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Microplastics Generated by Roadway Environments: A Critical Review of Sources, Pathways, Characterization and Mitigation Strategies

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Abstract

Roadway environments have become a source of microplastic (MP) pollution through the degradation of plastic-containing materials associated with transport infrastructure. This review critically analyses the current state of knowledge on MPs generated from tire wear, brake wear, road markings, recycled-plastic modified asphalt, erosion control materials and roadside litter, with emphasis on their transport pathways, characterization and potential control measures. Tire wear is consistently identified as the dominant source of roadway-derived MPs generated through tire-pavement friction. In contrast, emerging sources such as recycled plastic-modified pavements, generated through mechanical wear and environmental degradation, remain insufficiently studied, and their relative contributions under field conditions are poorly understood. The review also reveals that stormwater runoff is the dominant transport pathway for roadway-derived MPs, followed by atmospheric deposition. However, major inconsistencies in sampling, extraction and analytical methods make comparisons across studies difficult. Moreover, this review evaluates potential mitigation strategies, including upstream source reduction through material reformulation and regulatory/economic frameworks, as well as downstream pathway controls using green infrastructure and emerging technologies such as TiO_2 photocatalytic pavements, whose scalability remain uncertain. Overall, the review summarizes the current state of knowledge on roadway-derived MPs while identifying critical gaps, particularly the need for standardized methods and comprehensive field-based studies. Addressing these gaps is essential for improving ecological and human health risk assessments, given the potential for roadway-derived MPs to enter aquatic food webs, contaminate water resources and contribute to human exposure through environmental pathways.

Keywords: Microplastics; Roadway; Chemical analysis

Introduction

Plastics are versatile, durable and affordable materials that have become indispensable in modern society, resulting in global production exceeding 400 million metric tons in 2022 [1,2]. However, their resistance to biodegradation has led to the widespread accumulation of plastic waste in landfills and natural environments. Consequently, it is estimated that approximately 12 billion metric tons of plastic waste will have been disposed of in landfills or released into the environment by 2050 [3].

Microplastics (MPs) are defined as smaller plastic particles that are less than 5 mm in length [4, 5]. MPs result from the long-term physical, chemical

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or biological breakdown of larger plastic items. The small size and pervasiveness of MPs enable their widespread dispersal, making them an important emerging environmental pollutant [6]. Further, accurate quantification of MPs in complex environmental matrices can be difficult because of low detection frequencies and high detection limits associated with the small size of MPs [3]. These factors contribute to MPs eventually entering the food chain and being found in various foods and drinks [7].

Beyond environmental concerns, MPs have emerged as a potential public health issue. Human exposure occurs through ingestion, inhalation and dermal contact and MPs have been detected in human blood, lungs, placental tissue, arterial plaques and other organs [8]. Although the long-term health implications remain uncertain, laboratory and epidemiological studies suggest that MPs may contribute to inflammation, oxidative stress, endocrine disruption and cardiovascular effects. The widespread occurrence of MPs in environmental media therefore raises concerns regarding chronic human exposure and associated health risks.

Urban areas greatly contribute towards the release of MPs into the environment. Mani et al. [9] and Yonkos et al. [10] reported higher concentrations of MPs at locations near urban centers compared to more remote or less developed areas. While MPs in urban environments originate from a variety of sources, it has been reported that roads and vehicles can be potential contributors towards MP pollution [11]. Recent studies indicate that tire and road wear particles are among the largest sources of primary MPs released into the environment. Estimates suggest that tire wear contributes approximately 5-10% of global MP emissions and may account for one-third to one-half of unintentionally released MPs in some environments [12,13]. Tire wear particles have also been identified as one of the dominant MP sources entering aquatic systems through roadway runoff and stormwater transport pathways.

Growing populations and urbanization have led to an increase in highway construction and vehicular travel, contributing to MP emissions in roads [14,15]. Moreover, recycled plastics are now being used in applications such as asphalt modifiers, composite construction materials, drainage systems, geotextiles, erosion control products and other roadway maintenance and construction materials [16]. While these applications may provide environmental and economic benefits, they also represent potential sources of MP generation through weathering, abrasion and degradation over time. Therefore, there is a need to better understand the mechanisms and extent of MP generation and dispersion from roadway environments.

With a growing recognition of the potential for the roadway environment to contribute towards MP pollution, several critical knowledge gaps have been identified. Given the current important and ubiquitous use of plastic-based materials used to construct and maintain roadways as well as the myriad of external inputs of plastics to roadway networks that contribute towards the generation of MPs within roadway environments, it is important to address several critical knowledge gaps that remain. Although standardized methods for MP extraction, identification and quantification are still emerging, their inconsistent adoption in studies involving complex roadway matrices such as stormwater and road sediment limits comparability of results across studies. In addition, there is limited quantitative understanding of the types and relative contributions of MP emissions generated by different roadway-related sources, including degraded erosion control netting and emerging materials such as recycled plastic modified asphalt pavements whose contributions remain less studied. Improved characterization of roadway-derived MPs is also needed to better evaluate potential environmental and human exposure pathways, particularly because roadway runoff can transport MPs into receiving waters that ultimately serve as sources of drinking water, recreation and aquatic habitat.

This review will therefore consolidate existing information on the sources, pathways and characterization of MPs specific to roadway environments. It will also identify and examine current knowledge gaps related to MPs originating from road related activities. In addition, the review will discuss emerging and established mitigation strategies aimed at reducing MP generation and transport from roadway systems. Overall, this work aims to advance understanding of MP pollution from road related activities, support informed decision making and guide future research in this field.

Methodology

A structured literature search was conducted across Web of Science, Scopus, Google Scholar, PubMed, and ScienceDirect for publications from 2000 to 2026 using Boolean combinations of keywords related to roadway MPs, including tire wear, brake wear, road markings, recycled plastic-modified asphalt pavements, erosion control netting, MP transportation pathways, polymer identification and MP mitigation strategies. The search returned a body of literature which was subsequently screened through duplicate removal and title and abstract screening to exclude non-English publications and studies not directly relevant to roadway-derived MPs. Further full-text screening excluded studies lacking sufficient methodological detail, lacking extractable data or not directly relevant to the research scope. In addition to peer-reviewed literature, relevant technical reports, standards and agency documents (e.g., AASHTO and FDOT test methods, VDOT material specifications, NCHRP syntheses, EPA guidance, EU regulations), were included to capture engineering specifications, regulatory frameworks and operational practices not fully represented in journal publications.

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Sources of Microplastics in Roadway Environments

Roadway environments serve as major contributors of MP pollution due to the continuous mechanical abrasion and environmental degradation of materials used in transportation infrastructure and vehicle components. Figure 1 summarizes the primary and emerging sources responsible for MP generation in roadway environments;

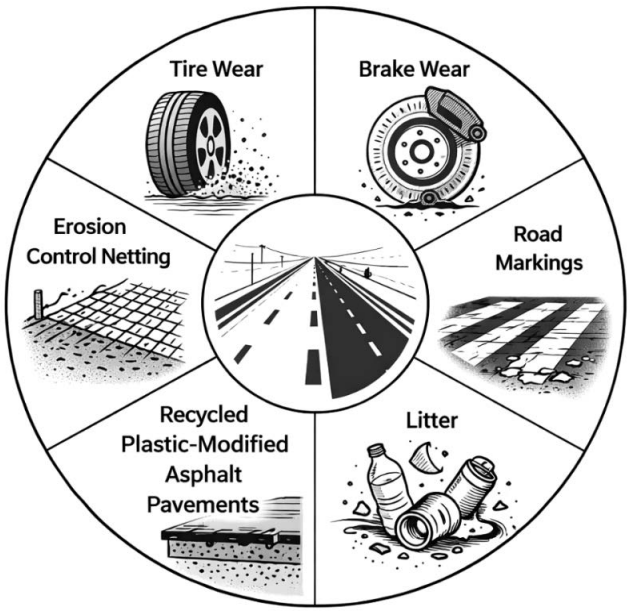

Figure 1. Sources of roadway microplastics

Tire Wear

When vehicles drive, accelerate and brake, small particles of tire material, often referred to as tire wear particles (TWPs), are worn off the surface of the tire by friction and released into the environment. These particles are composed of different polymers and other materials used in tire manufacturing, which contain various additives, mainly synthetic styrene-butadiene (SB), natural rubber, polyethylene (PE), polyethylene terephthalate (PET), polypropylene (PP) and a range of chemicals [17-20]. Through several computational estimates, the wear of tires on roads has been identified as the largest source of MP pollution in the environment [21,22]. Meng et al. [23] reports that global TWP emissions are estimated at approximately 0.81 kg per capita per year, contributing to a global total of approximately 6.1 million tons per year, which represents about 1.8% of total plastic production. Notably, the United States is estimated to have the highest per capita release of TWPs, at approximately 4.70 kg per capita per year, primarily due to its extensive road network and high vehicle ownership rates [21].

TWPs are generated through the friction between tires and the road surface. This friction results in abrasion which generates both shear forces and heat, contributing to the formation of TWPs. Shear forces primarily produce relatively larger coarse size fraction MP fragments (>20 μm) which generally settle near their ground-level emission sources where they further degrade into increasingly smaller fragments through weathering, sunlight exposure and abrasion. On the other hand, heat creates localized high-temperature zones on the tire surface, leading to TWP volatilization and the emission of particles, usually in the fine mode (<2.5 μm), capable of long-range atmospheric transport [24-27].

TWP emissions are largely influenced by factors such as vehicle size, traffic intensity, distance travelled, driving speed and climatic conditions. These relationships are typically reported using emission factors expressed as mass per distance (mg/km). For example, Hillenbrand et al. [28] reported median emission factors of approximately 90 mg/km for passenger cars, 700 mg/km for trucks, and 1200 mg/km for trailer trucks, showing a clear increase in emissions with vehicle size and load.

Traffic intensity has also been shown to significantly influence particle concentrations in roadway environments. Mierzyńska et al. [30] reported statistically significant differences in observed TWP concentrations across low-, medium- and high-traffic roads, with average values of 62.32 particles/L, 335.97 particles/L and 792.76 particles/L, respectively.

Distance travelled is another major factor influencing TWP and MP generation. Based on empirical and extrapolated data compiled by Kole [21], country specific annual mileage has a linear relationship with annual TWP emissions. For example, cars and 4 wheeled light vehicles in India have an estimated annual mileage of approximately 10,000 km and annual TWP emissions of approximately 52,000 tonnes/year. In comparison, the same vehicle class in the US has an estimated annual mileage of approximately 18,000 km and annual TWP emissions of 587,000 tonnes/ year, with the higher U.S. values largely reflecting longer per-capita annual vehicle travel distances.

Vehicle speed has also been shown to influence TWP generation. Kwak et al. [30] aimed at characterizing TWPs (and roadways particles) from on-road driving and laboratory experiments showed a linear correlation between speed and TWPs. During constant speed conditions the average PM10 and PM2.5 concentrations of TWPs increased with increasing speed: 50km/h - 13 PM10 and 20 PM2.5; 80km/h - 25 PM10 and 32 PM2.5; 110km/h - 26 PM10 and 33 PM2.5; and 140km/h - 29 PM10 and 36 PM2.5. These results indicate that higher driving speeds substantially elevate emissions from tire wear.

Climatic conditions have also been shown to influence TWP emissions. In cold-climate environments, road safety measures such as the use of studded tires are common. Although studded tires improve traction on snow and ice,

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the metal studs embedded in the tread intensify mechanical abrasion between the tire and pavement, which accelerates TWP generation [31,32]. Using a mobile laboratory vehicle to directly measure emissions, a study by Kupiainen [33] found that studded tires produced significantly higher PM_{10} road dust emissions than non-studded tires at speeds above 50 km/h, with tires containing 110 heavy studs generating 2.4-2.8 times more PM_{10} at 60 km/h and 2.3-3.3 times more between 70-90 km/h. Moreover, winter maintenance activities such as snow plowing also contribute towards the redistribution of TWPs already accumulated in roadway environments. For example, Vijayan et al. [34] quantified tire and road wear particles in roadside snowbanks in two Swedish municipalities and found high MP loads. Average tire and roadway particles reached 20,000 ± 48,000 particles/L, with peak concentrations of 197,000 particles/L. The smallest fraction (50-100 µm), the size most readily produced by snow plowing, comprised ~80% of all particles. The study concluded that snow plowing mechanically scours the pavement surface, moving MPs from both tire and road wear particles into roadside snowbanks, which then act as temporary reservoirs that release accumulated MP particles during snowmelt. In contrast, hot-climate conditions may also enhance TWP generation. Temperature influences tire-road interactions by increasing frictional heating and softening tire rubber, which can accelerate wear and particle release [21]. Field measurements by Kang [35] showed that concentrations of tire and road wear particles collected from roadside environments were approximately 7.6–24.2% higher during summer than winter, suggesting that elevated temperatures promote particle generation. In addition, high pavement temperatures can increase the degradation and weathering of both tire rubber and pavement materials, potentially contributing to greater emissions of tire and road wear particles [36]. Together, these findings demonstrate that climatic conditions, whether through winter traffic safety practices or elevated temperatures, can influence the generation and redistribution of TWPs in roadway environments.

Break Wear

Vehicle components such as brake wear particles (BWPs) are recognized as another significant source of MPs in roadway environments. Evangeliou et al. [37] reported that BWPs account for approximately 0.5 million tons of MPs released globally each year. During braking, repeated friction between the brake pads and discs causes the pads to gradually wear down, releasing fine particles into the environment. Most braking systems are complex, typically made of binders, fibers, fillers, friction modifiers, lubricants and abrasives [38], resulting in BWPs being a composite of both metallic and MP materials.

Factors influencing BWP formation may include vehicle weight, speed, brake temperature and humidity. Heavier vehicles generate more BWPs than lighter vehicles due to greater braking force requirements. The increased mass means that more friction and pressure are needed to stop the vehicle, leading to higher rates of abrasion on brake components and consequently, greater emission of BWPs. According to Garg et al. [39], approximately 80% of a brake's friction material is typically lost over its lifetime. Based on this and accounting for vehicle weight, they concluded that brake wear emissions are estimated at 11–18 mg per vehicle-kilometer for passenger cars and about 29 mg per vehicle-kilometer for large pickup trucks. Vehicle speed also has a direct impact on the concentrations of BWPs. Higher vehicle speeds increase the kinetic energy that must be dissipated during braking, leading to greater frictional forces and heat generation at the brake-pad surface. This elevated stress accelerates material abrasion, resulting in more BWP formation. Vasiljević et al. [40], experimentally demonstrated that increasing vehicle speed by 20 km/h can raise BWP concentrations by several tens of percent. Testing four different brake pads, they found that speed had the strongest influence on PM2.5 particles, with average concentrations rising from 4 to 45, 348 and 851 $\mu g/m^3$ at 20, 40, 60 and 80 km/h, respectively.

Finally, conditions such as brake temperature and humidity significantly influence BWP release. Li et al. [42] found that higher brake temperatures significantly increase BWP emissions by accelerating the thermal degradation and oxidation of brake materials. Particle number concentrations rose sharply from about 10^{11} at 100°C to 10^{14} at 550°C. It was noted that at temperatures above 475°C, violent decomposition produced large amounts of incompletely oxidized organic compounds, leading to high concentrations of BWPs, particularly below 200 nm, which later agglomerated into larger particles (above 200 nm). Humidity, on the other hand, suppresses BWP formation because the water film acts as a lubricant. Mirzababaei and Filip [42] examined the influence of humidity on the wear of automotive friction materials, testing both non-asbestos organic and semi-metallic brake pads under relative humidities ranging from 50% to 80% Relative Humidity. Their results showed that wear decreased noticeably with increasing humidity on both material types: for the semi metallics break material, average wear decreased from 0.06 to 0.05 and 0.02 g at 50, 65 and 80% Relative Humidity respectively whilst for non-asbestos organic material, the average wear dropped from 0.06 to 0.02 and 0.02 g at 50, 65 and 80% Relative Humidity respectively.

Road Markings

Road markings applied during road construction and maintenance are a recognized source of MPs through chipping, abrasion and weathering. Global estimates vary widely - Boucher and Friot [43] attribute approximately 7% of MP emissions to road markings, while other studies report ranges from 0.7% [44] to 19% [45]. State transportation agencies, such as the Virginia Department of Transportation [46], employ a diverse set of marking materials (Table

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1), reflecting broader international variation in material technologies. These materials differ substantially in polymer chemistry, solids content, thickness and durability, factors that directly influence MP generation.

Table 1: Table 1. Virginia Department of Transportation Road Markings Materials List (VDOT, 2019)

	Material
Type A	Paint (Latex-based (or waterborne) paint with glass beads or other material added for retroreflectivity)
Type B-I	Liquid thermoplastic
Type B-II	Preformed thermoplastic
Type B-III	Epoxy resin made using pigmented resin and a hardener
Type B-IV	Plastic-backed tape (cold preformed plastic tape)
Type B-VI	Patterned preformed tape
Type B-VII	Polyurea
Type D-III	Wet reflective removable tape (for temporary work zone marking)
Type E	Removable black tape

Distinguishing among road marking systems is critical, as each exhibits distinct degradation pathways and abrasion behaviors that directly influence MP generation. Babić et al. [47] rank the average durability of road marking systems as follows:

1. Road marking tapes - superior durability compared to other systems
2. Epoxy + acrylic systems - high durability (~5 years)
3. Thermoplastic markings - moderate durability (2-4 years)
4. Solvent-based paints - low to very low durability (6-12 months)

Similarly, Chu et al. [48] report that water-based paints typically have short lifespans of around 6-12 months. Material durability is therefore a key determinant of MP emissions. For example, although thermoplastics generally contain a higher proportion of polymer binder, their superior resistance to mechanical wear and extended service life (~2-4 years) can reduce the frequency of reapplication, thereby lowering cumulative emissions relative to less durable paints, which often require renewal within a year and are likely to result in higher annualized MP emissions [49].

Regional and operational conditions further modulate MP emission rates from road markings. In colder climates, winter maintenance practices tend to intensify mechanical abrasion and accelerate material degradation. For instance, Vijayan et al. [51] reported mean concentrations of approximately 430 particles/L of road marking-derived particles in melted snow samples collected in Sweden, attributing these elevated levels to the combined effects of studded tire use and snow removal operations. Collectively, these findings highlight that MP emissions from road markings are governed by the interplay between material properties, durability and region-specific operational stressors, reinforcing the need for differentiated analyses rather than aggregated emission estimates when evaluating environmental impacts of road markings as a source of MPs in roadway environments.

Recycled-Plastic Modified Asphalt Pavements

Recycled-plastic modified (RPM) asphalt pavements are road surfaces that are made by incorporating waste plastic into asphalt mixtures to improve their technical properties, reduce the environmental impact of plastic waste and provide an alternative use for plastic waste [51]. Commonly incorporated plastics include polyethylene (PE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET). Two techniques of incorporating plastic into asphalt have been explored: the wet method, where the recycled plastics are first blended with hot bitumen before the plastic-modified bitumen is added to the hot aggregates and the dry method, where recycled plastics are used as aggregate substitutes and mixed with the aggregates before adding hot bitumen [52].

Although RPM pavements are a promising approach to reducing the amount of landfilled and incinerated plastic and improving asphalt pavement performance, recent studies have highlighted their potential role in contributing to MP pollution. A laboratory-based procedure was developed by Enfrin [53] to evaluate MP release from RPM pavements, using a Wet Track Abrasion machine alongside a multi-step extraction and analysis method to quantify MP generation from the RPM pavement. The study compared both wet and dry methods of plastic incorporation. The wet mixes contained a blend of recycled and virgin low-density polyethylene (PE) added to the mix at rates of 1 – 6 % by weight of binder. The dry mixes contained either recycled polyethylene terephthalate (PET) or recycled Acrylonitrile–Butadiene–Styrene (ABS) added to the mix at rates of 0.5 – 4 % by weight of the total mix. Both mix types had a binder content of 5%. Considering this, the wet mixes contained only 0.3% at most, over 16 times less than that of the dry mixes (4% max). Despite this significant difference, the study found that the wet mixes released MPs faster than the dry mixes (0.048 g/m2/min vs. 0.018 g/m2/min respectively). This trend was attributed to the wet mixes having a more uniform distribution of plastics through the asphalt matrix. Moreover, MP generation was enhanced at cold temperatures. Testing conducted at 5˚C increased the release of MPs released from the low-density PE mixes by almost three times compared to the 25˚C tests. Most notably, the study found that 99% of MPs generated were smaller than 40 µm regardless of plastic type, amount, or method of addition. The authors concluded that the release of MPs relies not only on environmental conditions but also on the combination of several factors including the incorporation method of plastic in asphalt.

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Smyth et al. [54] carried out a two-year field study with complementary laboratory testing, investigating how pavement degradation influences MP generation in stormwater across various pavement types, namely: asphalt, concrete and recycled rubber pavers. The findings of the study confirmed that pavement wear is a contributing source of MPs in stormwater, with asphalt pavements proving to be the most susceptible to rutting, releasing the most MPs in the field. The median MP concentrations for asphalt pavements were above 600 microparticles/L in comparison to the concrete lot whose median MP concentrations were at 216 microparticles/L and the recycled rubber parking lot with the lowest median MP concentrations of 115 microparticles/L. In the laboratory, an opposite trend in microparticle count was observed. Recycled rubber pavers exhibited the highest MP release (median = 5504 microparticles) followed by the concrete lot pavers (median = 631 microparticles) and the asphalt lot cores with the least MP release (median = 369 microparticles). Although the researchers found other potential sources of MP pollution such as tire wear particles, littering and road markings in their field samples, they demonstrated that pavement wear is a unique source of MPs distinct from other sources of MPs in stormwater. The study therefore emphasizes the need for the thorough evaluation of novel RPM pavement materials prior to large-scale implementation.

Another study was performed by Habbouche et al. [55] and it aimed at assessing RPM asphalt pavements constructed in Virginia in a laboratory set-up. The results revealed distinct MP particles in the material abraded from PE-based polymer samples during mass loss testing. However, because Cantabro, the mass loss test used, is an accelerated weathering method intended to compare the durability of a mix to others, the rate at which MPs from this material would be released into roadway environments at the pilot location remains uncertain.

Recent studies have reported differing conclusions regarding the magnitude of MP emissions from RPM pavements relative to other roadway MP sources. In 2024, Duan et al. [56] developed methods to detect and quantify MP release from asphalt pavements containing recycled linear low-density PE added at rates of 1% and 2.5% by total weight. The Hamburg Wheel-Tracking Test was used to simulate extreme pavement degradation under heavy loading and moisture [57], while the permeability test assessed MPs leaching from crack surfaces [58]. Results showed that although RPM asphalt pavements have the potential to release MPs, the estimated emissions were about three orders of magnitude lower than those generated by tire wear on pavement surfaces. This suggests that incorporating recycled plastics into asphalt may not substantially increase overall roadway-derived MP pollution. However, these findings contrast with other studies that have reported measurable MP generation from pavement degradation, highlighting the need for long-term field validation to better quantify the environmental significance of RPM pavements as a source of MPs.

Erosion Control Netting

Erosion control netting has been used in road construction to stabilize soil, support vegetation growth and reduce sediment runoff [59]. Erosion control netting is typically manufactured of fibers such as straw, wood, excelsior, coconut, plastic, or a combination thereof, and stitched or glued to, or between, geosynthetic netting or woven natural fiber netting [60]. Erosion control netting is usually selected based on site criteria such as slope, potential water flow velocity, desired plant species, ecosystem and soil type, along with longevity (or duration until deteriorated) [61]. A review by Kärrman et al. [62] highlighted that that polypropylene, commonly used in plastic erosion netting, can lead to long-term environmental challenges. Due to ultraviolet exposure, weathering and/or mechanical wear, the nets break down and are released as buoyant MPs into stormwater runoff [63]. Although erosion control netting has proven to be a good environmental management tool, its pollution potential from the breakdown of plastic netting has not yet been studied. Importantly, once released, these buoyant MPs can be transported via stormwater systems into receiving surface waters, potentially reaching reservoirs, rivers and other drinking water sources. This transport pathway raises concerns regarding human exposure through ingestion, as well as broader ecological impacts, particularly in urban watersheds where stormwater is a primary conduit for contaminant delivery.

Human Activities

Human activities such as inadequate waste management and littering, contribute to the release of MPs in roadway environments. Common types of plastic litter include plastic bags, food wrapping, single-use cups and beverage bottles. Plastic litter deposited in roadway environments gradually fragments into smaller MPs through mechanical forces and natural weathering, eventually accumulating in nearby soil or dispersing to surrounding areas [64].

Conclusion

In roadway environments, tire wear, brake wear, road markings, RPM asphalt pavements, erosion control netting and human activities have all been identified as contributors to MP emissions, however, few studies provide field-based data and existing research relies on often incomparable methodologies. Tire wear dominates emission estimates, yet reported values differ widely due to variations in experimental design, vehicle type, traffic conditions, climate conditions and particle size ranges, reflecting a lack of standardization. Road markings also exhibit substantial variability, with emissions strongly influenced by material type, durability and region specific abrasion factors, leading to global estimates that vary

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by nearly a factor of ten. Laboratory-based investigations of RPM asphalt pavements have produced contradictory findings, with wet incorporation releasing MPs more rapidly than dry mixes despite lower plastic content, indicating that environmental conditions and recycled plastic incorporation method strongly influence MP emissions. While some studies suggest that RPM pavements may represent a relatively minor source of MPs compared to tire wear particles, others have demonstrated measurable MP release from pavement degradation, highlighting ongoing uncertainty regarding their environmental significance. Similarly, erosion control netting remains underrepresented in quantitative assessments, despite its potential for long-term MP release through ultraviolet exposure, weathering and/or mechanical wear. Overall, while this section synthesizes current knowledge on roadway MP sources and their emission factors, existing data are incomplete, context-dependent and often derived from laboratory-based experiments. Furthermore, the conflicting findings reported for emerging sources such as RPM asphalt pavements highlight the need for long-term field-based monitoring to validate laboratory observations and determine the relative importance of these sources under real-world conditions in order to generate accurate emission estimates and guide effective mitigation strategies.

Pathways of Microplastic Pollution in Roadway Environments

Stormwater Runoff

Stormwater runoff provides a direct pathway for MPs and has been identified as the most significant conduit for the transportation of MPs from roadway environments into aquatic ecosystems [65-67]. According to Premarathna et al. [64], initially, tire wear particles settle in nearby soil and are later transported by stormwater runoff into aquatic ecosystems, leading to both environmental and human health hazards. Several studies have reported MP concentration of between 66 particles per liter to as high 4400 particles per liter in stormwater samples [68-70].

Modern urban and roadway drainage systems channel stormwater runoff into surface and ground water. Although MPs can temporarily settle in low-lying areas of these systems under low-flow conditions due to their low density (polypropylene, a common roadway MP polymer has a density of about 0.9 g/cm3) in comparison to water (1 g/cm^3), heavy rainfall and resulting turbulent flows are likely to remobilize and transport them into surface waters [71,72]. Rainfall intensity and flow rate therefore play a crucial role in generating stormwater runoff and serve as key drivers for the transport of MPs in urban environments [73,74]. A study by Treilles et al. [75] investigated MPs in stormwater during four rain events. The highest MP concentrations (~129 items/L) were observed in two of the rain events and at the beginning of both rain events whilst the lowest MP concentrations were observed at the end of the rain events (~3 items/L). During these two rain events, the high MP concentration peaks were linked to the increase in flow rate. Generally, the transport of MPs to aquatic ecosystems is most pronounced during the initial phase of a rainfall event commonly referred to as the first flush, after which the input rate tends to decline as precipitation continues [76,77,78].

Atmospheric Transport

Due to their low density and size, MPs in roadways can be airborne when exposed to mechanisms such as vehicle-induced turbulence, shear stress, or wind [79]. These processes also affect the movement and distribution patterns of MP pollution, shaping source-sink dynamics in both terrestrial and marine ecosystems [80]. Although MPs may participate in local air-ground surface exchanges, some MPs have been detected in the atmosphere in remote areas far away from source regions, suggesting potential long-distance atmospheric transportation [81]. The Interstate Technology and Regulatory Council [82] explains how MPs transported in the atmosphere may vary by location, that is, smaller MPs tend to be found in remote areas whilst larger MPs tend to be found in urban areas. According to Allen et al. [83], the transmission distance of MPs in the atmosphere is approximately 19 km per month. Another study by Evangeliou et al. [84] examined atmospheric transport and the deposition of MPs on a global scale using simulations and concluded that atmospheric transport of MPs not only disperses MPs across the terrestrial environment but also contributes to their deposition into the aquatic environment.

Conclusion

Although both stormwater runoff and atmospheric transport are recognized as major pathways for roadway-derived MPs, stormwater is generally considered the dominant route for their transfer into aquatic environments. Reported MP concentrations in stormwater range widely from 66 to 4,400 particles/L, a variability that likely reflects not only environmental heterogeneity but also methodological differences such as sampling design (grab vs composite), event-based versus time-integrated monitoring, inconsistent reporting units (particles/L vs mass-based metrics) and analytical detection limits related to polymer identification techniques. This substantial variability highlights an important limitation in current MP research: differences in sampling and analytical methodologies can significantly influence reported concentrations, making it difficult to directly compare results across studies or derive representative transport estimates. These inconsistencies hinder cross-study comparability and limit the ability to derive representative MP transport coefficients. As a result, there is a critical need for improved and standardized sampling and analytical approaches to reduce methodological uncertainty and improve the reliability of MP quantification in stormwater systems. In contrast, the

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atmospheric transport pathway is less well-characterized, with empirical data comparatively sparse. A common assertion is that smaller MPs are transported to remote areas while larger particles remain concentrated in urban regions, yet this claim requires further consideration of particle fragmentation during transport, deposition-resuspension dynamics and seasonal variability. Overall, while stormwater and atmospheric transport are clearly important in MP transportation, current understanding of MP pathway dynamics remains limited mainly by methodological heterogeneity, highlighting the need for standardized and comprehensive approaches to accurately quantify MP transport in roadway environments.

Characterization of Microplastics

According to Lambert et al. [85], "microplastics" is an umbrella term that covers many particle shapes, sizes and polymer types, and as such, the physical and chemical properties of MPs differ in characterization. This data on MP characteristics is commonly collected to provide clues regarding their potential sources and to inform their fate in the environment, in biota and in humans. Further refinement of MP characteristics such as surface topology, tensile strength and texture has been used in other studies to improve polymer characterization and strengthen source attribution [86-88]. The main characterization categories of MPs is shown in Figure 2;

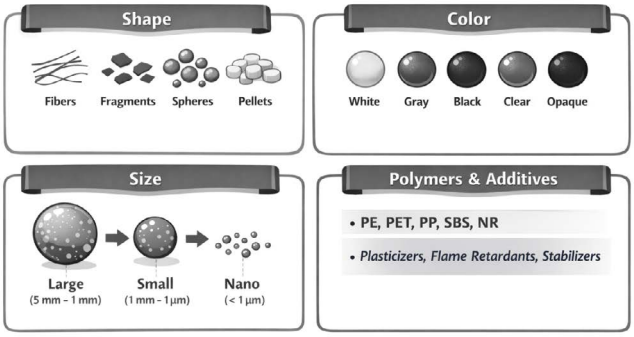

Figure 2. Microplastics characterization categories

Shape

MPs exist in different shapes and the shape of a MPs is often used to assign it to a certain category, which helps in source identification. Common MP shapes include fiber, fiber bundle, fragment, sphere, pellet, film and foam [89]. Distinct MP shapes are often linked to particular products, for example, a study by Yukioka et al. [90] investigated the occurrence and characteristics of MPs in surface road dust in Japan, Vietnam and Kathmandu Nepal and concluded that fragmented shapes originated from vehicle tire wear particles.

The shape of MPs does not only provide clues about their sources but also the surface degradation and erosion processes they have undergone as well as their likely time in the environment. For example, MPs with sharp edges are thought to indicate recent entry into the environment, whereas smoother edges suggest a longer residence time [91,92].

Moreover, the shape of MPs can influence how they move through the environment. For example, thin, flat films offer a larger surface area for transport by air compared to heavier fragments of the same mass [83]. Additionally certain shapes may pose greater physical risks to organisms with smaller, angular particles having a greater potential to easily penetrate biological membranes than those with longer, regular surfaces [91,89].

Color

Traditionally, color characterization of MPs has relied on visual assessment, assigning each item to a predefined color category. However, this method is highly subjective and the color categories vary widely between studies, leading to inconsistency. A review of MPs in road dust by Yang et al. [19] asserted that MPs in roadway environments are mainly white/transparent, orange/yellow, blue/green, red/pink and black/gray.

The color of MPs is typically a result of additives introduced during manufacturing to enhance product appearance and functionality [93] and it can sometimes indicate the source of the MPs. For example, transparent/white MPs found in roadway environments often come from plastic litter such as plastic bags, food wrapping, single-use cups and beverage bottles [94] while black MPs are commonly associated with tire wear particles [95]. The wide range of MP colors reflects the variety of MP pollution sources, however, Wang et al. [96] found that environmental weathering, sunlight exposure, abrasion or sample processing can alter or fade the original colors. As a result, caution is needed when using color for MP source identification.

Zhao et al. [97] also highlights that the color of MPs can influence their ability to adsorb, release and degrade pollutants as well as their biological toxicity. Moreover, color may influence the likelihood of MP ingestion by organisms, for instance, visually guided predators may mistake brightly colored MPs for prey and ingest them. As such, color should be considered when evaluating the ecological risk and toxicity of MPs in the environment.

Size

MPs are broadly classified by size, with one of the most widely adopted classifications proposed by Crawford and Quinn [98] and adopted by USEPA [99] and similar agencies, which defines;

i. Large MPs as particles ranging from 5 mm to 1 mm,
ii. Small MPs as those between 1 mm to 1 µm and
iii. Nanoplastics as particles smaller than 1 µm size (<1 µm).

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The size of MPs plays a key role in their ingestion, bioaccumulation and toxicity profile in biota and in humans. 'Small' MPs tend to pose a higher toxicity risk to different ecosystems and human health than 'large' MPs [100]. The size of MPs may also inform how they are transported and where they ultimately end up. Liu et al. [101] reports that the retention of MPs during their transportation process across different environmental compartments via stormwater runoff is affected by MP size. A review by Yang et al. [19] concluded that MPs with a size less than 1 mm are the most common in roadway environments and are therefore easily transported by stormwater runoff into aquatic ecosystems. A study by Monira et al. [102] aimed at identifying, classifying and quantifying MPs in road dust and stormwater found that most of the MPs found in industrial and residential areas of Melbourne Metropolitan City, Australia, had an average maximum dimension smaller than 2 mm for both road dust and stormwater samples. The findings of the study further confirmed that roadway environments are significant contributors towards MP pollution and demonstrated how small-sized MPs are easily mobilized, increasing the potential for rapid entry into aquatic environments.

Polymers and Additives

Beyond their physical attributes, MPs possess distinct chemical properties that contribute to their widespread distribution and potential harm. Some of the most common forms of MP polymers found in roadway environments include synthetic styrene-butadiene (SBS), natural rubber (NR), polyethylene (PE), polyethylene terephthalate (PET) and polypropylene (PP) [17,19]. Each polymer type has unique properties, which can influence the behavior and fate of MPs in different environments [103]. Additionally, MPs can contain a variety of additives that are used during production to enhance their properties such as improving flexibility, durability, color and resistance to heat and/or ultraviolet light. Examples of commonly used additives are plasticizers, flame retardants, lubricants colorants and stabilizers [93].

Rosso et al. [15] quantified and chemically characterized MPs in highway road dust, identifying vinyl ester and polytetrafluoroethylene as dominant polymers and attributing their presence primarily to vehicle components from tires to car chassis, seats, cooling systems, or even in engine and vehicle parts and gaskets. The same study also detected a wide range of additives, most commonly lubricants and plasticizers. Since lubricants and plasticizers are commonly used in packaging materials production, these could originate from plastic litter accumulated in the highway curbside or from vehicles [104]. Another notable source of the additives detected in the samples was likely tire wear particles on highway asphalt, supported by the presence of vulcanizers, accelerators and pre-vulcanizing retardants commonly used in tire and elastomer rubber manufacturing. Due to the identified polymers and additives, the authors concluded that vehicle traffic, packaging materials and the wear of tires were the major sources of MPs in highway road dust.

Conclusion

MP characterization in roadway environments typically focuses on shape, color, size and polymer/additive composition, providing key insights into sources and fate, however, current approaches exhibit limitations. Shape is often used to infer MP sources and transport pathways, for example, fibers, fragments, films and pellets can indicate tire wear, packaging or consumer plastics. However, visual identification is subjective and may overlook irregular particles. Color can also help with source attribution, but it is easily altered by weathering, UV exposure and sample processing, which complicates interpretation. On the other hand, size classifications (large, small, nanoplastics) influence MP movement and environmental fate. Lastly, polymer and additive analyses commonly detect SBS, NR, PE, PET and PP, along with additives such as plasticizers, lubricants and flame retardants - patterns consistent with roadway sources like tire wear and vehicle components. Still, because many additives are used across multiple products, linking MPs to specific sources based solely on polymers or additives remains difficult. Overall, while multiple MP characteristics can provide valuable clues about their origins and behavior, each method has limitations and accurate source attribution requires integrating several lines of evidence.

Microplastic Analysis

As MPs are increasingly being recognized as emerging pollutants, research efforts have surged, leading to the development and expansion of diverse methodologies for analyzing MPs in various environmental matrices. Cowger et al. [86] asserts that this has resulted in a broad spectrum of techniques that has led to inconsistencies that complicate cross-study comparisons and large-scale synthesis of findings.

Although no validated method currently exists for MP analysis [105], it typically follows a fundamental sequence as shown in Figure 3;

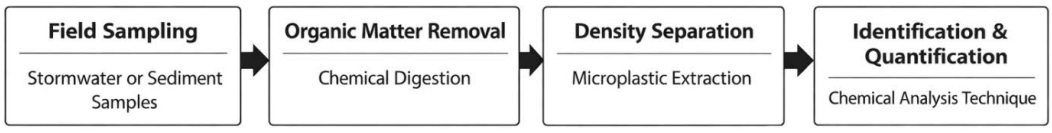

Figure 3. Microplastic analysis process flow chart (adapted from Halle et al. [106])

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The sequence of MP analysis steps may be modified based on the sample type, research objectives and available methodologies, provided that the analytical integrity is preserved.

Field Sampling

Analysis of MPs in roadway environments begins with the collection of stormwater or sediment samples. The choice of sampling medium depends not only on available equipment but also on the specific research objective. For example, if the goal is to assess MPs originating from tire wear particles, stormwater management systems may provide the most suitable sampling location because they collect runoff from road surfaces where tire wear particles accumulate and are transported during rain events. Both the sampling method and the volume collected can affect the representativeness of the results, which are typically reported as total MPs per unit of sample (e.g., per liter of water) [107].

Automated flow-weighted composite sampling is usually preferred in stormwater MP research because it provides consistent flow-based runoff collection during storm events without the need for manual intervention. This improves sample representativeness and minimizes labor and human error [108]. In a study by Järlskog et al. [69], researchers investigated the presence of various categories of MPs on road surfaces within an urban reconstruction area and in stormwater from the same location. For stormwater sampling, two automatic samplers were installed in a manhole downstream of the stormwater management system. Composite, flow-weighted sampling was conducted throughout each runoff event. Initially, the samplers were programmed to collect sub-samples when flow rates exceeded 5 L/s. Due to fluctuating flow conditions, the autosamplers were later adjusted to collect samples when water levels in the 1200 mm diameter pipe rose above 75 mm. This threshold was selected to exclude minor rainfall events that were less than 3 mm and to ensure adequate sample volumes were collected during significant storm events (a tipping bucket rain gauge with 0.2 mm tipping volume was used to monitor rainfall). Several other studies have also used automated, composite flow weighted sampling in their MP research [105,109].

Chemical Digestion of Organic Matter

The density of organic matter is often similar to that of MPs and because organic matter is only partially removed during density separation it can interfere with subsequent chemical analysis. For example, when using instruments such as Thermogravimetric Analysis (TGA) for chemical analysis, organic material can decompose at similar temperatures as some MPs. This overlap can cause confusion between mass losses from organic matter and those from polymer degradation, reducing the accuracy of polymer type differentiation [110]. When using instruments such as Fourier Transform Infrared Spectroscopy (FTIR), organic residues can mask or overlap polymer-specific absorption bands, making it harder to correctly identify the polymer type [111]. When using techniques like Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS), some constituents of organic matter may release the same pyrolysis products as the targeted polymers, leading to potential MP overestimation [112]. Excessive organic matter in a sample can also lead to filter clogging during laboratory sample-pretreatment, which slows down the filtration process and decreases overall filtration efficiency [113]. Therefore, it is essential to eliminate organic matter using a chemical digestion process prior to density separation and chemical analysis.

Common chemical digestion agents include alkaline solutions acids, oxidizing agents and enzymes [114,115,23]. To enhance digestion efficiency, these agents are applied in varying concentrations and at different temperatures as highlighted in Table 2;

Table 2. Common chemical digestion agents, recommended concentrations, temperature and digestion time in the removal of organic matter

Digestion Agent	Concentration	Temperature	Digestion time	Citation/s
Hydrogen Peroxide (H_2O_2)	30%	<75^{0}C	Variable (until no organic matter is visible)	Masura *et al.* [116]; Huang *et al.* [23]
`1Q31`	Z321	Room temperature to 50^{0}C	24 hours	Tan *et al.* [117]; Löder *et al.* [118]
Potassium Hydroxide (KOH)	10%	45^{0}C	24 hours	Tan *et al.* [117]
Potassium Hydroxide (KOH)	1–10%	Room temperature to 60^{0}C	24 hours	Tan *et al.* [117]; Huang *et al.* [23]
Nitric Acid (HNO_3)	65%	Room temperature	24 hours	Claessens *et al.* [119]; Tan *et al.* [117]
Enzymatic Digestion	Proteinase (2000U/L) Lipase (2500U/L) Cellulase (200U/L)	Proteinase 50^{0}C Lipase 40^{0}C Cellulase 50^{0}C	24 hours per enzyme	Löder *et al.* [118]; Tan *et al.* [117]
Sodium Hydroxide (NaOH)	10M	45^{0}C-60^{0}C	24 – 48 hours	Rani *et al.* [113]; Tan *et al.* [117]
Mixed Acid e.g Nitric Acid: Perchloric Acid (HNO_3:$HClO_4$)	Variable	Room temperature	24 hours	Tan *et al.* [117]

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Density Separation

The objective of the density separation method is to separate MPs from the sample matrix and thus simplify and improve the subsequent analysis and characterization process of MPs. The density separation process involves mixing the collected sample with a chosen density solution, allowing time for separation and then collecting floating plastics. Since the density of plastic (~0.8-1.6 g/cm−3) is much lower than that of sediment (~2.7 g/cm−3), this difference can be used to segregate MPs from sediment. Thus, solutions with >1.4 g/cm−3 density are used to segregate MPs from sediment and this will result in MPs floating in saturated salt solutions that are denser than the MP particles, while heavier sediment settles at the bottom [120]. Subsequently, the floating supernatant containing MP particles is extracted and vacuum filtered using appropriately sized membrane filter papers to remove liquid from the sample.

Common density separation salt solutions include sodium chloride (NaCl), sodium bromide (NaBr), sodium iodide (NaI), calcium chloride ($CaCl_2$) and zinc chloride ($ZnCl_2$), with the selection depending on the density of the target polymer. For example, deionized water and saturated NaCl are cost-effective and environmentally friendly for low-density polymers like polyethylene (PE), polypropylene (PP) and polystyrene (PS), whereas denser solutions are needed to recover higher-density polymers such as polyethylene terephthalate (PET), polyvinyl chloride (PVC) or polytetrafluoroethylene (PTFE) [121]. It is important to note that certain polymers, such as polycarbonate and polyamide, can degrade or react when exposed to strong acidic or alkaline solutions [122]. Therefore, the selection of a density separation solution must be carefully matched to the target polymer to avoid material alteration. Additionally, the effectiveness of density separation is influenced by the organic matter content in samples. For instance, the density separation technique is less suitable for solid samples with lightweight organic material where fine particles tend to stay suspended in the supernatant unless a solution such as NaBr is used as the separating solution as it can be adjusted to achieve high recovery rates with simple handling [123,93]. NaBr has high MP recovery primarily because of its ability to create a high-density aqueous solution (~1.53 g/cm−3), which allows it to separate a wide range of MP polymers from organic matter. Table 3 compares commonly used density separation salt solutions in MPs research;

Table 3. A comparison of commonly used density separation salt solutions in MPs research, polymers of interests and typical recovery rates

Separation Solution and Typical Concentration	Polymers Recovered	Typical Recovery Rate	Citation/s
NaCl >99%	PE, PP (mainly low-density polymers)	60–80%	Frias *et al.* [121]; Claessens *et al.* [119]; Schütze *et al.* [123]
$CaCl_2$ ≥94 %	PE, PP, PS (partially PET, limited PVC)	70-90%	Duong *et al.* [124]; Liu *et al.* [93]; Gran *et al.* [125]
NaBr 99%	PE, PP, PS and high-density polymers PET, PVC, PTFE	85–95%	Schütze *et al.* [123]; Frias *et al.* [121]
$ZnCl_2$ 98%	Almost all common MPs (PE, PP, PS, PET, PVC, etc.)	80–98%	Imhof *et al.* [126]; Crutchett *et al.* [127]; Duong *et al.* [124]; Ponti *et al.* [128]
NaI 99%	Most common MPs including PVC and PET	>95%	Quinn *et al.*[129]; Claessens *et al.*, [119]; Katsumi *et al.* [130]; Nava and Leoni [131]

Table 4. Common visual analysis methods

Method	Advantages	Disadvantages	Detection limits	Citation/s
Light Microscopy	• simple to use • low cost • minimal chemical risk	• time consuming • laborious • prone to human bias • low accuracy	> ~50 µm	Dris *et al.* [136]; Sanchez Garcia *et al.* [105]; von Moos *et al.* [140]; Zhang *et al* [81]; Huang *et al.* [137]; Kotar *et al.* [141]
Fluorescent Microscopy	• cost effective • short staining durations (10–30 minutes)	• false positives • extensive sample preparation	~10–20 µm	Enfrin *et al.* [53]; Shruti *et al.* [139]; Maes *et al.* [142]; Shamim [138]

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Although density separation is the commonly used method for isolating MPs from a sample, it has limitations when applied to large runoff volumes or when particles are strongly bound to sediment. To improve its efficiency, various procedural modifications have been introduced, including reusing the same solution, combining different density solutions and replacing manual stirring with other techniques such as aeration, ultrasonication and centrifugation [132,133].

Oil-based separation methods have also been explored due to the hydrophobic nature of plastics. The principle of this method is based on the oleophilic attraction between plastic polymers and oil, allowing them to separate from other materials. Imhof et al. [126] tested pine oil combined with a froth conditioner to facilitate the release of MPs from sediment and this approach yielded relatively low recovery rates (55%), especially for high-density MPs. In contrast, when Lechthaler [134] experimented with canola oil, it demonstrated higher efficiency, achieving a recovery rate of over 90% with a minimal retention of organic matter. A different study by Karlsson et al. [135] added a drop of olive oil to salt-saturated solutions and there was an improved recovery rate of MPs from 64% to 82%. While oil-based methods may require an additional detergent cleaning step and have some limitations, they can be effectively combined with saturated solutions to improve overall MP recovery.

Identification and quantification

Identification and quantification of MPs is the succeeding step after sampling, chemical digestion and a complex density separation procedure. This step confirms that the separated particles are surely MPs. For the effective analysis of MPs generated from roadway environments, it is essential to select suitable identification and quantification techniques that align with the specific research objectives. Employing a well-considered combination of detection methods will provide more comprehensive and reliable data.

MP analysis methods are generally categorized into four main groups: visual, spectroscopic, thermal and combined techniques.

Visual Analysis Techniques

Early studies on MP pollution relied on basic visual analysis methods such as microscopy to identify MP particles [136]. Currently, visual analysis methods are commonly used as preliminary techniques to estimate particle counts and examine physical attributes of MPs like size, shape and color [105].

Light microscopy is an example of a traditional visual analysis method that evaluates a sample with a microscope under normal visible light conditions. It is especially useful for particles larger than 50 µm and in MPs research, it often serves as a screening tool before more advanced chemical identification methods [137].

Fluorescent microscopy is another visual analysis technique whereby a fluorescent dye binds to MPs (because of their hydrophobic nature) and fluoresces under specific wavelengths of light. Although dyes such as Eosin B, Rose Bengal, Hostasol Yellow 3G and Oil Red EGN have shown certain limitations [107], Nile Red has proven effective for staining physiologically neutral lipids. Its strong affinity for these lipids enables it to fluoresce primarily in hydrophobic environments [138]. A review by Shruti et al. [139] concluded that the Nile Red fluorescent microscopy analysis method can serve as an effective standalone alternative to the visual identification of MPs. However, since not all particles that fluoresce with Nile Red are necessarily MPs, thorough sample preparation or supplementary chemical analysis is required to confirm the accuracy of the results. More characteristics of common visual analysis techniques are presented in Table 4;

Spectroscopy Analysis Techniques

Spectroscopy analysis techniques are based on the interaction of radiation with molecular vibrations and are efficient methods for the representative analysis of MP particles. These methods enable the identification of polymer types, as well as the quantification and characterization of MP particles [143].

Fourier Transform Infrared Spectroscopy (FTIR) is a vibrational spectroscopy analysis method whereby infrared light is directed at the sample and based on the molecular structure of the MPs, specific wavelengths are absorbed, generating distinctive spectral bands unique to different polymer types [111]. These unique polymer spectra enable differentiation of plastics from other organic and inorganic materials. The availability of standardized polymer spectral libraries enables the provision of information regarding chemical bonds and functional groups in samples, supporting accurate identification [107]. However, environmental MPs often show some spectral variation; thus, a 70% match rate is commonly used as a threshold in many studies [101].

Attenuated Total Reflection-Fourier Transform Infrared Spectroscopy (ATR-FTIR) is a surface-sensitive infrared spectroscopy analysis method that is used to analyze larger particles (>300 µm), mainly because of the particle's surface thickness and irregularity [101]. ATR-FTIR uses ATR crystals, commonly made of diamond, zinc selenide or germanium to measure how a sample absorbs infrared light. The sample is pressed directly against the ATR crystal surface to achieve internal reflection of infrared light. After interacting with the sample, the remaining infrared light exits the crystal and is detected by an FTIR spectrometer, providing chemical mapping of samples [101,138].

Raman Spectroscopy is another commonly used vibration spectroscopy analysis technique that is based on inelastic scattering of light [137]. In Raman Spectroscopy, a laser beam is directed onto the sample, which produces back-

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scattered light with frequencies characteristic of the MP molecular structure and atomic composition. This results in unique spectral fingerprints for each polymer, allowing for accurate identification and detailed analysis of polymer types [111]. Table 5 summarizes the characteristics of common spectroscopy techniques;

Combined Analysis Techniques

Combined analysis techniques have been used in MPs research to overcome the limitations of individual methods and to ultimately improve accuracy of polymer identification.

Table 5. Common spectroscopy techniques

Method	Advantages	Disadvantages	Detection limits	Citation/s
FTIR	• minimal sample preparation • non-destructive • high sensitivity and accuracy	• spectral overlap	≥20 µm	Xu *et al.* [111]; Munari *et al.* [145]; Prata *et al.* [107]
ATR-FTIR	• improves analysis of irregular, thick, or opaque particles • no sample pre-treatment	• ATR crystals are an additional cost • ATR crystals are prone to wear and tear • manual presorting may be required	>300 µm	Xu *et al.* [111]; Liu *et al.* [146]
Raman	• high spatial resolution • no interference from water • low sample quantity requirements • suitability for high-throughput screening • environmentally friendly	• longer measurement times • fluorescence interference • subjective particle selection • reduced effectiveness with weathered plastics	1 µm	Xu *et al.* [111]; Du and Wang [147]; Yang *et al.* [19]; Werbowski *et al.*, [148]

Table 6. Common thermal techniques

Method	Advantages	Disadvantages	Detection limits	Citation/s
TGA	• minimal sample pretreatment • rapid results (typically 2-3 hours) • effective for analyzing complex solid matrices	• overlapping thermal degradation profiles • destructive	Does not provide particle size	Majewsky *et al.* [149]; Fan *et al.* [151]; Mansa and Zou [110]

Micro-Fourier Transform Infrared Spectrometry (µ-FTIR) is a combined analysis technique whereby a microscope is attached to an FTIR spectrometer. The equipment automatically scans the filter, providing localized chemical mapping or imaging of MPs in a contactless manner [146]. µ-FTIR is commonly performed in either transmission or reflection mode, with transmission being the most widely used for analyzing environmental samples [152,153]. To improve imaging performance, µ-FTIR systems can be equipped with multi-detectors such as linear array or focal plane array detectors. These enhancements enable automated analysis over large areas and the rapid collection of millions of spectra within a few hours [154].

Thermogravimetric Analysis-Fourier Transform Infrared Spectroscopy (TGA-FTIR) is another combined chemical analysis technique that simultaneously determines the thermal decomposition behavior of a sample (TGA) and the chemical composition of the evolved gases (FTIR) [110]. TGA-FTIR offers information regarding the composition of MPs by continuously capturing FTIR spectra throughout the whole thermal degradation process. As the polymer is heated and decomposes, many spectra are recorded in real time, each linked to specific temperature intervals. This allows researchers to not only identify the types of polymers present but also detect associated additives and understand their thermal decomposition patterns [155].

Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS) is a combined analysis technique whereby MPs are thermally decomposed under inert conditions at temperatures ranging from 500 °C to 800 °C [156]. Py-GC-MS relies on degradation (Py) products generated at defined temperatures under the exclusion of oxygen. The resulting gases are carried into a gas chromatography (GC) column and subsequently analyzed by a mass spectrometer (MS) which identifies the decomposition products by ionizing individual molecules [107]. By analyzing specific pyrolysis products, Py-GC-MS enables the determination of polymer mass, allowing for the simultaneous identification and quantification of various MPs in complex environmental samples. In addition, this technique can detect plastic-associated additives and

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degradation by products, providing essential data for accurate environmental and human health risk assessments [143].

Thermo-Extraction and Desorption coupled with Gas Chromatography-Mass Spectrometry (TED-GC-MS) combines thermal extraction and desorption with gas chromatography and mass spectroscopy. The TED-GC-MS analysis method involves two main steps. First, the sample is subjected to controlled pyrolysis using a thermogravimetric analyzer (TGA), typically under an inert nitrogen atmosphere. During this phase, temperature gradually increases, usually up to around 600 °C, causing the sample to thermally degrade. The resulting gaseous decomposition products are purged from the TGA and transferred through a heated coupling device to a solid phase adsorber [143]. In the second stage, the solid phase is loaded with an excerpt of the decomposition products and the adsorber is transferred to a thermal desorption unit of the GC-MS instrument [157]. In the thermal desorption unit, the decomposition products are thermally desorbed, mobilized and cryo-focused in a cooled injection system. When the thermal desorption process is finished, the trapped analytes are quickly reheated, separated through a GC column and measured quantitatively by MS [158]. TED-GC-MS produces a chromatogram showing the breakdown products formed during pyrolysis, along with mass spectra that can be matched to reference libraries, allowing for the identification of MP polymer even in complex environmental samples [157]. More characteristics of commonly used combined analysis techniques are presented in Table 6;

Conclusion

The MP analysis section highlights substantial methodological progress, yet it also exposes persistent limitations that affect reproducibility, comparability and accurate quantification. Since no validated method currently exists for MP analysis, this absence of standardization permeates every stage of the workflow, from sampling field sampling to chemical digestion, density separation and subsequent analysis Field sampling strategies, including grab versus flow-weighted composite approaches, differ widely across studies, resulting in variability in particle representativeness and concentration estimates. Chemical digestion, though essential for removing organic matter, relies on diverse reagents and temperatures, with some approaches risking polymer integrity or incomplete removal of organics, leading to interference with subsequent chemical analysis. Density separation methods also show contradictions. For example, while NaCl is widely used for its low cost, its recovery efficiency is limited for high-density polymers, whereas denser solutions like $ZnCl_2$ or NaI offer higher recovery but introduce environmental, cost, or polymer-stability concerns. Identification techniques further illustrate tradeoffs. For instance, visual methods are rapid but subjective and limited to larger particles (>50 µm), spectroscopic methods offer polymer-specific information yet struggle with irregular, weathered, and especially nanoplastic (<1 µm) particles, while thermal and combined techniques provide chemical composition and additive profiling but ignore particle morphology and require costly, complex instrumentation. Consequently, nanoplastics are likely underrepresented in the current literature because their small size makes them particularly difficult to detect, identify and quantify using many existing analytical techniques. Collectively, these methodological inconsistencies, coupled with instrument-specific biases and matrix-dependent

Table 7. Common combined analysis techniques

Method	Advantages	Disadvantages	Detection limits	Citation/s
µ-FTIR	• non-destructive • minimal sample handling	• spectral distortion due to surface conditions	≥10–20 µm	Olivatto *et al.* [159]; Zeng [160]; Xu *et al.* [111]; Liu *et al.* [146]
TGA-FTIR	• provides both degradation profile and gas composition • commonly accessible • rapid analysis	• identification limited to polymers with unique absorption bands • pre-concentration of samples	Does not provide particle size	Mansa and Zou [110]
Py-GC-MS	• simultaneous identification and mass-based quantification • analyzes MPs from diverse sources • no extensive sample preparation • highly sensitive	• no information on the size, shape, or count of MPs particles • complex and costly instrumentation • overlapping pyrolysis byproducts	0.06 -0.0002 µg	Nandikes *et al.* [156]; Prata *et al.* [107]; Zhou *et al.*[155]
TED-GC-MS	• capable of a one-step analysis • high sensitivity	• complex and costly instrumentation	0.06 µg	Fischer and Scholz-Böttcher [162]; Picó and Barceló [163]; Mansa and Zou [110]; Goedecke *et al.* [164]

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recovery efficiencies and the continued underrepresentation of nanoplastics, reveal a field still constrained by non-standardized approaches, highlighting the need for internationally standardized and validated methods to ensure reproducible and comparable MP data across environmental studies.

Potential Microplastic Control Measures

Mitigating MP emissions from roadway environments demands a coordinated strategy that addresses the full chain of sources and transportation pathways. This section introduces the range of practical and emerging interventions currently shaping this integrated approach and outlines how they can be implemented to support more resilient and sustainable roadway systems.

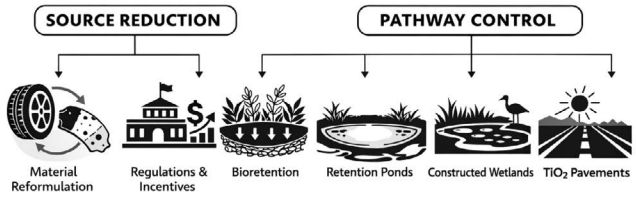

Figure 4. A summary of roadway microplastic reduction strategies

Source Reduction

Minimizing MP particle generation prior to environmental release remains the most sustainable and cost-effective strategy to mitigate their environmental footprint than downstream treatment interventions.

Material Reformulation

Material reformulation represents a primary MP source-control strategy within roadway systems. Engineering interventions that target abrasion resistance at the material scale have demonstrated measurable reductions in particle generation. For tires, advances in tread compound chemistry, such as optimized styrene-butadiene rubber (SBR) formulations and improved filler dispersion, have been associated with lower wear rates and improved mechanical stability. For example, A study by Pradeepkumar et al. [165] reported that SBR formulations reinforced with silica fillers exhibit superior thermo-oxidative aging resistance compared with conventional carbon black-based fillers. The silica-filled SBR compound showed the lowest aging coefficient of 2, whereas silica/carbon black blends and carbon black-filled formulations displayed substantially higher aging coefficients of 30 and 35, respectively. These findings suggest that silica can serve as an effective reinforcing filler for improving the durability of tire tread compounds, providing a potential pathway for developing longer-lasting tires that may also reduce tire-wear derived MP emissions in roadway environments.

Similar material-driven MP mitigation strategies are emerging in braking systems. A review by Saha et al. [166] highlighted advances in bio-based brake pad formulations as sustainable alternatives to conventional friction composites, emphasizing the potential of bio-based resinous binders, plant fibers and naturally derived additives to reduce MP emissions. The authors noted that continued experimental optimization and performance validation are necessary to support large-scale adoption and mitigate MP emissions from brake wear. Complementary work by Carlevaris et al. [167] found that incorporating 6 -12 wt % rice husk as a natural filler in brake materials preserved braking performance while potentially improving wear characteristics. Collectively, these findings indicate that substituting conventional polymer-intensive friction materials with bio-derived components may represent a viable pathway for mitigating brake-wear related MPs in roadway environments.

Beyond vehicle components, polymer-derived roadway materials such as thermoplastic road markings and synthetic erosion control netting contribute secondary MPs through mechanical wear and UV degradation. Substitution with natural-based alternatives has shown promise. Aksoy et al. [168] developed hemp-oil-based road marking paints with rapid drying (surface: 12 min, through: 34 min), high abrasion resistance (125 L) and hiding power (96.7%), matching or exceeding conventional systems with drying (surface: 12 min, through: 37 min) and abrasion resistance of 95 L. Similarly, Rofi and Rafiur [169] demonstrated that jute geotextiles in subgrades increased California Bearing Ration (CBR) values up to 280% for black cotton soil, 155% for murum soil and ~275% for mixed soils, enhancing load-bearing capacity while reducing dependence on synthetic geosynthetics. While these natural are promising, durability-performance tradeoffs require lifecycle evaluation. The use of recycled plastics in asphalt also demands careful assessment, as noted by Smyth et al. [54] and Duan [56], to ensure structural gains do not introduce secondary MPs.

Regulatory and economic frameworks

Regulatory and economic instruments are central to enabling large-scale MP source control within roadway environments. The US currently does not have a dedicated federal regulatory framework specifically addressing roadway-derived MP sources. However, the European Union (EU), under the EURO 7 Regulation, has established a precautionary and structured regulatory model that introduces stricter regulations for tire and brake particle emissions such as European Union [170]. This EU approach serves as a practical benchmark that could inform and guide the development of a comparable US regulatory framework for managing roadway MP sources.

Environmental policy analyses emphasize that frameworks addressing MP pollution are most effective when regulatory measures are combined with innovation incentives

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rather than relying solely on bans, as this approach may accelerate technological transitions and reduces barriers to market adoption [171]. For example, since lighter vehicles have proven to generate lower levels of tire and brake wear [28,39], incentives may therefore be created so that the vehicle industry brings lighter and smaller vehicles onto the market and they are purchased [172]. Such integrated policy strategies that combine both regulatory and economic incentives can stimulate technological advancement while reducing environmental harm, particularly for persistent and difficult-to-eliminate MP sources in roadway environments.

Pathway control

Given the predominance of stormwater transport as the principal vector conveying MPs from roadway environments to aquatic ecosystems, pathway control strategies targeting runoff interception and treatment represent a critical MP mitigation priority. Green infrastructure has been extensively implemented in numerous cities worldwide as an innovative stormwater management approach not only to address urban hydrology but to also mitigate water quality concerns, including MP pollution.

Bioretention

Bioretention systems and rain gardens have been identified as green infrastructure technologies with a high potential to reducing MP emissions from roadway stormwater through filtration and soil-media adsorption. A study by Mufidah and Soewondo [173] investigated the effectiveness of a lab-scale bioretention cell in removing MPs from stormwater runoff. An artificial influent simulating runoff from highways, commercial and residential areas was treated under varying vegetation types and discharge rates to assess removal performance and kinetics. The results showed high removal efficiencies ranging from 92.4% to 99.3% (mean 97.2%), with no significant effect of vegetation or discharge variation ($\alpha = 5\%$). First-order kinetic constants between 0.0327 and 0.0356 further confirmed consistent and efficient MP attenuation in bioretention cells. A field-based study by Galfi et al. [174] further validated the effectiveness of bioretention cells in controlling stormwater transportation of MPs. The researchers analyzed MP in influent and effluent stormwater and filter soils using TED-GC-MS and Py-GC-MS, identifying PVC, PET and PS as dominant polymers. Influent concentrations (115–496 µg/L) were reduced to 3–52 µg/L in effluent, demonstrating reductions of one to two orders of magnitude. Accumulation in the upper 0-15 cm soil layer further confirmed that bioretention cells act as effective sinks, limiting MP transport from impervious urban surfaces to receiving waters. These findings demonstrate that bioretention cells can be highly useful in removing MPs from roadway environments.

Retention Ponds

Retention ponds are also recognized as effective green infrastructure for controlling MP pollution along the stormwater transportation pathway. A Strategic Road Network study by Atkins and Jacobs [175] concluded that retention ponds are among the most effective mitigation measures for reducing MP export from road runoff, particularly tire wear particles generated by vehicular traffic. In the study, retention ponds reduced tire wear particle concentrations from an average influent concentration of 4.1 ± 3.22 mg/L to 0.22 ± 0.13 mg/L in effluent, corresponding to an average removal efficiency of 77.2%. Removal of other MPs averaged 42.7% ± 16.4. Sediment analysis revealed substantial accumulation of tire wear particles (mean 3.83 mg/g), indicating effective particulate settling and long-term retention. These findings align with previous international observations that sedimentation-based systems are particularly effective for denser or particle-bound MPs [176,101]. However, long-term management must account for sediment accumulation and potential remobilization during high-flow events.

Constructed Wetlands

Constructed wetlands are increasingly recognized as effective green infrastructure for mitigating MP pollution in stormwater. A field study by Ziajahromi et al. [177] found significantly higher MP concentrations at the inlet (1810 ± 410 MPs/kg) than at the outlet (315 ± 190 MPs/kg; $p = 0.02$), indicating that sedimentation within the wetland substrate plays a key role in retaining particles as stormwater flows through. Similarly, Wang et al. [178] reported an 88% MP removal efficiency, highlighting wetlands' ability to act as sinks and reduce downstream MP transport. However, Pramanik et al. [179] observed a lower removal efficiency of 28% when comparing inlet and outlet stormwater concentrations, suggesting that effectiveness can vary depending on wetland design and monitoring methods. These findings underscore the need for continued research and the retrofitting of existing stormwater green infrastructure to enhance MP capture in roadway environments.

Titanium Dioxide (TiO_2) Pavements

Apart from established green infrastructure practices that have shown to reduce MP transport via stormwater, emerging material-based technologies are also being explored. One such innovation involves self-cleaning, photocatalytic pavements enhanced with titanium dioxide (TiO_2), which have demonstrated the ability to purify stormwater while mitigating mold and bacterial growth on asphalt and concrete roadway surfaces. TiO_2 has been reported to be highly efficient at degrading MPs through catalyzing the evaporation process of MPs into carbonate CO3 and H2O, subjective to vegetative uptake, with independent studies indicating up to 98% MP removal efficiency [180]. A 2022 laboratory study by Zolinger and Filip [181] further confirmed that TiO_2-enhanced photocatalytic pavement applications are capable of rapidly degrading MP pollutants in roadway environments.

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SEM analysis confirmed substantial reductions in polystyrene microsphere diameter following UV exposure (375 nm, 110 W), corresponding to significant volume loss over time. After 2 hours of irradiation, polystyrene microspheres exhibited a 94.8% volume reduction (from 523,599 nm^3 to 27,282 nm^3), while 24 hours of exposure resulted in up to 99.6% volume loss (from 523,599 nm^3 to 2,026 nm^3), with visual evidence of near-complete MP particle disappearance in SEM imaging. However, it is important to note that current evidence for TiO_2-based MP degradation is largely limited to controlled laboratory conditions, where irradiation intensity, exposure time and pollutant composition are idealized compared to real roadway environments. The scalability of this technology to full-scale pavement systems remains uncertain, particularly given challenges related to long-term photocatalyst durability, energy dependency (UV availability), potential formation of intermediate degradation byproducts and cost implications for large-scale infrastructure deployment. These uncertainties currently limit its practical applicability as a near-term roadway MP mitigation strategy.

Conclusion

Mitigating MP emissions generated by roadway environments requires an integrated approach combining upstream source reduction with downstream pathway control. Source-oriented strategies, including material reformulation in tires, brake pads and roadway infrastructure, show promise for reducing MP generation before environmental release, with innovations such as advanced tire tread chemistry, bio-based brake materials and natural road markings demonstrating potential to lower MP emissions while maintaining performance. However, many of these solutions remain studied at the laboratory scale. Moreover, regulatory and economic frameworks are limited in some regions, notably the United States, despite models like the EU's EURO 7 regulation. Downstream pathway controls, including bioretention systems, retention ponds and constructed wetlands, have shown a high removal efficiency for MPs transported via the stormwater pathway. However, these green infrastructure systems may function as sinks that accumulate MPs in sediments, soils and filter media. While such retention reduces downstream transport, it also raises questions regarding the long-term fate of retained particles. Extreme storm events, flooding, sediment disturbance and maintenance activities could potentially remobilize previously captured MPs, creating a secondary pathway for environmental release. If such remobilization occurs, MPs may be transported to downstream aquatic ecosystems and drinking water sources, highlighting the need for long-term field investigations of BMP performance under a range of hydrologic conditions. Emerging technologies, such as TiO_2 photocatalytic pavements, have shown potential for MP degradation, but current evidence is also limited to laboratory studies, with uncertainties in scalability, by-products and cost. Overall, while these mitigation strategies demonstrate considerable potential to reduce roadway-derived MPs, further field-scale validation, long-term performance assessment and life-cycle evaluation are needed. An integrated framework combining source control, retrofit green infrastructure and emerging material-based technologies is essential to achieve effective and sustainable management of MP pollution in roadway environments.

Conclusions

Roadway environments clearly function as complex, multi source contributors of MP pollution. This review demonstrates that while substantial progress has been made in identifying dominant sources, major gaps persist in quantifying emerging contributors such as recycled plastic-modified asphalt pavements and erosion control netting, understanding transportation dynamics and standardizing analytical methods. Across the literature, findings remain fragmented by inconsistent sampling designs and laboratory-based evidence that limits real world applicability, even as mitigation strategies continue to advance. In addition, although roadway-derived MPs are increasingly recognized as potential environmental contaminants, relatively few studies have linked roadway emissions to human exposure, particularly for populations living, working or attending school near high-traffic corridors. Future research could therefore integrate field-based measurements with exposure assessment and human health risk modeling to better evaluate stormwater-related and atmospheric exposure pathways and to support evidence-based environmental and public health decision-making. Overall, the review highlights a need for coordinated, standardized and field-based research capable of generating reliable, comparable data that can meaningfully guide the design and implementation of sustainable strategies for reducing MPs generated by roadway environments.

Recommendations for future research:

- Field-based studies on underrepresented roadway MP sources such as recycled-plastic modified asphalt pavements and erosion control netting
- Development and standardization of MP sample collection and analysis protocols
- Design and testing of retrofit stormwater treatment systems specifically for roadways MP capture
- Development of regulations and guidelines targeting MP emissions from traffic-related sources

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