Review

Incorporating Waste Plastics into Pavement Materials: A Review of Opportunities, Risks, Environmental Implications and Monitoring Strategies

Ali Ghodrati * , Nuha S. Mashaan * , Themelina Paraskeva

Posted Date: 24 June 2025

doi: 10.20944/preprints202506.1932.v1

Keywords: waste plastics; asphalt pavement; pavement durability; microplastics; environmental impact; plastic emissions monitoring; risk mitigation; circular economy; sustainable pavement materials; life cycle performance

Review

Incorporating Waste Plastics into Pavement Materials: A Review of Opportunities, Risks, Environmental Implications and Monitoring Strategies

Ali Ghodrati [1,*], Nuha S. Mashaan [2,*] and Themelina Paraskeva [3]

[1] Mineral Recovery Research Centre (MRRC), School of Engineering, Edith Cowan University, Joondalup, WA 6027, Australia
[2] Mineral Recovery Research Centre (MRRC), School of Engineering, Edith Cowan University, Joondalup, WA 6027, Australia
[3] Mineral Recovery Research Centre (MRRC), School of Engineering, Edith Cowan University, Joondalup, WA 6027, Australia
* Correspondence: n.mashaan@ecu.edu.au (N.M.), a.ghodrati@ecu.edu.au (A.G.)

Abstract

The integration of waste plastics into pavement materials offers a dual benefit of enhancing road performance and mitigating the environmental burden of plastic waste. This review critically examines the opportunities and challenges associated with incorporating waste plastics in pavement construction, with an emphasis on their impact on mechanical properties, durability, and lifecycle performance of pavements. Special attention is given to the environmental implications, particularly the potential generation and release of micro- and nano-plastics during the pavement lifecycle. The paper further evaluates current monitoring and analytical methodologies for detecting plastic emissions from road surfaces and explores emerging approaches for minimizing environmental risks. By providing a comprehensive synthesis of existing knowledge, this review seeks to support sustainable practices and inform policy development within the frameworks of circular economy and environmental stewardship.

Keywords: waste plastics; asphalt pavement; pavement durability; microplastics; environmental impact; plastic emissions monitoring; risk mitigation; circular economy; sustainable pavement materials; life cycle performance

1. Introduction

The rapid rise of global plastics production, accompanied by insufficient waste management, has resulted in the massive accumulation of plastic waste in both aquatic and terrestrial ecosystems. In response to this growing challenge, researchers and industry stakeholders are actively investigating innovative ways for reusing waste plastics, in line with the fundamentals of the circular economy. The incorporation of recyclable plastics into pavement materials has emerged as a potential strategy, providing the simultaneous advantages of decreasing plastic pollution and enhancing pavement performance [1,2].

Over the past two decades, considerable progress has been made in understanding the interactions between various waste plastics, notably polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC) and bituminous binders and mixtures [1,3,4]. These thermoplastics, which constitute the majority of post-consumer plastic waste demonstrate advantageous thermal and mechanical properties, making them ideal for pavement modification [5,6]. thermosetting polymers, which do not re-melt upon heating up, are typically considered less suitable for such purposes.

The concept of incorporating plastics into pavements is not new; initial investigations go back to the 1990s. The increase in plastic waste production, anticipated to exceed 1 billion tonnes per year by 2050 [7] encouraging research in this field. Current findings indicate that waste plastics might improve the mechanical and durability characteristics of pavements, decrease dependency on virgin materials, and contribute to climate change mitigation through lowering the embodied carbon of road works [8–10].

The current practice includes three principal strategies for incorporating plastics into pavements: the wet method, the dry method, and hybrid or mixed methods [1,3]. In the wet method, polymers are mixed with the hot bitumen binder, enhancing its viscosity, elasticity, and resistance to rutting and fatigue [11,12]. In contrast, the dry method involves incorporating shredded or pelletized plastics into the heated aggregates [4]. The dry method attracted considerable interest because of its simplicity and capacity for incorporating greater plastic materials [13,14]. Hybrid methods are designed to combine the advantages of both approaches, although their commercial applicability remains limited. The selection of process significantly affects performance results, environmental hazards, and practical executions. Wet-processed binders often demonstrate enhanced rheological properties; nonetheless, they provide difficulties with storage stability and phase separation [15]. Dry-processed mixes, although easier to integrated into existing asphalt plants, may lead to a less uniform distribution of plastics and greater microplastic release over their service life [10,16].

Numerous investigations have consistently indicated enhancements in mechanical performance. Plastic-modified binders demonstrate elevated softening points, reduced penetration values, and improved rutting resistance [5,15,17]. When properly dosed, generally 3–8% by binder weight in wet processes and up to 10% by aggregate weight in dry processes, plastics can enhance the tensile strength, fracture resistance, and fatigue life of asphalt mixtures [3,18]. High plastic content may increase binder viscosity to levels that hinder workability and compaction, or cause brittleness at low temperatures, hence elevating the danger of thermal cracking [6,17]. The compatibility of plastics with bitumen is a crucial issue, influenced by polymer polarity, molecular weight, crystallinity, and the presence of additives [5,12].

In addition to mechanical performance, environmental consequences have undergone more scrutiny. Research indicates that specific plastics can elevate emissions of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) during the mixing process [16]. Furthermore, the prolonged emission of microplastics (MPs) from roadway surfaces due to Traffic flow and environmental degradation has become a significant issue [10]. Leaching behavior is also another area of active research. Research indicates minimal leaching of heavy metals and nutrients from plastic-modified pavements, but higher concentrations of dissolved organic carbon (DOC) have been seen in some cases [19]. Standardized leaching tests, such as the US EPA TCLP and EN 12457, are contributing to a better comprehension of potential groundwater impacts [20]. From a life cycle perspective, the incorporation of plastics into pavements presents distinct environmental advantages when properly optimized. Life cycle assessments (LCAs) consistently demonstrate decreases in greenhouse gas emissions, energy usage, and raw material consumption comparing to traditional pavements [8,9]. Nonetheless, these advantages may be offset if plastic feedstocks necessitate extensive transportation or energy-intensive preprocessing [21].

This review offers an updated perspective on the opportunities, hazards, and environmental consequences of plastic-modified pavements, acknowledging their potential to enhance sustainable materials management and robust road infrastructure. Identifying this potential necessitates a comprehensive methodology that systematically assesses performance, environmental trade-offs, and long-term consequences. This study brings together recent research findings, highlights significant gaps, and explores demands for future research, technology advancement, and policy development.

Preprints.org (www.preprints.org) | NOT PEER-REVIEWED | Posted: 24 June 2025 doi:10.20944/preprints202506.1932.v1

2. Types and Sources of Waste Plastics Used in Pavement

The incorporation of waste plastics in pavement construction materials has attracted considerable attention as a sustainable method for mitigating plastic pollution and promoting the circular economy [5,10,22]. Plastics used to construct asphalt pavements are predominantly derived from several waste streams, including municipal solid waste, industrial plastic remnants, agricultural plastic films, and marine debris [10]. The primary sources continue to be municipal and industrial waste, which consistently supply polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET) [22,23].

Plastics are primarily categorized into thermoplastics and thermosetting polymers. Thermoplastics become flexible when heated and can be remolded repeatedly, making them advantageous for asphalt modification as they can blend with bitumen at elevated temperatures. Common thermoplastics utilized in pavements comprise HDPE, LDPE, PP, PET, PS, and PVC [5,6,10,22]. Conversely, thermo-setting plastics have irreversible chemical transformations after curing and cannot be remelted, restricting their recyclability in asphalt [5,6].

A key characteristic affecting the suitability of plastic waste for pavement applications is the melting point of the plastic. The asphalt mixing process typically proceeds in temperatures ranging from 140°C to 180°C. Consequently, plastics possessing melting points within or beneath this range can efficiently melt and combine with bitumen. For instance, LDPE has a melting point of roughly 105–115°C, HDPE at 120–130°C, PP at 160–170°C, PS between 210–250°C, and PET at 250–260°C. PVC lacks a fixed melting point, instead decomposing around approximately 200°C. The melting point range is essential, as plastics with elevated melting points (such as PET and PS) may necessitate increased energy input or may not fully melt during mixing, resulting in inadequate dispersion or environmental hazards from degradation by-products [5]. Consequently, LDPE, HDPE, and PP are preferred due to their melting points being more compatible with standard asphalt production temperatures [5,6,10,24].

Various plastic types demonstrate innate advantages and disadvantages that extend beyond their mechanical properties in pavement applications. LDPE provides flexibility and ease of processing; yet it is prone to ultraviolet (UV) degradation and exhibits reduced strength. HDPE offers superior strength and moisture resistance, although may exhibit brittleness at low temperatures. Polypropylene exhibits chemical resistance and possesses a higher melting temperature; yet its adhesion to bitumen is inadequate in the absence of compatibilizers. PET exhibits significant tensile strength and chemical resistance, although necessitates extremely high temperatures for melting. PS offers significant rigidity; nonetheless, it is intrinsically fragile and susceptible to fracturing. PVC provides chemical and flame resistance; however, it raises environmental issues due to the emission of harmful gases when subjected to heating at pavement mixing temperatures [5,6,10,22,24].

The worldwide output of various plastics indicates their relative availability for recycling. Relevant research indicate that polyethylene (LDPE and HDPE combined) constitutes around 36% of global plastic manufacturing, making it the most prevalent form of plastic wastes. Polypropylene constitutes approximately 21%, whereas PVC provides roughly 12%, and both PET and PS account for around 7% each. These data underscore the viability of securing sufficient LDPE, HDPE, and PP for extensive pavement applications [5,6,10,25]. Table 1 presents a comparative assessment of the essential features, sources, and applicability of some of the most regularly used waste plastics in asphalt applications. Each plastic type exhibits distinct physical and chemical characteristics that influence the mechanical behavior and performance of the resulting pavement materials. The incorporation of waste plastics into asphalt has been shown to enhance key engineering properties, including increased stiffness, improved resistance to rutting, and enhanced durability under cyclic loading. For instance, polyethylene and polypropylene, owing to their thermoplastic nature and compatibility with bitumen, tend to improve the binder's elasticity and temperature susceptibility. This translates to better high-temperature performance and reduced deformation under heavy traffic loads.

Table 1. Characteristics, Sources, and Suitability of Common Waste Plastics in Asphalt Pavement Applications.

Reference	Plastic Type	Melting Point (°C)	Common Waste Sources	Key Advantages	Key Disadvantages
[6,10]	LDPE	110–120	Bottles, packaging films, bags	Good compatibility, flexibility, easy processing	UV degradation, lower strength
[6,10,26]	HDPE	~130	Containers, pipelines, industrial packaging	Elevated strength, moisture resistance	Fragile at low temperatures
[5,6]	PP	145–165	Straws, furnishings, automotive parts	superior chemical resistance, improves high-temp performance	Inadequate adhesion with bitumen unless compatibilized
[6,10]	PVC	160–210 (decomposes)	Pipes, cables, window frames	Flame resistance, stiffness	Releases toxic gases (e.g., HCl), poor thermal cracking resistance
[5,6]	PS	210–249	Food containers, cutlery, CD cases	Elevated rigidity, enhanced rutting resistance	Extremely brittle, poor low-temp performance
[6,10]	PET	~260	Beverage containers, fabrics	High tensile strength, chemical resistance	Requires substantial energy to melt, brittle at low temperatures
[6,10]	EVA	65–80	Sole materials, films, cables	Elastomeric properties, good low-temp performance	High viscosity, phase separation risks above 2 wt%
[6]	ABS	No true melting pt	E-waste, electronics	Improves viscosity and thermal characteristics	Limited compatibility, minimal recyclability

[6]	PU	No true melting pt	Upholstery, insulation, footwear	High strength	Decomposes, environmental risk when subjected to heating

3. Methods of Incorporating Plastics into Pavements

The incorporation of waste plastics into asphalt pavement can be accomplished through several techniques, including the wet process, dry process, and a hybrid referred to as the mixed method. In the wet method, plastic waste is melted and incorporated directly into the heated asphalt binder at elevated temperatures (often 160 °C –180°C), employing high-shear mixing to attain uniformity. This technique enhances the interaction between plastic and binder, resulting in superior elastic recovery and rutting resistance; however, it necessitates specialized equipment and presents issues such as phase separation and inadequate storage stability at elevated temperatures [5,6,24,27].

In contrast, the dry process is the direct incorporation of solid plastic waste frequently in shredded, pelletized, flaked, or powdered form into the heated aggregates prior to the addition of the binder. This technique enables polymers to act as filler or reinforcement, coating aggregate surfaces without directly altering the binder. It is easier to apply in existing asphalt plants and requires less expenditure; however, it may lead to less uniform dispersion, diminished moisture resistance, and lower enhancement of binder properties compared to the wet method [6,28].

An intermediate mixed method has been proposed, including elements of both wet and dry processes. This method involves pre-coating low-melting-point polymers onto heated aggregates, facilitating partial diffusion into the binder when added later. This approach enhances polymer distribution while minimizing dependence on specialized wet-process equipment. Nonetheless, it encounters obstacles like adjusting mixing temperature, assuring adequate plastic diffusion, and gaining consistency at scale [5,6,29]. The dimensions and morphology of plastic particles substantially affect the efficacy of the modified asphalt. Plastics utilized as modifiers may exist in forms including pellets, flakes, fibers, powders, or strips. Smaller particles facilitate superior dispersion and coating, improving compatibility and minimizing the possibility of phase separation, while bigger or irregularly shaped particles might result in inconsistent blending, reduced compaction, or the formation of voids. Uniformity in particle size is crucial for attaining desirable aggregate gradation and mixture workability [5,6,24].

Multiple factors affect the efficacy of each approach, such as plastic type and melting point, mixing temperature, time, shear rate, particle shape, and dosage. Plastics having melting points lower than asphalt mixing temperatures, such as LDPE and HDPE, are more appropriate for the wet process as they can liquefy and integrate with the binder under standard processing conditions. Conversely, higher-melting polymers such as PET and PS, which remain solid at asphalt mixing temperatures, are more appropriate for the dry process, serving as solid fillers or partial aggregate substitutes [13,14,22,30]. Compatibility and homogeneity present significant challenges, particularly in the wet process. Molecular weight, polarity, crystallinity, and asphaltene content of bitumen affect the interaction between plastic and binder. Poor compatibility may result in phase separation, yielding non-uniform mixes and diminished performance. Investigated solutions encompass the incorporation of compatibilizers (such as maleic anhydride-grafted polyolefins and polyphosphoric acid) or the functionalization of plastic surfaces to enhance adhesion with bitumen [6,17,27].

The proportion of plastic waste is generally optimized between 3–8% by weight of binder in the wet process, and may exceed 10% in the dry process, dependent on particle size and desired qualities. Exceeding optimum thresholds may result in heightened stiffness, decreased fatigue lifespan, and impaired workability [6,22,31]. Laboratory investigations and field experiments have confirmed the efficacy of these approaches. Field applications in India, Australia, and Europe have demonstrated good performance of dry-process roads with LDPE, HDPE, and PET at doses of approximately 8–10%, demonstrating enhanced rutting resistance and durability in both tropical and temperate regions. Nonetheless, field validation across varying traffic loads and climatic conditions is still constrained [6,10].

Every method possesses advantages and disadvantages. The wet approach provides superior binder modification and durability but requires greater energy and equipment expenditure, as well as poses dangers of storage instability. The dry technique is economical, simpler to implement, and allows for increased plastic content; yet it may lead to diminished moisture resistance and decreased binder-plastic interaction. The mixed technique provides a compromise, potentially enhancing distribution and diffusion while reducing the need for equipment modifications, although managing mixing conditions is more complex [6,10]. Table 2 presents a comparative overview of recent studies investigating different incorporation strategies, emphasizing critical characteristics such as plastic kinds, doses, mixing settings, and the advantages and disadvantages of each method.

Incorporating waste plastics into asphalt presents distinct advantages from both environmental and economic standpoints, such as diminished landfill utilization, reduced demand for virgin polymers, and a lowered environmental impact, demonstrated by a 17–25% reduction in greenhouse gas emissions, dependent on the type and quantity of plastic used. Economically, savings are realized by substituting a portion of the binder or aggregates with less expensive waste plastics, although initial expenses may increase due to the needs of processing, sorting, and quality assurance. Lifecycle studies highlight that environmental and economic advantages are optimized by utilizing locally sourced, uncontaminated plastic streams while considering transportation and processing logistics [8–10,32].

Despite promising outcomes, several problems and constraints remain. The wet process has challenges related to phase separation, compatibility, and aging, necessitating the use of compatibilizers or chemical treatments. The dry technique encounters challenges in attaining uniform dispersion and consistent compaction, particularly with elevated plastic contents. The mixed technique is still inadequately explored, with ambiguity around its long-term diffusion behavior and environmental release. Moreover, concerns regarding microplastic production from pavement degradation and possible fume emissions during mixing necessitate additional scrutiny to guarantee safety and sustainability [6,10,33].

Table 2. Methods of Incorporating Plastics into Pavements.

Reference	Incorporation Method	Plastic Type	Plastic Dosage	Mixing Temp (°C)	Application Scale	Benefits	Limitations / Drawbacks
[13]	Dry (Plastic-Coated Aggregates)	LDPE	7% by weight of reference (unmodified) binder	190	Lab South African dense graded asphalt mixtures)	Enhanced bonding and volumetric consistency; applicable in existing plants	Restricted to low-melting plastics; no change in optimum binder content; issues withphase uniformity

[32]	Wet (Binder Modifier)	Hard plastics with graphene	0.5% by weight of binder	Not specified	LCA Case Study (Europe)	Extended maintenance-free operating periods (MFOP); up to 70% environmental impact reduction	Necessitates preprocessing and quality control infrastructure
[29]	Mixed	RLDPE	1.5% by weight of total mix	Aggregate at 185, RAP/P-RAP at 95, Binder at 155	Lab scale	Superior rutting resistance among P-RAP mixes, adequate compatibility, fracture energy, and fatigue resistance	Requires precise control of mixing order and temperature for effective blending

4. Performance of Waste Plastic-Modified Bitumen Binder and Mixture

4.1. Characteristics of Plastic-Modified Bitumen Binder

Studies demonstrate that incorporating plastics including LDPE, HDPE, PP, PET, PS, and PVC into bitumen alters its physical, chemical, and rheological properties, with effects depending on the type of polymer, dosage, blending conditions, and interaction mechanisms [5,6].

4.1.1. Mechanical and Rheological Enhancements

The use of waste polymers generally results in diminished penetration values, indicating enhanced stiffness and decreased vulnerability to deformation at elevated temperatures [34,35]. Reductions in penetration vary from 15% to 63%, depending on the type of polymer, its concentration, and the mixing technique employed [34]. The higher stiffness enhances rutting resistance but may result in brittleness at low temperatures [34,36]. The softening point rises in direct correlation with plastic content, hence improving the high-temperature performance of asphalt. LDPE-modified binders have softening points ranging from 57 to 68.5 °C, HDPE from 51 to 79 °C, and LLDPE from 50 to 67 °C [34]. This improvement is attributed to the formation of polymer networks within the binder, enhancing its resistance to flow [36].

Plastic-modified bitumen has enhanced viscosity, which improves coating and drainage resistance, although raises issues regarding mixing and compaction [34,35]. The increased viscosity may surpass workability limits, particularly when plastic content exceeds 5 wt% [6,34,36]. The increase in viscosity is associated with the swelling of polymer particles and the establishment of a three-dimensional polymer network inside the bitumen [5,34,36]. Bitumen modified with 10% plastic

doi:10.20944/preprints202506.1932.v1

waste and controlled particle size (0.063–4 mm) exhibited enhanced workability and consistent viscosity [34]. At 135 °C, the viscosity of this blend roughly approximated that of conventional polymer-modified bitumen, confirming its suitability for practical applications [34].

Thermal stability evaluations demonstrated that plastic waste-modified binders maintained chemical stability at standard mixing temperatures (~150 °C), with no notable oxidation detected using FTIR spectroscopy [12,34,36].

Superpave performance assessments validate improved rutting resistance (elevated $G^*/\sin\delta$) with plastic modification; nevertheless, fatigue resistance ($G^*\cdot\sin\delta$) may diminish at higher plastic contents [6]. The incorporation of 5% polyethylene considerably diminished ductility, underscoring an elevated risk of low-temperature cracking [34]. Hybrid systems that integrate LDPE and crumb rubber enhance both rutting and fatigue resistance, with LDPE contributing rigidity and crumb rubber enhancing elasticity [34,35]. Excessive polymer content may result in poor low-temperature performance unless compatibilizers are included [34]. Response surface optimization research determined that optimal low-temperature rheological performance was achieved with 3% LDPE and 2.02% crumb rubber. This formulation reduced creep stiffness and enhanced the m-value in BBR testing, signifying a balance between flexibility and rigidity [35].

4.1.2. Enhancing Compatibility and Reducing Aging

Recent discoveries indicate that photo-oxidative aging of polyethylene improves its compatibility with bitumen. PE oxidized for roughly 8 days demonstrated the maximum binding energy with bitumen due to the development of polar carbonyl groups. This oxidation facilitated molecular coupling and enhanced resistance to diffusion, hence enhancing stiffness and rutting resistance [36]. Compatibility issues emerge from differences in polarity, molecular weight, and crystallinity between plastic and bitumen. HDPE and PP, having high crystallinity, frequently demonstrate phase separation when stored at elevated temperatures, whereas LDPE and EVA offer superior compatibility because of their reduced crystallinity and branching [6,27,37].

Aminolysis-based PET additives such as BAET and BHETA enhanced binder adhesion and stripping resistance [38]. BAET, due to its superior terminal group structure, delivered more pronounced improvements compared to BHETA [39]. Hybrid systems combining SBS, recycled LDPE/PP, and sulfur (as a compatibilizer) showed up to 330% improvement in elastic recovery after UV exposure and reduced oxidation indicators (carbonyl/sulfoxide peaks) in FTIR analysis [40,41].

4.1.3. Effect of Bitumen Modification Mixing Parameters and Plastic Particle Size

Stable dispersion and storage is significantly influenced by mixing factors such as plastic dose, mixing temperature, shear rate, and mixing duration [42]. The conditions of blending, namely temperature, shear rate, and mixing duration substantially influence performance [17]. Optimal blending generally occurs at temperatures ranging from 150 to 180 °C, with shear rates above 3000 rpm for a minimum duration of 90 minutes [42,43]. Elevated temperatures pose a threat to plastic degradation or bitumen oxidation [17].

Plastic waste with smaller particle sizes was observed to enhance phase distribution and binder stability. Microscopic analysis verified a more uniform polymer dispersion in contrast to blends containing bigger plastic particles [42]. Smaller plastic particles (<1 mm) enhance dispersion, minimizing coalescence and phase separation [6]. The risk of agglomeration increases with larger particle size [42]. Table 3 presents an extensive overview of the several waste plastics utilized in bitumen modification, including their standard dosages, mixing circumstances, and related performance effects.

Table 3. Performance of Plastic-Modified Bitumen Binder.

References	Plastic Type	Dosage (wt%)	Mixing Temp (°C)	Shear Rate / Time	Key Performance Impacts	Compatibility / Aging
[34,36]	LDPE	Up to 5% (by weight of the unmodified binder)	160–180	≥3000 rpm / ≥90 min	↑ Softening point (57–68.5 °C), ↓ Penetration (up to 63%), ↑ Viscosity, improved rutting resistance	Moderate compatibility: phase stability depends on particle size and dosage
[34]	HDPE	Up to 5% (by weight of the unmodified binder)	160–180	≥3000 rpm / ≥90 min	↑ Softening point (51–79 °C), ↑ Stiffness, ↓ Penetration	Reduced compatibility resulting from elevated crystallinity; susceptible to phase separation
[36]	Photo-oxidized PE	Not specified	170	5000 rpm / 60 min	↑ G*/sinδ, ↑ Stiffness, ↑ Compatibility and Homogeneity, ↓ Diffusion coefficient	Elevated compatibility attributed to polar groups; improved dispersion and interaction
[35]	LDPE + Crumb Rubber	3% LDPE + 2% CR	~170	3000 rpm / 90 min	Optimized low-temp performance (↓ stiffness, ↑ m-value); improved fatigue and rutting resistance	Effective synergistic interaction; refined by response surface methodology

4.2. Characteristics of Plastic-Modified Bituminous Mixtures

Several literature reviews highlight the benefits of using plastic waste such as PET, HDPE, and PP in asphalt mixtures [4,5,14,44,45]. These reviews combine findings from more than twenty years of global research, illustrating that plastic may improve mechanical characteristics, decrease resource dependency, and boost sustainability metrics of asphalt mixtures.

4.2.1. Mechanical and Durability Performance

Recent research by [46] presented a chemically recycled PET additive synthesized using aminolysis, which considerably enhanced rutting resistance, moisture resistance, and low-temperature cracking performance, particularly at a 2% dose. Nonetheless, the optimal dynamic creep resistance was seen at 1% additive concentration, suggesting that the optimal dosage may vary with performance criteria. The results were statistically validated by ANOVA analysis [46]. Recent findings from Balanced Mix Design (BMD) experiments indicate that the addition of 0.25–1.0% LDPE or LLDPE by weight of aggregate enhances rutting resistance and cracking performance relative to control mixes. LLDPE exhibited superior cracking tolerance (CTIndex), although LDPE had enhanced moisture resistance [47].

[48] demonstrated that longer (18 mm), rough-surfaced PET fibers significantly enhanced the cracking resistance and hardness of asphalt mixtures at both ambient and sub-zero temperatures, as assessed by the SCB test. The advantages became more apparent as the loading rate of the SCB test reduced, indicating the necessity for protocol enhancement in evaluating crack performance. Field trial evidence confirms this, as illustrated in Ontario, Canada, where PET fibers utilized in cold climes exhibited enhanced low-temperature crack resistance compared to mixed plastics [49].

[50] assessed dry-processed plastic and rubber-modified composites subjected to aging and moisture conditioning. Short-term ageing enhanced tensile strength and stiffness in all mixtures, however long-term aging produced uneven effect benefiting plastic-modified asphalt but degrading that of rubberised mixtures. Moisture conditioning led to performance declines of up to 17% in rutting resistance and 9% in modulus across all modified mixtures, underscoring the significance of appropriate mix design for durability. Table 4 provides a comparative review of experimental research assessing the mechanical and durability performance of asphalt mixes modified with different types of plastics, doses, and blending methods.

Table 4. Plastic-modified Asphalt Mixture Performance.

Reference	Plastic Type	Dosage	Incorporation Method	Performance Outcomes	Notable Insights
[46]	PET (chemically recycled)	1–3% by wt. of binder	Wet process (aminolysis)	↑ Rutting & moisture resistance; ↓ Low-temp cracking; Optimal dynamic creep at 1%	Dosage-performance tradeoff; ANOVA confirmed significance
[47]	LDPE / LLDPE	0.25–1.0% by wt. of aggregate	Dry process	↑ Rutting resistance, CTIndex (LLDPE); ↑ Moisture resistance (LDPE)	LLDPE showed better crack tolerance; LDPE showed better moisture resistant
[48,49]	PET fibers	Not specified (18 mm fibers)	Dry process (fiber reinforcement)	↑ Cracking resistance and toughness in SCB tests	More effective at low loading rates and cold climates

[51]	LLDPE	0.5% by wt. of aggregate (dry); 1.0% by wt. of binder (wet)	Both dry and wet processes	Wet: Comparable to SBS; Dry: ↓ CTIndex, ↑ Stiffness	Wet method showed more balanced overall performance; Dry method leads to brittleness
[52]	LDPE / HDPE	Unspecified; flakes/powder	Modified dry process (PlasticAid)	↑ Compactability, ↓ Rut depth, ↑ Crack resistance (flakes)	Powder less effective than flakes
[53]	Waste plastic granules + RAP	0.3–0.5% granules	Hybrid (mi	Maintained strength; ↑ Sustainability	No compromise in volumetrics or workability
[54]	PET + crumb rubber	2% PET + 10% rubber	Dry process	↑ Marshall stability, stiffness, ITS	Synergistic effects observed (PET enhances stiffness and temperature resistance; Crumb rubber improves elasticity and fatigue life.)
[55]	Polyethylene + Rubber	Not specified	Dry-mixed composite	↑ Rutting resistance; balanced fatigue life	Twin-screw extrusion improved integration
[56]	Multilayered Plastic	High-dose (unspecified)	Dry process	↑ Air voids, ↓ Moisture resistance	High content increases compaction challenges

4.2.2. Blending Methods and Processing Techniques

[51] assessed dry and wet methods using LLDPE. The dry method (0.5% by weight of aggregate) enhanced mixture stiffness and improved rutting resistance, but resulted in diminished cracking resistance, as seen by a lower CTIndex in IDEAL-CT testing. In contrast, the wet-processed mixture (1.0% LLDPE in binder) exhibited performance comparable to the SBS-modified control in HWTT,

dynamic modulus, and fatigue resistance, with minimal surface cracking after 10 million ESALs. Conversely, the dry mixture demonstrated 3.5% surface cracking under the same stress conditions, underscoring the brittleness impact linked to the presence of dry LLDPE.

[52] presented the “PlasticAid” method, employing shredded LDPE and HDPE as a compaction aid through a modified dry process. Their research demonstrated greater compatibility, reduced rut depth, and improved cracking resistance (as measured by the CT-index), particularly with the utilization of LDPE flakes. Powdered forms exhibited less efficacy. A study by [53] evaluated a hybrid method that combined 50% reclaimed asphalt pavement (RAP) with 0.3–0.5% waste plastic granules. The mixtures-maintained strength (in terms of stiffness and volumetric properties) and improved sustainability indicators without compromising workability.

4.2.3. Hybrid and Composite Systems

A study by [54] illustrated the synergistic advantages of blending PET with crumb rubber, revealing that an optimal composition of 2% PET and 10% rubber attained superior Marshall stability, stiffness, and indirect tensile strength compared to each material individually. Similar improvements in crack resistance and fracture energy have been noted with the addition of cross-linked polyethylene (Si-XLPE) waste, which enhanced toughness under Mode I, II, and mixed loading conditions [57].

Studies by [55,58] discovered that the use of crumb rubber with polyethylene in dry-mixed composite particles improved rutting resistance while maintaining fatigue life. Rubber-plastic composite particles, produced using twin-screw extrusion, resulted in mixes exhibiting enhanced deformation resistance and satisfactory moisture sensitivity.

4.2.4. Challenges and Practical Considerations

Despite the advantages of utilizing waste plastics as alternative materials in asphalt mixtures, several challenges impede extensive use. A significant issue is the diversity in efficacy contingent upon plastic type, dosage, and shape [14,59]. Higher plastic contents often reduce mixture density and amplifies air spaces, adversely affecting compaction and moisture resistance [56,60].

Field investigations by [61] emphasize that the adhesion between plastic and aggregates is significantly influenced by aggregate mineralogy. Basic rocks such as dolomite and limestone exhibit superior bonding with plastic in contrast to acidic rocks like granite. Another practical concern is the limited availability of comprehensive long-term field performance data. Despite promising outcomes in experiments conducted in Singapore, India, and the UK with 5–8% plastic content, widespread implementation necessitates thorough monitoring across various climates and traffic circumstances.

Quality control is another critical issue. Variable properties of plastic feedstock such as polymer type, contamination level, and particle size can influence the consistency of outcomes. The processing infrastructure requires enhancement to provide secure handling, mixing, and emissions management, especially during the heating of plastic waste.

5. Environmental Aspects and Health Risks

5.1. Fuming

The incorporation of recycled plastics into asphalt, although ecologically beneficial, presents considerable issues related to the emission of volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs). These compounds are predominantly emitted during the production or application of plastic-modified asphalt at elevated temperatures (generally 140–200 °C), when bitumen and polymeric additives experience thermal degradation and volatilization [16].

Research indicates that raising the mixing temperature can significantly increase emissions. For example, VOC emissions rose by as much as 50.3%, and PAH emissions by up to 50.4% when the operating temperature was elevated from 160 °C to 180 °C [16]. Increased emissions result from the degradation of long-chain hydrocarbons in bitumen and plastic additives, releasing chemicals such benzene, toluene, styrene, and benzo[a]pyrene, some of which are recognized carcinogens [62].

Nonetheless, not all forms of plastic exhibit same behavior. Certain polymers, such as recycled low-density polyethylene (LDPE) and commingled polyethylene (cPE), when integrated into bitumen via the wet process, showed decreased total VOC and PAH emissions compared to conventional bitumen. For instance, incorporating 6% cPE at 140 °C resulted in an 11.2% decrease in VOC emissions [16]. The decreases are partially attributable to the adsorption properties of plastics, which physically or chemically retain VOCs and PAHs on their surfaces during mixing [16].

Conversely, some plastics, such as recycled acrylonitrile butadiene styrene (rABS), particularly at elevated temperatures of 180 °C, may lead to heightened emissions due to the degradation of polymer chains. The emission of benzene and other polycyclic aromatic hydrocarbons (PAHs) markedly increases with elevated rABS concentration, as observed with increases up to 19.5% for PAHs [16].

The inhalation of these chemicals poses health concerns. Although VOC carcinogens such as benzene and styrene exhibited minimal non-carcinogenic and carcinogenic risks at occupational exposure levels, PAHs such benzo[a]pyrene and dibenz[a,h]anthracene presented low to potential health risks [33]. Environmental risk studies indicate that asphalt workers, particularly under high-temperature conditions or when inappropriate plastic types are utilized, may be subjected to potentially harmful pollutants. Mitigation techniques have been investigated. Warm mix asphalt (WMA) technologies, which decrease operating temperatures, have demonstrated a substantial reduction in emissions [16]. Furthermore, additions such activated carbon, zeolite, geopolymer binders, and latex might diminish the release of VOCs and PAHs through improved adsorption and physical trapping processes [63–66].

5.2. Leaching Characteristics and Release of Microplastics from Plastic-Modified Asphalt Mixtures

Plastic-modified asphalt mixtures have become increasingly favored for their ability to diminish plastic waste and improve surface performance [67,68]. Nonetheless, their environmental sustainability must be evaluated regarding leaching behavior and microplastic (MP) emissions during their their service life [10,69]. Recent studies suggest that the integration of plastic into asphalt raises concerns about the emission of toxic chemicals and microplastics as a result of environmental exposure, mechanical abrasion, and thermal degradation [10].

Leaching investigations of asphalt mixtures including waste plastics have predominantly concentrated on the discharge of heavy metals, nutrients, dissolved organic carbon (DOC), and other hazardous substances into aquatic environments [10]. For example, leachability tests conducted on asphalt pavement modified with plastic particles, utilizing Cantabro abrasion, demonstrate a restricted release of conventional water contaminants, including nutrients and heavy metals [20]. DOC, including many organic pollutants, is an essential parameter to monitor due to its potential to affect the mobility, bioavailability, and toxicity of other contaminants, as well as to stimulate microbial proliferation and algal blooms in aquatic ecosystems [20].

Standardized leaching tests, including US EPA Method 1311 (TCLP), Method 1312 (SPLP), EN 12457, and ISO 21268, have been utilized to assess the possible leachability of asphalt components [20,70]. Nonetheless, discrepancies in particle size preparation and testing conditions impede comparability among studies [10,70]. Recent methodologies, such as utilizing particles from Cantabro abrasion instead of random crushing, provide a more authentic representation of field conditions [20]. The release of MPs from plastic-modified asphalt has gained considerable attention. Microplastics (MPs) are predominantly produced through mechanical abrasion caused by vehicular traffic, environmental weathering, and UV exposure [10,71]. Laboratory simulations utilizing Wet Track Abrasion machines have shown that microplastics can be released from both wet- and dry-incorporated plastics, but the mechanisms and degrees of release vary [72]. Wet incorporation methods generally integrate polymers more uniformly into the bitumen matrix, potentially enhancing surface exposure. Conversely, the dry approach often utilizes bigger plastic particles acting as aggregates, exhibiting variable surface exposure depending on their placement inside the pavement [33].

Phase separation between plastic and bitumen has been recognized as a significant cause to both leaching and microplastic release [10,73]. Plastics that exhibit inadequate compatibility with bitumen may segregate during mixing and application, particularly those characterized by high molecular weight or low maltene fractions, resulting in the possible leaching of unbound polymers and additives [10]. These incompatibilities elevate the probability of plastic fragments detaching during operation, hence facilitating microplastic formation [33].

Toxicological issues arise from the release of microplastics (MP) due to residual additives, including flame retardants, phthalates, and heavy metals, which may leak into surrounding soils and waterways [10,69,73]. MPs also serve as carriers for these contaminants and may facilitate their entry into biological systems via ingestion or dermal contact [10,74]. In ecosystems, these particles can experience bioaccumulation and biomagnification, hence increasing ecological concerns [73,75]. Although promising results indicate that the encapsulation of MPs in bitumen mastics can diminish release by more than 99% [33], long-term environmental monitoring is essential to validate laboratory-based hypotheses [10]. Recent studies utilizing road dust analysis and batch leaching under simulated rainfall indicate that well-integrated plastic-modified asphalts exhibit performance comparable to traditional asphalts for dissolved organic carbon and metal leaching. [20,69,73,76].

5.3. Life Cycle Environmental Impact and Life Cycle Cost Characteristics of Plastic-Modified Asphalt Pavement

The environmental impact of conventional asphalt pavements is primarily influenced by the material production phase, particularly because of the extraction and processing of virgin bitumen and aggregates [77–79]. Several studies have shown that replacing these materials with recycled plastic polymers such as PET, HDPE, LDPE, and PP can significantly decrease energy usage, greenhouse gas (GHG) emissions, and related environmental impacts [21,80–82].

Environmental benefits also encompass diminished dependence on virgin aggregates, diversion of plastic waste from landfills, and a reduced carbon footprint [9,81–84]. The lightweight characteristics of plastic aggregates enhance handling and transportation [21]. Furthermore, the encapsulation of plastic within asphalt matrix may diminish the release of microplastics, providing a dual environmental advantage [9,73]. PE-modified asphalt was found to offer economic and environmental advantages. Incorporating 5% PE binder can decrease bitumen consumption by nearly 1 ton per kilometer of roadway and divert roughly 1.125 million plastic bags from landfills for each kilometer [34].

The incorporation of 4% PET and ABS in asphalt binders resulted in substantial decreases in rehabilitation cycles and net present worth (NPW) expenses, thus reducing the equivalent annualized cost (EAC) by as much as 50% relative to traditional mixtures [80]. According to [21], noted that the utilization of recycled polyethylene resulted in a 12.5% decrease in pavement thickness or a 7% extension of maintenance intervals, producing net environmental advantages. In a cradle-to-grave LCA study, [9] found that PMAPs utilizing PET and HDPE through the dry process enhanced pavement longevity by 14–65%, depending on structural design and traffic conditions. Although early impacts in raw material production were greater, these were mitigated by reduced maintenance requirements and landfill diversion. However, the progressive deterioration of pavement roughness over time has resulted in heightened vehicle emissions, which may overshadow total Global Warming Potential unless maintenance cycles are meticulously optimized.

A study by [9] compared dry and wet process plastic-modified mixtures to SBS-modified asphalt and determined that recycled plastic surpassed SBS-modified mixes in the majority of environmental parameters. Wet process mixtures demonstrated greater environmental benefits owing to superior dispersion and performance, despite elevated initial energy requirements for processing. Similarly, [85] indicated that the combining 40% RAP with 2% PET may diminish life cycle expenses by as much as 31.8% and lessen GHG emissions by 37.6%. A study by [86] determined that wet-process plastic pellets diminished climate change, acidification, ozone depletion, and photochemical oxidation potentials by 8.6% to 15.6%, 4.7% to 8.9%, 7.2% to 13.4%, and 4.5% to 8.6%, respectively. Additionally, [9,32] emphasized that the integration of recovered plastics into asphalt advanced circular economy objectives by redirecting substantial amounts of post-consumer plastics from landfills.

Nonetheless, economic viability and ecological efficacy are significantly influenced by mixture formulation, local accessibility of plastic waste, and processing logistics [73]. Some research indicated that elevated GWP was associated with plastics necessitating long-distance transportation or energy-intensive preparation [8,9,78].

Some studies also raised concerns over uncertainty in long-term environmental behavior. If plastic-modified pavements result in increased surface roughness or microplastic release, their life-cycle benefits could be partially negated [9]. As such, integration with other sustainable practices—such as warm mix asphalt technologies, RAP, and improved compaction control—is encouraged to maximize net benefit [77,78]. Table 5 summarizes key findings from studies included in Section 5 of this review paper, addressing fume emissions, leaching and microplastic release, as well as the life cycle environmental and economic implications related to plastic-modified asphalt mixtures.

Table 5. Environmental Aspects of Plastic-Modified Asphalt.

References	Plastic Type	Incorporation Method	Key Findings	Conditions	Environmental Impacts
[16]	cPE, LDPE, rABS	Wet process	VOC and PAH emissions increased with temperature; 6% cPE at 140°C reduced VOC by 11.2%; rABS at 180°C increased PAH by 19.5%	140–180°C, 6% cPE, rABS variants	Temperature-sensitive fume emissions; cPE shows mitigation potential
[33]	Various, incl. LDPE, HDPE	Wet and Dry	MPs generated via mechanical wear (e.g., from traffic); wet method embeds more uniformly in the bitumen, which reduces exposure; dry leaves surface-more exposed plastics, increasing the	Simulated traffic & abrasion	Wet: less MP release; Dry: method more susceptible to MP shedding

			risk of microplastic release.		
[20]	Unspecified plastic particles	Dry	Cantabro abrasion yielded realistic leachate with low nutrient/heavy metal levels but noted DOC mobility	Leaching post-Cantabro abrasion	Low metals; DOC remains concern for aquatic systems
[73]	Various	Wet/Dry	Poor compatibility leads to phase separation and plastic loss; increases leaching and MPs	Environmental exposure, field sim.	Elevated risk of MPs from poorly compatible blends
[9]	PET, HDPE	Dry	RPM increased pavement life by 14–65%, reducing maintenance; road roughness raised vehicle emissions	FlexPave™, AASHTOWare simulations	Net benefit only if roughness is controlled; major landfill diversion

[8]	LDPE, PS	Wet & Dry	Plastic-modified asphalt outperformed SBS in all except for ozone depletion; transport & processing energy contributes significantly to the total environmental impact	Full LCA: cradle to installation	Using waste plastics Generally better than SBS in terms of environmental impacts; wet process tends to result in cleaner environmental outcomes over the long term
[86]	PE (LDPE, HDPE)	Wet and Dry	Wet process showed stronger environmental gains than dry; recycling locally amplifies benefits	Case study in Victoria, Australia	Wet method better for GHG; dry method is constrained by synthetic aggregate replacement efficiency
[34]	PE	Not specified	5% PE saved >1 ton bitumen and diverted 1.125 million plastic bags/km	5% PE binder	Significant plastic waste diversion and material savings
[85]	PET	Dry process with up to 40% RAP	2% PET + 40% RAP reduced life cycle costs by 31.8% and GHG emissions by 37.6%	2% PET binder, up to 40% RAP	Significant reduction in both cost and emissions with recycled content synergy
[32]	Hard polyolefins + graphene	Wet (modifier granulate)	Impact reductions of ~70% (standard	0.5% plastic modifier; 20-year LCA	Circular use of hard plastics enables substantial

	thickness scenario) and ~30% (reduced thickness)	impact mitigation and durability gains

6. Critical Discussion

The incorporation of waste plastics into asphalt pavements has drawn academic and industrial attention in the last five years, surged by escalating plastic pollution, policy shifts towards circular economy purposes, and advancements in bitumen modification technology. The review highlights potential mechanical and environmental advantages while also exposing considerable contradictions, methodological unraveling, and unresolved environmental issues that must be addressed prior to the determination of sustainable or risk-informed broad adoption.

Studies on mechanical performance consistently indicate enhancements in rutting resistance, stiffness, and high-temperature durability, especially when LDPE, HDPE, or PP are utilized within optimized dosage ranges (generally 3–8 wt% of binder for wet processes and up to 10 wt% of aggregate for dry processes). However, above these thresholds, other investigations (e.g.,[34]) observed diminished workability, higher brittleness, and increased viscosity, indicating a limited performance range. Experimental inconsistencies are apparent in test circumstances, with several research use SCB or IDEAL-CT for fracture resistance, while others utilize indirect tensile strength or Marshall characteristics, hence complicating direct comparisons. Even when employing Balanced Mix Design (BMD) frameworks, as evidenced by [51], contradictory results between laboratory cracking indices and field cracking resistance highlight the necessity for standardized testing protocols and performance thresholds customized for plastic-modified systems.

Environmental impacts of plastic-modified asphalt are far from negligible. While several life cycle assessments [8,9] demonstrate reduced greenhouse gas emissions, raw material consumption, and maintenance requirements compared to conventional pavements, these advantages are context-dependent. For example, environmental benefits are reduced when plastic feedstocks necessitate long-distance transportation or energy-intensive preprocessing [21]. Furthermore, recent research on microplastic emissions [10,33] underscores the hazards linked to wear-induced separation, particularly in dry-processed pavements where plastics function as discrete particles. Despite the potential of encapsulation techniques and warm mix asphalt (WMA) technology to mitigate emissions and plastic exposure, field validation is still limited. Moreover, there is less agreement regarding permissible release rates of micro- and nano plastics, as well as the ecotoxicological effects of long-term roadway exposure.

The concern of fume and chemical emissions during production and installation represents another inadequately examined danger area. Some polymers, including LDPE and cPE, have been associated with reductions in VOCs at moderate mixing temperatures [16], but others, such as rABS, increase PAH emissions under comparable conditions [62]. Health risk assessments [33] indicate that occupational exposure to polycyclic aromatic hydrocarbons (PAHs), such as benzo[a]pyrene, may present low to moderate health concerns, particularly under high-temperature conditions. Mitigation techniques employing additives such as activated carbon [64]and zeolite [65] demonstrate potential but have not been completely incorporated into normal practice. A critical necessity exists to develop temperature-dependent emission profiles for various plastic types and blending techniques, accompanied by occupational exposure modeling and sensor-based fume monitoring.

Leaching behavior remains a crucial yet insufficiently explored topic. Leaching tests employing realistic wear particle simulations (e.g., from Cantabro abrasion) have demonstrated a limited release of heavy metals alongside increased levels of dissolved organic carbon (DOC) [20]. The effects are depending not only on the type of plastic but also on its interaction with bitumen, particle size, and environmental stresses, including UV radiation. advancements in testing method such as the implementation of the US EPA TCLP, SPLP, and EN 12457 standard cross-study comparability is impeded by inconsistencies in sample preparation and aging procedures. Moreover, the majority of leaching investigations are performed under batch circumstances, neglecting dynamic traffic loading, seasonal weathering, and pH variations, hence constraining their real-world applicability.

Methodological divergence is a persistent troubling issue for the researchers and stakeholders in this field. The lack of uniform blending techniques, testing temperatures, plastic pre-treatment protocols, and dose criteria significantly impedes comparable evaluation. For example, research indicating enhancements in fatigue resistance through hybrid systems (e.g., LDPE + crumb rubber) frequently varies in plastic particle size and surface treatment, making hard to determine exactly what is causing a specific effect because there are multiple overlapping variables or changes happening at the same time. Similarly, variations in aging settings (e.g., RTFOT versus PAV, or short-term versus field aging) affect compatibility and storage stability evaluations, compromising generalizability. Consequently, there is an immediate necessity for performance specification frameworks designed for plastic-modified binders and mixtures, like the Superpave system, but specifically addressing polymer-related attributes.

From a policy and implementation standpoint, the absence of consistent long-term field data is a key bottleneck. Despite experiments in Canada [49], the US [51], and India demonstrate promising outcomes under certain climates and traffic volumes, the limited number of well-documented case studies precludes the generalization of the results or conclusions to broader conditions. Performance variability resulting from feedstock inconsistencies, plastic contamination, or local aggregate characteristics persists as a significant concern [14,61]. Governments and industry partners should consider establishing regional pilot networks and databases to systematically document performance, environmental, and economic metrics of plastic roads under real-world conditions.

Finally, although plastic-modified asphalt corresponds with specific sustainability objectives (such as waste reduction and resource efficiency), it could compromise other goals if not implemented carefully. The potential release of persistent pollutants such as phthalates, flame retardants, or MPs complicates its environmental profile. Consequently, life cycle assessment (LCA) systems must explicitly integrate pollutant leaching and fume exposure scenarios, in addition to embodied carbon and cost reductions. As highlighted by [87–89], the combination of LCA with dynamic leaching models and risk-based thresholds is essential for comprehensively addressing environmental trade-offs.

7. Conclusions and Future Research Needs

This review assesses current methods of incorporating waste plastics into asphalt pavements, synthesizes key findings regarding the mechanical performance, environmental consequences, and life cycle impacts of plastic-modified asphalt pavements (PMAPs), and critically examines prior research on microplastic release, fuming, and leaching behavior. The main conclusions are detailed below. Subsequently, future research needs are outlined to guide further investigations and facilitate the secure and sustainable application of this emerging technology.

7.1. Conclusions

The most robust and consistent finding is that certain waste plastics—primarily LDPE, HDPE, PP, and to a lesser extent PET can substantially improve the mechanical properties of asphalt binders and mixtures. The enhancements include superior rutting resistance, elevated softening point, enhanced fatigue life, and extended service life. Optimal results are often attained when plastic content is meticulously regulated (3–8% in wet processes; up to 10% in dry), and when plastic particle size and compatibility correspond with binder and mixture requirements.

The method of incorporation plays a critical role. Wet-processed plastic-modified binders typically exhibit enhanced rheological properties, improved compatibility, and diminished long-term environmental hazards, especially in mitigating microplastic emissions. Dry-process applications are more straightforward to scale and permit greater plastic reuse, although they may demonstrate less uniform dispersion and increased hazards of microplastic release due to traffic abrasion. Hybrid systems and functionalized plastic modifiers are emerging as viable strategies to balance performance and sustainability.

Life cycle assessments (LCA) consistently demonstrate that plastic-modified asphalt pavements can diminish greenhouse gas emissions, raw material consumption, and maintenance frequency—particularly when utilizing locally obtained waste plastic and minimizing transport and preprocessing impacts. Moreover, the incorporation of polymers inside the asphalt matrix can reduce microplastic emissions when designs are optimized.

However, several critical concerns remain. Fuming studies underscore the possibility for elevated VOC and PAH emissions when unsuitable plastics (e.g., ABS, PVC) or excessive processing temperatures are employed. The danger of long-term microplastic release differs among research and is affected by the incorporation method, type of plastic, and environmental exposure. Furthermore, field validation is limited: the majority of existing data originates from laboratory studies or short-term trials, without adequate large-scale, multi-climate monitoring.

Feedstock variability such as differences in polymer crystallinity, contamination, and molecular weight continues to challenge reproducibility and although most Life Cycle Assessments (LCAs) indicate net environmental advantages, certain trade-offs (e.g., escalating surface roughness with time, emissions from transportation) may undermine benefits if not carefully managed through integrated pavement design.

In conclusion, integrating waste plastics into asphalt pavements presents a significant opportunity to improve road performance while advancing sustainable waste management objectives. To safely and effectively capitalize on this potential, future advancements must concentrate on standardizing material specifications, perfecting processing techniques, confirming long-term field performance, and rigorously evaluating environmental impacts through unified testing and monitoring frameworks.

7.2. Future Research Needs

To promote the sustainable and responsible application of plastic-modified asphalt pavements, the following research priorities should be addressed:

- **Long-term field validation**

  Execute ongoing investigations for several years across varied climates and traffic situations to evaluate pavement durability, aging characteristics, and environmental impacts (e.g., microplastic release, VOC/PAH emissions).

- **Standardization of materials and processes**

  Develop globally accepted standards for plastic feedstock quality, incorporation methods, and performance evaluation to guarantee consistency and promote regulatory approval.

- **Advanced processing techniques**

  Investigate the use of functionalized plastics, hybrid modifiers (e.g., plastics combined with crumb rubber or nanomaterials), and optimized blending methods to enhance binder compatibility, dispersion, and long-term stability.

- **Comprehensive environmental assessment**

  Enhance testing methodologies to more accurately measure microplastic emissions, leaching characteristics, and cumulative ecosystem impacts under realistic service and aging conditions.

- **Enhanced life cycle modeling**

  Refine life cycle assessment (LCA) frameworks to include dynamic factors such as maintenance practices, evolving vehicle impacts, recyclability, and integration with complementary sustainable technologies (e.g., RAP, warm mix asphalt).

By addressing these priorities through interdisciplinary collaboration, the asphalt and waste management sectors can realize the full potential of plastic-modified pavements as a high-performance, sustainable alternative for future infrastructure.

Author Contributions: Conceptualization, A.G. and N.H.; methodology, A.G.; resources, A.G.; writing—original draft preparation, A.G.; writing—review and editing, A.G. and N.H.; visualization, A.G., N.H. and T.P; supervision, N.H. and T.P. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available in the article.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Wu, S.; Montalvo, L. Repurposing waste plastics into cleaner asphalt pavement materials: A critical literature review. *Journal of Cleaner Production* **2021**, *280*, 124355.
2. Hasheminezhad, A.; Farina, A.; Yang, B.; Ceylan, H.; Kim, S.; Tutumluer, E.; Cetin, B. The utilization of recycled plastics in the transportation infrastructure systems: A comprehensive review. *Construction and Building Materials* **2024**, *411*, 134448.
3. Singh, A.; Gupta, A. Upcycling of plastic waste in bituminous mixes using dry process: review of laboratory to field performance. *Construction and Building Materials* **2024**, *425*, 136005.
4. Usman, I.U.; Kunlin, M. Influence of Polyethylene Terephthalate (PET) utilization on the engineering properties of asphalt mixtures: A review. *Construction and Building Materials* **2024**, *411*, 134439.
5. Grady, B.P. Waste plastics in asphalt concrete: A review. *SPE Polymers* **2021**, *2*, 4-18.
6. Xu, F.; Zhao, Y.; Li, K. Using waste plastics as asphalt modifier: A review. *Materials* **2021**, *15*, 110.
7. OECD. *Global Plastics Outlook: Policy Scenarios to 2060*; 2022.
8. Diab, L.; Al-Qadi, I.L. Life cycle assessment for the use of waste plastics in asphalt concrete mixes. *Transportation Research Record* **2024**, 03611981241245674.
9. Abernathy, A.M.; Colosi, L.M.; Samaraee, A.A.; Ozbulut, O.E.; Lloyd, L.N.; Habbouche, J. Life Cycle Assessment of Recycled Plastic Modified Asphalt Pavements: A Case Study in Virginia. *Transportation Research Record* **2024**, 03611981241302338.
10. Enfrin, M.; Giustozzi, F. Recent advances in the construction of sustainable asphalt roads with recycled plastic. *Polymer International* **2022**, *71*, 1376-1383.
11. Cardoso, J.; Ferreira, A.; Almeida, A.; Santos, J. Incorporation of plastic waste into road pavements: A systematic literature review on the fatigue and rutting performances. *Construction and Building Materials* **2023**, *407*, 133441.
12. Veropalumbo, R.; Russo, F.; Oreto, C.; Buonocore, G.G.; Verdolotti, L.; Muiambo, H.; Biancardo, S.A.; Viscione, N. Chemical, thermal, and rheological performance of asphalt binder containing plastic waste. *Sustainability* **2021**, *13*, 13887.

13. Mturi, G.; Ncolosi, N.; O'Connell, J.; Simelane, M. The incorporation of the plastic-coated aggregates into a South African asphalt mixture. *Road Materials and Pavement Design* **2025**, 1-16.
14. Shah, M.M.; Yousaf, J.; Khalid, U.; Li, H.; Yee, J.-J.; Naqvi, S.A.Z. Plastic roads: asphalt mix design and performance. *Discover Applied Sciences* **2024**, *6*, 195.
15. Mashaan, N.S.; Dassanayake, C. Rutting and Aging Properties of Recycled Polymer-Modified Pavement Materials. *Recycling* **2025**, *10*, 60.
16. Boom, Y.J.; Enfrin, M.; Grist, S.; Robert, D.; Giustozzi, F. Laboratory evaluation of PAH and VOC emission from plastic-modified asphalt. *Journal of Cleaner Production* **2022**, *377*, 134489.
17. Joohari, I.B.; Maniam, S.; Giustozzi, F. Effect of long-term aging on polymer degradation and fatigue resistance of hybrid polymer-modified bitumen. *Journal of Materials in Civil Engineering* **2022**, *34*, 04022286.
18. Mashaan, N.S.; Chegenizadeh, A.; Nikraz, H.; Rezagholilou, A. Investigating the engineering properties of asphalt binder modified with waste plastic polymer. *Ain Shams Engineering Journal* **2021**, *12*, 1569-1574.
19. Lim, S.M.; He, M.; Hao, G.; Ng, T.C.A.; Ong, G.P. Recyclability potential of waste plastic-modified asphalt concrete with consideration to its environmental impact. *Construction and Building Materials* **2024**, *439*, 137299.
20. Lim, S.M.; Ng, T.C.A.; He, M.; Amio, B.E.C.; Hao, G.; Zulkati, A.; Kapilan, S.; Ng, H.Y.; Ong, G.P. Refining leaching protocols of waste-plastic incorporated asphalt mixes for environmental impact assessment. *Journal of Cleaner Production* **2025**, *487*, 144610.
21. Rangelov, M.; Dylla, H.; Sivaneswaran, N. Life-cycle assessment of asphalt pavements with recycled post-consumer polyethylene. *Transportation Research Record* **2021**, *2675*, 1393-1407.
22. Vargas, C.; El Hanandeh, A. Systematic literature review, meta-analysis and artificial neural network modelling of plastic waste addition to bitumen. *Journal of Cleaner Production* **2021**, *280*, 124369.
23. Salehi, S.; Arashpour, M.; Kodikara, J.; Guppy, R. Comparative life cycle assessment of reprocessed plastics and commercial polymer modified asphalts. *Journal of Cleaner Production* **2022**, *337*, 130464.
24. Nouali, M.; Ghorbel, E.; Derriche, Z. Phase separation and thermal degradation of plastic bag waste modified bitumen during high temperature storage. *Construction and Building Materials* **2020**, *239*, 117872.
25. Geyer, R.; Jambeck, J.R.; Law, K.L. Production, use, and fate of all plastics ever made. Sci Adv 3: e1700782. **2017**.
26. Al-Abdul Wahhab, H.; Dalhat, M.; Habib, M. Storage stability and high-temperature performance of asphalt binder modified with recycled plastic. *Road Materials and Pavement Design* **2017**, *18*, 1117-1134.
27. Polacco, G.; Filippi, S.; Merusi, F.; Stastna, G. A review of the fundamentals of polymer-modified asphalts: Asphalt/polymer interactions and principles of compatibility. *Advances in colloid and interface science* **2015**, *224*, 72-112.
28. Zoorob, S.; Suparma, L.B. Laboratory design and investigation of the properties of continuously graded Asphaltic concrete containing recycled plastics aggregate replacement (Plastiphalt). *Cement and concrete composites* **2000**, *22*, 233-242.
29. Enfrin, M.; Boom, Y.J.; Giustozzi, F. Future recyclability of hot mix asphalt containing recycled plastics. *Construction and Building Materials* **2023**, *368*, 130396.
30. Lu, D.X.; Enfrin, M.; Masood, H.; Giustozzi, F. Performance Evaluation of Post-Consumer and Post-Industrial Recycled Plastics as Binder Modifier in Asphalt Mixes. *International Journal of Pavement Research and Technology* **2024**, 1-14.
31. Duarte, G.M.; Faxina, A.L. Asphalt concrete mixtures modified with polymeric waste by the wet and dry processes: A literature review. *Construction and Building Materials* **2021**, *312*, 125408.

doi:10.20944/preprints202506.1932.v1

32. Capuano, L.; Magatti, G.; Dettori, M.; Mantecca, P. Use of recycled plastics as a second raw material in the production of road pavements: An example of circular economy evaluated with LCA methodology. *Procedia Environmental Science, Engineering and Management* **2020**, *7*, 37-43.
33. Boom, Y.J.; Enfrin, M.; Grist, S.; Giustozzi, F. Analysis of possible carcinogenic compounds in recycled plastic modified asphalt. *Science of the Total Environment* **2023**, *858*, 159910.
34. Tahmoorian, F.; Liyanapathirana, S.; Yeaman, J.; Egwurube, J. Performance of hot-mix asphalt and modified binders containing polyethylene. *Journal of Transportation Engineering, Part B: Pavements* **2023**, *149*, 04023001.
35. Zanjirani Farahani, H.; Palassi, M.; Sadeghpour Galooyak, S. Using response surface methodology to optimize rubber and LDPE contents in bitumen at low-temperature performance. *Petroleum Science and Technology* **2022**, *41*, 139-158.
36. Zhang, T.; Chen, Y.; Hu, K.; Zhang, W.; Chen, G. Investigating the compatibility mechanism of bitumen modified with photo-oxidative aging of polyethylene using molecular dynamics simulation. *Journal of Materials in Civil Engineering* **2023**, *35*, 04023424.
37. Joohari, I.B.; Giustozzi, F. Chemical and high-temperature rheological properties of recycled plastics-polymer modified hybrid bitumen. *Journal of Cleaner Production* **2020**, *276*, 123064.
38. Odubela, C.A.; Yaacob, H.; Warid, M.N.B.M.; Karim, K.J.A.; Kamaruddin, N.H.B.M.; Al-Saffar, Z.H.; Rahim, M.I.K. Rheological and chemical properties of reclaimed asphalt pavement using polyethylene terephthalate (PET) additive as a modifier. *Environmental Science and Pollution Research* **2025**, 1-10.
39. Padhan, R.K.; Mohanta, C.; Sreeram, A.; Gupta, A. Rheological evaluation of bitumen modified using antistripping additives synthesised from waste polyethylene terephthalate (PET). *International Journal of Pavement Engineering* **2020**, *21*, 1083-1091.
40. Akkouri, N.; Bourzik, O.; Haddaji, Y.; Sadiq Bhat, F.; Baba, K.; Agzenai ben salem, Y. Impact of solar exposure on chemical and rheological properties of hybrid polymer modified bitumen with recycled plastics. *Road Materials and Pavement Design* **2024**, 1-24.
41. Joohari, I.B.; Maniam, S.; Giustozzi, F. Influence of compatibilizers on the storage stability of hybrid polymer-modified bitumen with recycled polyethylene. In *Plastic Waste for Sustainable Asphalt Roads*; Elsevier: 2022; pp. 215-232.
42. Javadi, N.H.S.; Hajimohammadi, A.; Heydari, S.; Ng, J.J.K.C.; Kypreos, J.E.; Khalili, N. Investigating the applicability of storage stability test for waste plastic modified bitumen: Morphological analyses. *Construction and Building Materials* **2024**, *441*, 137451.
43. Lanotte, M.; Desidery, L. Rutting of waste plastic-modified bitumen. In *Plastic Waste for Sustainable Asphalt Roads*; Elsevier: 2022; pp. 97-114.
44. Ben Zair, M.M.; Jakarni, F.M.; Muniandy, R.; Hassim, S. A brief review: application of recycled polyethylene terephthalate in asphalt pavement reinforcement. *Sustainability* **2021**, *13*, 1303.
45. Ma, Y.; Zhou, H.; Jiang, X.; Polaczyk, P.; Xiao, R.; Zhang, M.; Huang, B. The utilization of waste plastics in asphalt pavements: A review. *Cleaner Materials* **2021**, *2*, 100031.
46. Baradaran, S.; Rahimi, J.; Ameri, M.; Maleki, A. Mechanical performance of asphalt mixture containing eco-friendly additive by recycling PET. *Case studies in construction materials* **2024**, *20*, e02740.
47. Ghos, S.; Sumter, C.R.; Arevalo, P.C.; Ali, S.A.; Zaman, M.; Hobson, K.R.; Kalicki, G.; Metzer, D. Performance of asphalt mixes containing postconsumer recycled plastic using balanced mix design approach and dry process. *Transportation Research Record* **2022**, *2676*, 720-732.
48. Ma, J.; Hesp, S.A. Effect of recycled polyethylene terephthalate (PET) fiber on the fracture resistance of asphalt mixtures. *Construction and Building Materials* **2022**, *342*, 127944.

49. Ma, J.; Yuan, H.; Nawarathna, H.M.; Hesp, S.A. Sustainable application of recycled plastics in asphalt pavement: Case study of a trial in Newtonville, Ontario, Canada. *Canadian Journal of Civil Engineering* **2024**, *52*, 597-612.
50. Radeef, H.R.; Hassan, N.A.; Katman, H.Y.; Mahmud, M.Z.H.; Abidin, A.R.Z.; Ismail, C.R. The mechanical response of dry-process polymer wastes modified asphalt under ageing and moisture damage. *Case Studies in Construction Materials* **2022**, *16*, e00913.
51. Yin, F.; Kmetz, M.; Timm, D.; West, R.; Taylor, A. Laboratory and Field Performance Characterization of Recycled-Plastic-Modified Asphalt Mixtures at the National Center for Asphalt Technology Test Track. *Transportation Research Record* **2025**, 03611981251318331.
52. Chiang, C.-L.; Mivehchi, M.; Wen, H. Towards a use of waste polyethylene in asphalt mixture as a compaction aid. *Journal of Cleaner Production* **2024**, *440*, 140989.
53. La Macchia, J.N.; Baglieri, O.; Dalmazzo, D.; Santagata, E. Engineering Properties of Road Paving Mixtures with High Content of Reclaimed Asphalt and Recycled Waste Plastics. *Materials* **2024**, *17*, 5681.
54. Alemu, G.M.; Melese, D.T.; Mahdi, T.W.; Negesa, A.B. Combined performance of polyethylene terephthalate waste plastic polymer and crumb rubber in modifying properties of hot mix asphalt. *Advances in Materials Science and Engineering* **2023**, *2023*, 6320490.
55. Liu, T.; Li, X.; Li, R.; Pei, J.; Zhao, X. Performance of dry mixed rubber–plastic composite modified asphalt mixture. *Journal of Materials in Civil Engineering* **2022**, *34*, 04022243.
56. Qabur, A.; Baaj, H.; El-Hakim, M. A Laboratory Study on Enhancing Asphalt Mixture Properties through Dry Mixing with High-Dose Multilayer Plastic Packaging Pellet Additives. *Journal of Materials in Civil Engineering* **2025**, *37*, 04025049.
57. Pourfeiz, A.; Modarres, A.; Ghodrati, A.; Ayar, P.; Yousefi, A.A. Study on mode I, mode II and mixed mode I/II fracture behavior of hot mix asphalt containing silane crosslinkable polyethylene waste. *Theoretical and Applied Fracture Mechanics* **2023**, *124*, 103810.
58. Zhang, J.; Li, H.; Liu, P.; Liang, M.; Jiang, H.; Yao, Z.; Airey, G. Experimental exploration of influence of recycled polymer components on rutting resistance and fatigue behavior of asphalt mixtures. *Journal of Materials in Civil Engineering* **2020**, *32*, 04020129.
59. Mishra, B.; Gupta, M.K. Performance study on bituminous concrete mixes using varying content and sizes of shredded polyethylene terephthalate. *Journal of Materials in Civil Engineering* **2021**, *33*, 04020436.
60. Fonseca, M.; Capitão, S.; Almeida, A.; Picado-Santos, L. Influence of plastic waste on the workability and mechanical behaviour of asphalt concrete. *Applied Sciences* **2022**, *12*, 2146.
61. Haider, S.; Hafeez, I.; Ullah, R. Sustainable use of waste plastic modifiers to strengthen the adhesion properties of asphalt mixtures. *Construction and Building Materials* **2020**, *235*, 117496.
62. Boom, Y.J.; Enfrin, M.; Grist, S.; Giustozzi, F. Recycled plastic modified bitumen: Evaluation of VOCs and PAHs from laboratory generated fumes. *Science of The Total Environment* **2022**, *832*, 155037.
63. Zhang, X.; Xiao, Y.; Long, Y.; Chen, Z.; Cui, P.; Wu, R.; Chang, X. VOCs reduction in bitumen binder with optimally designed Ca (OH) 2-incorporated zeolite. *Construction and Building Materials* **2021**, *279*, 122485.
64. Xiao, Y.; Wan, M.; Jenkins, K.; Wu, S.; Cui, P. Using activated carbon to reduce the volatile organic compounds from bituminous materials. *Journal of Materials in Civil Engineering* **2017**, *29*, 04017166.
65. Cui, P.; Wu, S.; Li, F.; Xiao, Y.; Zhang, H. Investigation on using SBS and active carbon filler to reduce the VOC emission from bituminous materials. *Materials* **2014**, *7*, 6130-6143.
66. Rasoulzadeh, Y.; Mortazavi, S.; Yousefi, A.; Khavanin, A. Decreasing polycyclic aromatic hydrocarbons emission from bitumen using alternative bitumen production process. *Journal of Hazardous Materials* **2011**, *185*, 1156-1161.

67. Lee, S.-Y.; Kim, K.-W.; Yun, Y.-m.; Le, T.H.M. Evaluation of eco-friendly asphalt mixtures incorporating waste plastic aggregates and additives: Magnesium, fly ash, and steel slag. *Case Studies in Construction Materials* **2024**, *20*, e02756.
68. Duan, Y.; Wu, K.; Serrat, C.; Arteaga-Larios, F.; Brown, H.; DuBois, C.; Buttlar, W.G.; Deng, B. Assessment of microplastics production from waste plastics-modified asphalt pavement. *Resources, Conservation and Recycling* **2024**, *202*, 107329.
69. Bualuang, T.; Jitsangiam, P.; Jakrawatana, N.; Teeratitayangkul, P.; Vongruang, P.; Thienchai, C.; Wongchana, P.; Prommarin, J. Utilization of plastic waste in hot mix asphalt using dry mixing processes: Laboratory assessment of airborne microplastics. *Results in Engineering* **2025**, *25*, 104464.
70. Azadgoleh, M.A.; Mohammadi, M.M.; Ghodrati, A.; Sharifi, S.S.; Palizban, S.M.M.; Ahmadi, A.; Vahidi, E.; Ayar, P. Characterization of contaminant leaching from asphalt pavements: A critical review of measurement methods, reclaimed asphalt pavement, porous asphalt, and waste-modified asphalt mixtures. *Water Research* **2022**, *219*, 118584.
71. Mohammadi, R.; Ameri, M. A systematic review on sustainable utilization of plastic waste in asphalt: assessing environmental and health impact, performance, and economic viability. *Environmental Science and Pollution Research* **2024**, 1-26.
72. Enfrin, M.; Myszka, R.; Giustozzi, F. Paving roads with recycled plastics: Microplastic pollution or eco-friendly solution? *Journal of Hazardous Materials* **2022**, *437*, 129334.
73. Ashish, P.K.; Sreeram, A.; Xu, X.; Chandrasekar, P.; Jagadeesh, A.; Adwani, D.; Padhan, R.K. Closing the Loop: Harnessing waste plastics for sustainable asphalt mixtures–A comprehensive review. *Construction and Building Materials* **2023**, *400*, 132858.
74. Golgoli, M.; Farahbakhsh, J.; Najafi, M.; Khiadani, M.; Johns, M.L.; Zargar, M. Resilient forward osmosis membranes against microplastics fouling enhanced by MWCNTs/UiO-66-NH2 hybrid nanoparticles. *Chemosphere* **2024**, *359*, 142180.
75. Rosso, B.; Bravo, B.; Gregoris, E.; Barbante, C.; Gambaro, A.; Corami, F. Quantification and chemical characterization of plastic additives and small microplastics (< 100 μm) in highway road dust. *Toxics* **2023**, *11*, 936.
76. Myszka, R.; Enfrin, M.; Giustozzi, F. Microplastics in road dust: A practical guide for identification and characterisation. *Chemosphere* **2023**, *315*, 137757.
77. Praticò, F.G.; Giunta, M.; Mistretta, M.; Gulotta, T.M. Energy and environmental life cycle assessment of sustainable pavement materials and technologies for urban roads. *Sustainability* **2020**, *12*, 704.
78. Khan, S.; Li, H.; Ncube, M.H.; Butt, A.A.; Han, Y.; Harvey, J. Environmental implications of recycled materials in pavement construction: A comprehensive review and future research directions. *Transportation Research Part D: Transport and Environment* **2025**, *140*, 104642.
79. Ghodrati, A.; Asadi Azadgoleh, M.; Zalnezhad, M.; Mohammadi, M.M.; Ayar, P.; Vahidi, E. Performance improvement of slurry seal by glass powder: mechanical evaluation and life cycle assessment. *Road Materials and Pavement Design* **2025**, 1-23.
80. Zeiada, W.; Al-Khateeb, G.; Hajj, E.Y.; Ezzat, H. Rheological properties of plastic-modified asphalt binders using diverse plastic wastes for enhanced pavement performance in the UAE. *Construction and Building Materials* **2024**, *452*, 138922.
81. Assaf, H.; Abdo, A.A. Life cycle assessment of incorporating recycled materials in pavement design. *Journal of King Saud University-Engineering Sciences* **2024**, *36*, 473-484.
82. Rispoli, O.; Ajibade, O.O. Comparative life cycle assessment of a novel sustainable road pavement system adopting recycled plastic from PET bottles and carbonated aggregate. *Heliyon* **2024**, *10*.

83. Mohammadi, M.M.; Azadgoleh, M.A.; Ghodrati, A.; Zalnezhad, M.; Ayar, P.; Fini, E. Introducing waste glass powder as a sustainable constituent in microsurfacing. *Construction and Building Materials* **2023**, *395*, 132271.
84. Yousefi, A.A.; Underwood, B.S.; Ghodrati, A.; Behnood, A.; Vahidi, E.; Nowrouzi, A.; Ayar, P.; Haghshenas, H.F. Towards a durable and sustainable warm mix asphalt: Techno-economic and environmental evaluation considering balanced mix design approach. *Journal of Cleaner Production* **2025**, *486*, 144311.
85. Yao, L.; Leng, Z.; Lan, J.; Chen, R.; Jiang, J. Environmental and economic assessment of collective recycling waste plastic and reclaimed asphalt pavement into pavement construction: A case study in Hong Kong. *Journal of Cleaner Production* **2022**, *336*, 130405.
86. Santos, J.; Pham, A.; Stasinopoulos, P.; Giustozzi, F. Recycling waste plastics in roads: A life-cycle assessment study using primary data. *Science of the total environment* **2021**, *751*, 141842.
87. Piao, Z.; Bueno, M.; Poulikakos, L.D.; Hellweg, S. Life cycle assessment of rubberized semi-dense asphalt pavements; A hybrid comparative approach. *Resources, Conservation and Recycling* **2022**, *176*, 105950.
88. Mashaan, NS., De Silva, TS. (2024). Review on Assessment and Performance Mechanism Evaluation of Non-Structural Concrete Incorporating Waste Materials. *Applied Mechanics*, 5(3), 579-599.
89. Mashaan, NS., Yogi, B. (2025). Mining Waste Materials in Road Construction. *Encyclopedia*, 5(2), 83.