub> emissions by up to 60% relative to Hot Mix Asphalt, reinforcing that temperature-controlled and waste-integrated processes yield tangible environmental gains across construction materials.

The combination of energy efficiency and improved occupational health makes WMA one of the most promising sustainable asphalt technologies currently in large-scale use.

### **2.3 Reclaimed Asphalt Pavement (RAP) and Recycled Asphalt Shingles (RAS)**

Reclaimed Asphalt Pavement (RAP) represents a key strategy for achieving a circular economy within the asphalt sector. RAP is produced by milling or crushing existing pavements and reintroducing the reclaimed material into new asphalt mixtures. Previous studies have shown that incorporating 20–40% RAP can reduce embodied energy by 15–25% and lower material costs by 10–20% without significantly compromising pavement performance when proper mix design procedures are followed (Mogawer et al., 2012; Zaumanis et al., 2014). Recycled Asphalt Shingles (RAS), obtained from roofing waste, provide an additional bitumen-rich material that enhances binder stiffness while improving resource efficiency (Aurangzeb et al., 2014). By combining RAP and RAS, asphalt producers can substantially reduce the demand for virgin aggregates and asphalt binders while diverting significant quantities of waste from landfills.

The successful implementation of RAP and RAS technologies aligns closely with broader sustainability and circular economy objectives. Kusuma, Ismanto, and Hasan (2025) emphasized the importance of resource-efficient technologies and waste management practices in promoting sustainable production systems, while Kusuma, Ismanto, Hasan, and Phan (2025) highlighted the role of governance and strategic decision-making in supporting sustainable resource utilization. Furthermore, Saiyed et al. (2025a) demonstrated that green innovation capabilities can accelerate the adoption of environmentally responsible technologies, suggesting that innovation-driven approaches may facilitate greater utilization of recycled materials in pavement construction. These findings indicate that the environmental benefits of RAP and RAS depend not only on material performance but also on effective organizational strategies and sustainability-oriented management practices.

### **2.4 Bio-Asphalt**

Bio-asphalt, derived from renewable resources such as lignin, algae, and waste cooking oil, is emerging as a viable low-carbon alternative to conventional petroleum-based bitumen. Recent research indicates that bio-binders can replace between 10% and 50% of conventional asphalt binders while maintaining comparable mechanical and rheological properties (Wang et al., 2022). Similarly, Yao et al. (2021) reported that lignin-modified asphalt improves stiffness and resistance to aging while reducing life-cycle greenhouse gas emissions. These characteristics make bio-asphalt a promising material for reducing the environmental footprint of road infrastructure.

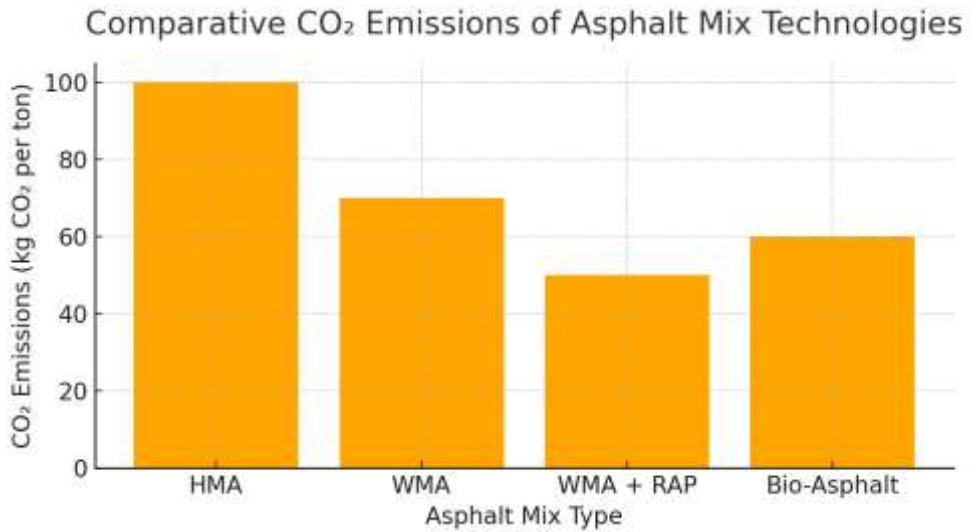
The adoption of bio-asphalt technologies is also influenced by organizational and institutional sustainability practices. Saiyed et al. (2025b) found that green human resource management (GHRM) practices contribute significantly to sustainable organizational performance by fostering environmental awareness and innovation. Similarly, Saiyed et al. (2026) reported that AI-enabled and gamified GHRM practices enhance employee environmental engagement, which may support the implementation of sustainable technologies such as bio-based construction materials. From a governance perspective, Hasan (2025) emphasized that Environmental, Social, and Governance (ESG) disclosure promotes accountability and long-term sustainability performance, creating incentives for organizations to invest in environmentally friendly innovations. Despite its potential benefits, large-scale adoption of bio-asphalt continues to face challenges related to higher initial costs, feedstock variability, and long-term durability under different climatic conditions. Consequently, further research, pilot-scale implementation, and supportive sustainability policies are required to establish performance standards and improve the commercial viability of bio-asphalt applications.

### **3. Sustainability Dimensions**

#### **3.1 Environmental Perspective**

Environmental performance is the cornerstone of sustainable asphalt technologies. Numerous empirical and simulation-based studies confirm that Warm Mix Asphalt (WMA) can lower total energy consumption by 20–35% and cut CO<sub>2</sub> emissions by 25–40% compared with conventional Hot Mix Asphalt (HMA) (Rubio, Martínez, Baena, & Moreno, 2012; Hasan, Islam, & Napiyah, 2021). When WMA is combined with Reclaimed Asphalt Pavement (RAP), cumulative emission reductions of nearly 50% have been achieved in life-cycle inventories (Aurangzeb, Al-Qadi, Ozer, & Lambros, 2014).

Furthermore, bio-asphalt derived from renewable feedstocks such as lignin and waste cooking oil provides additional environmental gains by replacing part of the fossil-based binder (Wang, Chen, & Zhang, 2022). Comprehensive Life Cycle Assessment (LCA) studies reveal that WMA and RAP mixtures exhibit markedly lower global-warming potential, acidification, and particulate emissions than HMA (Caputo et al., 2019). These outcomes demonstrate that sustainable asphalt technologies substantially advance decarbonization efforts and reduce dependency on non-renewable raw materials.

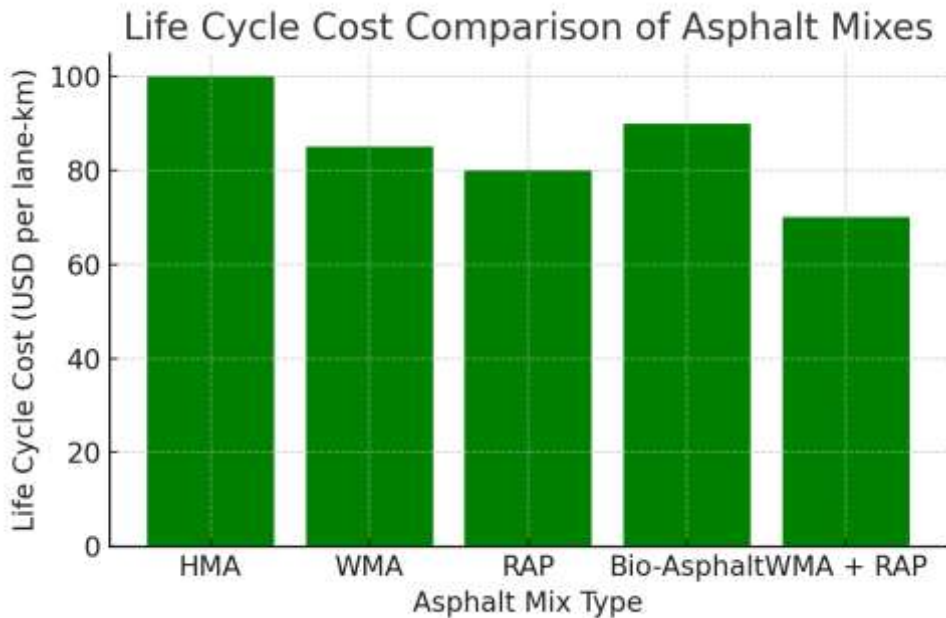


**Figure 1. Comparative CO<sub>2</sub> emissions of asphalt mix technologies — showing emission reductions achievable through WMA, RAP, bio-asphalt, and WMA+RAP combinations relative to conventional HMA.**

### 3.2 Economic Perspective

The economic viability of sustainable asphalt mixes is closely tied to reduced fuel use and material efficiency. WMA's lower production temperature yields direct fuel-cost savings of 10–20%, depending on plant type and fuel source (D'Angelo et al., 2008). The use of RAP further diminishes material expenses by partially substituting virgin aggregates and bitumen, thereby decreasing overall mix cost (Mogawer, Austerman, & Daniel, 2012).

Life-Cycle Cost Analysis (LCCA) frameworks consistently show that WMA–RAP combinations provide both short-term and long-term economic advantages through reduced energy bills, minimized maintenance interventions, and extended pavement life (Zaumanis & Mallick, 2015). Although bio-asphalt currently entails higher initial costs due to limited production scale and feedstock variability, ongoing research and industrial scaling are expected to enhance cost competitiveness in the near future (Yao, You, & Chen, 2021).



**Figure 2. Life cycle cost comparison of conventional and sustainable asphalt mix technologies — HMA carries the highest cost while WMA+RAP achieves the lowest life cycle cost; bio-asphalt has higher initial cost but lower long-term maintenance expenses.**

Graph 2 illustrates the life cycle cost comparison of various asphalt mix technologies. It shows that Hot Mix Asphalt (HMA) has the highest overall cost due to high energy consumption and maintenance needs. Warm Mix Asphalt (WMA) and Reclaimed Asphalt Pavement (RAP) significantly reduce costs by lowering fuel use and incorporating recycled materials. Although Bio-Asphalt has a slightly higher initial cost, its long-term performance offsets expenses through reduced maintenance. The combination of WMA and RAP achieves the lowest life cycle cost, demonstrating the most cost-effective and sustainable option among all mixes.

### 3.3 Technical Perspective

From a performance viewpoint, sustainable asphalt technologies display promising mechanical and durability characteristics. WMA mixtures offer improved workability and compaction at lower temperatures while maintaining or enhancing fatigue and rutting resistance compared with HMA (Rubab & Hamid, 2019). Properly designed RAP-containing mixes can meet or exceed conventional standards for stiffness and stability, provided rejuvenators are employed to restore aged binder properties (Zaumanis & Mallick, 2015).

Nevertheless, high RAP contents may increase mixture brittleness and susceptibility to cracking; thus, blending with bio-binders or rejuvenating additives is recommended to balance elasticity and strength (Yao et al., 2021). Continuous advances in binder chemistry and additive optimization are expanding the technical feasibility of sustainable asphalt at industrial scale.

### 3.4 Social Perspective

Beyond technical and environmental metrics, sustainability encompasses social well-being and occupational health. The reduced production temperatures of WMA and bio-asphalt mixes significantly decrease worker exposure to high heat and hydrocarbon fumes, leading to safer and more comfortable working environments (Sánchez-Garrido, Vega-Zamanillo, & Calzada-Pérez, 2021). Communities located near asphalt plants benefit from lower odor levels, noise reduction, and improved air quality.

Additionally, the circular reuse of materials such as RAP and RAS supports community acceptance and contributes to the United Nations Sustainable Development Goals (SDGs)—specifically SDG 9 (Industry, Innovation and Infrastructure), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). Through these combined benefits, sustainable asphalt technologies strengthen the social dimension of decarbonized infrastructure systems.

## **4. Life Cycle Assessment (LCA) Comparison**

Life Cycle Assessment (LCA) serves as a comprehensive and data-driven framework to evaluate the environmental implications of asphalt technologies throughout their entire life span—from raw material extraction to end-of-life recycling. It systematically quantifies the energy demand, greenhouse gas emissions, and resource depletion associated with each production stage, enabling a transparent comparison between conventional and sustainable asphalt systems.

Studies consistently show that sustainable technologies such as Warm Mix Asphalt (WMA) and Reclaimed Asphalt Pavement (RAP) significantly reduce environmental burdens compared to Hot Mix Asphalt (HMA). WMA requires lower production temperatures, resulting in a marked decrease in fuel consumption and carbon emissions per ton of asphalt produced. Similarly, incorporating RAP into new mixtures conserves virgin materials and reduces embodied energy, contributing to circular resource use.

Bio-asphalt introduces an additional sustainability dimension by utilizing renewable feedstocks that can offset part of the carbon footprint through biogenic carbon capture. However, LCA findings vary regionally due to differences in climate, material availability, and local energy sources. Integrating these findings into infrastructure policy frameworks enables governments and engineers to make evidence-based decisions that promote sustainable road construction while aligning with national decarbonization goals.

## **5. Future Directions**

The future of sustainable asphalt technologies is moving toward greater digitalization, circularity, and low-carbon innovation. Integrating smart construction systems such as digital twins, sensor-based monitoring, and artificial intelligence can enhance mix design accuracy, predict pavement performance, and continuously monitor emissions during production and operation. These data-driven tools are expected to revolutionize how sustainability metrics are tracked and optimized in real time.

Combining Warm Mix Asphalt (WMA), Reclaimed Asphalt Pavement (RAP), and bio-based binders into hybrid sustainable mixes represents a promising step toward balancing durability with environmental responsibility. Such integrated systems could significantly reduce life-cycle emissions while extending pavement lifespan.

Policy and regulatory measures will also play a critical role in driving the adoption of low-carbon technologies. Government incentives such as carbon credits, green certifications, and sustainable procurement frameworks can encourage industries to adopt environmentally conscious production methods. Future research should prioritize long-term field validation of laboratory findings, regional adaptation of sustainable materials, and large-scale testing of

bio-asphalt blends to ensure their recyclability, cost efficiency, and resilience under varying environmental conditions.

## 6. Conclusion

Decarbonizing pavement construction requires an integrated approach that addresses material efficiency, energy conservation, and environmental stewardship. Warm Mix Asphalt (WMA) provides a proven pathway to reduce emissions and enhance construction safety, while Reclaimed Asphalt Pavement (RAP) and bio-asphalt extend the benefits of resource recovery and circularity. Together, these technologies represent a paradigm shift toward sustainable infrastructure.

Life cycle analyses have shown that combining WMA, RAP, and bio-based binders can reduce greenhouse gas emissions by nearly half compared to conventional Hot Mix Asphalt. Beyond environmental benefits, these innovations improve economic performance and social acceptance, forming the foundation of future climate-resilient transportation systems.

The widespread adoption of sustainable asphalt technologies depends on coordinated efforts among researchers, policymakers, and industry leaders. Through continued innovation, supportive policy frameworks, and investment in sustainable materials, the pavement industry can evolve into a low-carbon, resource-efficient sector aligned with global net-zero emission objectives.

## References

- Aurangzeb, Q., Al-Qadi, I. L., Ozer, H., & Lambros, J. (2014). Quantifying environmental benefits of warm-mix asphalt over hot-mix asphalt using life-cycle assessment. *Transportation Research Record*, 2370(1), 10–20. <https://doi.org/10.3141/2370-02>
- Caputo, P., Loise, V., Porto, M., Eskandarsefat, S., Teltayev, B., & Rossi, C. O. (2019). Bitumen and asphalt concrete modified with bio-based materials: A review. *Materials*, 12(20), 3329. <https://doi.org/10.3390/ma12203329>
- D'Angelo, J., Harm, E., Bartoszek, J., Baumgardner, G., Corrigan, M., Cowser, J., ... Yeaton, B. (2008). *Warm-mix asphalt: European practice* (Report No. FHWA-PL-08-007). Federal Highway Administration.
- Das, A., Rahman, N. U., & Hossain, Z. (2025). Sustainability assessments of hot and warm mix asphalt paving technologies. In *Proceedings of the 10th North American International Conference on Industrial Engineering and Operations Management* (pp. 1-12).
- Hasan, M. (2025). The role of environmental, social, and governance (ESG) disclosure on firm value in ASEAN. *Advanced Business Journal*, 1(1), 11–17.
- Hasan, M. M., Islam, M. R., & Napiyah, M. (2021). Environmental impact assessment of hot and warm mix asphalt using life cycle assessment. *Construction and Building Materials*, 273, 121755. <https://doi.org/10.1016/j.conbuildmat.2020.121755>
- Kusuma, P. S. A. J., Ismanto, & Hasan, M. (2025). Food processing for a sustainable future: The role of resource-efficient technologies and waste management. In *BIO Web of Conferences* (Vol. 201, p. 05004). EDP Sciences.
- Kusuma, P. S. A. J., Ismanto, Hasan, M., & Phan, Q. H. (2025). Governance and strategy in sustainable food processing: A hierarchical framework. In *BIO Web of Conferences* (Vol. 201, p. 05005). EDP Sciences.

- Mogawer, W. S., Austerman, A. J., & Daniel, J. S. (2012). Performance characteristics of high RAP mixtures with rejuvenators and WMA additives. *Transportation Research Record*, 2294(1), 10–18. <https://doi.org/10.3141/2294-02>
- Rahman, N. U., Das, A., & Hossain, Z. (2025). Evaluating the use of steel slag and rice husk ash as replacements of aggregate in concrete: A sustainable next-gen concrete. In *Proceedings of the 10th North American International Conference on Industrial Engineering and Operations Management* (pp. 1-12).
- Saiyed, S., Hasan, M., Chowdhury, R., Hossain, M. A., Musa, S., & Kumar, V. (2025b). Green human resource management practices on the sustainable performance of India's sports sector. *Retos: Nuevas Tendencias en Educación Física, Deporte y Recreación*, 67, 946–961.
- Rubab, S., & Hamid, R. (2019). A review of warm mix asphalt technology: Environmental and technical aspects. *Sustainability*, 11(16), 4411. <https://doi.org/10.3390/su11164411>
- Rubio, M. C., Martínez, G., Baena, L., & Moreno, F. (2012). Warm mix asphalt: An overview. *Journal of Cleaner Production*, 24, 76–84. <https://doi.org/10.1016/j.jclepro.2011.11.053>
- Saiyed, S., Hasan, M., Chowdhury, R., Bin Parves, K. T., Hariyadi, E., & Kumar, V. (2025). Harnessing artificial intelligence to strengthen green innovation capacity in pursuit of sustainable development goals: Evidence from Taiwan's manufacturing sector. *Equilibrium. Quarterly Journal of Economics and Economic Policy*, 20(3), 877-904.
- Sánchez-Garrido, C., Vega-Zamanillo, Á., & Calzada-Pérez, M. A. (2021). Environmental evaluation of asphalt mixtures with reclaimed asphalt pavement (RAP) and warm mix asphalt (WMA) technologies. *Sustainability*, 13(7), 3932. <https://doi.org/10.3390/su13073932>
- United Nations. (2023). *Sustainable Development Goals Report 2023*. United Nations Publications.
- Wang, H., Chen, Y., & Zhang, Y. (2022). Bio-asphalt binder derived from waste cooking oil: Performance and environmental evaluation. *Journal of Cleaner Production*, 362, 132430. <https://doi.org/10.1016/j.jclepro.2022.132430>
- Yang, R., Wang, H., & Liu, H. (2020). Energy consumption and GHG emissions of asphalt pavement construction: A case study in China. *Energy Reports*, 6, 1170–1181. <https://doi.org/10.1016/j.egyr.2020.04.025>
- Yao, H., You, Z., & Chen, S. (2021). Lignin-modified asphalt binders: Bio-based alternatives to petroleum asphalt. *Construction and Building Materials*, 268, 121167. <https://doi.org/10.1016/j.conbuildmat.2020.121167>
- Zaumanis, M., & Mallick, R. B. (2015). Review of the rejuvenation of recycled asphalt pavements. *Construction and Building Materials*, 101, 155–165. <https://doi.org/10.1016/j.conbuildmat.2015.10.034>
- Zaumanis, M., Mallick, R. B., & Frank, R. (2014). Determining optimum rejuvenator dose for reclaimed asphalt pavement mixtures. *Construction and Building Materials*, 69, 159–166. <https://doi.org/10.1016/j.conbuildmat.2014.06.084>
- Saiyed, S., JR, A. N., Kumar, V., & Hasan, M. (2026). AI-enabled and gamified green HRM practices: Impacts on employee environmental engagement. *Oeconomia Copernicana*, 17(1), 181-224.