

Development of a Method to Identify and Quantify Microplastics Generated from the Roadway Environment

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FINAL REPORT

**DEVELOPMENT OF A METHOD TO IDENTIFY AND QUANTIFY MICROPLASTICS
GENERATED FROM THE ROADWAY ENVIRONMENT**

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ABSTRACT

Microplastics (MPs) are increasingly recognized as an emerging environmental contaminant originating from the fragmentation of larger plastic items. MPs have been identified in roadway environments related to conventional sources (e.g., particles from tires and brakes, road markings, erosion control netting, and litter) and emerging sources such as recycled plastic-modified asphalt pavements. Still, significant knowledge gaps persist regarding consistent analytical methods and the relative contributions of these diverse sources. This study developed a method to identify these sources of MPs and quantify their concentrations and then demonstrated this method at a field site.

Based on a review of academic literature and technical documents, a three-step method was created that incorporates hydrogen peroxide digestion, zinc chloride density separation with centrifugation, and thermogravimetric analysis-Fourier transform infrared (TGA-FTIR) spectroscopy. Testing in the laboratory with polymer-spiked sediment showed high recovery efficiency ($\approx 99.9\%$) in extraction and reliably identified polyethylene based on characteristic thermal and spectral signatures. The method was then applied to field-collected stormwater and sediment samples from a rural roadway site in Palmyra, Virginia. TGA-FTIR evaluation of field samples indicated that eight of the 12 samples contained MPs associated with acrylic road markings and tire wear particles. One sample was found to contain traces of degraded erosion control netting. MP concentrations in these samples ranged from 0.135 mg/g to 1.75 mg/g, with acrylic road markings and tire wear particles being the predominant type. In this regard, this method is reproducible and thus may characterize MPs in diverse roadway environments.

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The Virginia Department of Transportation can thus use this method, or a proposed enhancement thereof, to evaluate existing maintenance practices should regulatory conditions necessitate such work. This method may also inform the development of mitigation strategies for MPs required to comply with potential future regulatory requirements.

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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 (Herbort et al., 2018; Houssini et al., 2025). 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 (Lamichhane et al., 2023).

Microplastics (MPs) are defined as smaller plastic particles that are less than 5 mm in length (Arthur et al., 2009; Osman et al., 2023). MPs result from the long-term physical, chemical, 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 (Enyoh et al., 2025). Furthermore, 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 (Lamichhane et al., 2023). These factors contribute to MPs eventually entering the food chain and being found in various foods and drinks (Hu et al., 2022).

Urban areas greatly contribute toward the release of MPs into the environment. Mani et al. (2015) and Yonkos et al. (2014) reported higher concentrations of MPs at locations near urban centers compared with more remote or less developed areas. Although MPs in urban environments originate from a variety of sources, roadways and vehicles can be potential contributors toward MP pollution (Österlund et al., 2023). Growing populations and urbanization have led to an increase in highway construction and vehicular travel, contributing to MP emissions in roads (Horton et al., 2017; Rosso et al., 2023). 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 (National Academies of Sciences, Engineering, and Medicine, 2023). Although these applications may provide environmental and economic benefits, they also represent potential sources of MP generation through weathering, abrasion, and degradation over time. Therefore, a need exists to better understand the mechanisms and extent of MP generation and dispersion in roadway environments.

With a growing recognition of the potential for the roadway environment to contribute toward MP pollution, several critical knowledge gaps have been identified. Given the current important and ubiquitous use of plastic-based materials utilized to construct and maintain roadways and the myriad of external inputs of plastics to roadway networks that contribute to 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 the comparability of results across studies. In addition, quantitative understanding of the types and relative contributions of MP emissions generated by different roadway-related sources is limited, including degraded erosion control netting and emerging materials such as recycled plastic-modified asphalt pavements whose contributions remain less studied. Addressing these gaps, therefore, requires an integrated laboratory and field-based approach capable of reliably identifying and quantifying MPs across diverse roadway environments, providing the foundation for a comprehensive understanding of roadway-derived MPs and informing strategies to mitigate their environmental impacts.

PURPOSE AND SCOPE

The purpose of this research is to advance and apply analytical methods for the identification and quantification of MPs in roadway environments, building on prior investigations of MPs generated by recycled plastic-modified asphalt pavements. Throughout this study, previously developed methodologies were refined, validated, and applied to more complex roadway environments.

The scope of the research encompasses both laboratory and field contexts, including controlled experiments to explore MP behavior under known conditions and environmental sampling in real roadway settings. The study had four objectives:

1. To develop a methodology for the identification and quantification of MPs generated by roadway environments.
2. To demonstrate the method by identifying and quantifying MPs at one roadway site.
3. To evaluate the method's applicability for future use.

METHODS

Overview

To achieve the objectives of this research, three tasks were performed:

1. A literature review.
2. Method development and validation.
3. Field sampling and data analysis.

Literature review

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, and polymer identification. The search returned a body of literature that 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., from the Virginia Department of Transportation [VDOT] material specifications, VDOT annual average daily traffic dataset, the American Association of State Highway and Transportation Officials, ASTM International, and National Cooperative Highway Research Program syntheses) were included to capture engineering specifications, regulatory frameworks and operational practices not fully represented in journal publications.

Method Development and Validation

To identify a suitable MP analysis technique, thermogravimetric analysis-Fourier transform infrared (TGA-FTIR) spectroscopy was applied to evaluate its effectiveness in identifying and characterizing MPs in complex roadway environments. Given that internationally recognized ASTM standards for MP sample preparation (D8333-20) and analysis (D8401-24) are still emerging but are not yet universally adopted or fully optimized for all environmental matrices (ASTM International, 2020, 2024), this work incorporated targeted method development to refine extraction, separation, and analytical procedures for the specific conditions of this study. Method development was conducted through controlled laboratory spiking experiments. Clean road sediment was used as a representative matrix, and polypropylene (PP; < 5 mm), one of the most detected polymers in roadway environments, was used as the model MP. PP was spiked into sediment at known masses (0.01–0.2 g), reflecting its widespread use in roadway materials such as recycled plastic-modified asphalt pavements and erosion control products. Prior to spiking, the clean road sediment was analyzed using the methods outlined in subsequent sections of this report to verify that no MPs were present. All materials were sourced from ongoing projects at the Virginia Transportation Research Council (VTRC).

Chemical Digestion

Organic matter digestion was performed using 30% hydrogen peroxide, following established protocols (e.g., Lee et al., 2024; Masura et al., 2015). Road sediment samples were sieved through a 5-mm mesh to remove coarse debris and isolate the fine fraction most likely to contain MPs and then oven dried at 50°C to determine initial dry mass. PP was spiked into sediment at known masses (0.01–0.2 g). Hydrogen peroxide was then gradually introduced to control the exothermic reaction and prevent sample loss, followed by heating at approximately 70°C for 4 to 6 hours to promote oxidation of organic material while preserving polymer integrity. Digestion was considered complete once visible effervescence ceased and no further reaction was observed. After digestion, samples were oven dried and reweighed to quantify organic matter removal and prepare for density separation.

Density Separation

Density separation methods were systematically compared with optimized MP recovery. Figure 1 shows the three approaches evaluated.

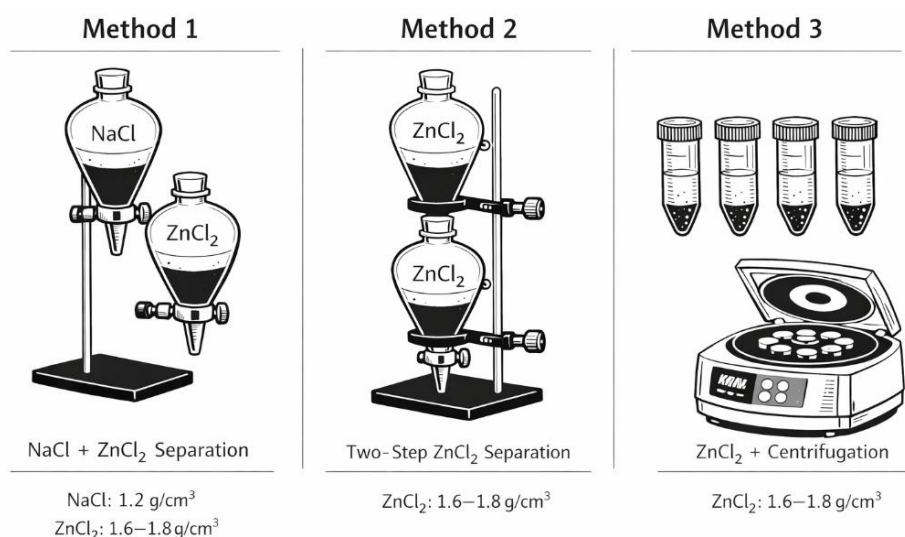


Figure 1. Schematic Representation of Three Density Separation Methods

For each method, approximately 50 g of dried PP-spiked sediment was processed using separatory funnels or centrifuge tubes. Samples were mixed thoroughly and allowed to settle or centrifuged at 4,700 rpm for 1 hour, depending on the method. The supernatant containing MPs was vacuum filtered onto pre-weighed polycarbonate track-etched filter membrane (0.8 µm pore size), followed by oven drying between 60 and 70°C and weighing. In the first method, a saturated sodium chloride (NaCl) solution was used to isolate low-density MPs, followed by separation in a saturated zinc chloride (ZnCl₂) solution to recover higher-density particles. Sonication was applied where necessary to detach particles from the filter membrane. Recovery efficiency, defined as the percentage of spiked reference material identified in a sample post density separation, was used as a comparative measure to evaluate the effectiveness of the separation methods, with lower values indicating MPs were not fully recovered and recovery efficiencies above 100% indicating materials other than MPs were recovered.

Chemical Analysis

Following optimization of pretreatment procedures, chemical analysis was conducted using TGA-FTIR spectroscopy to confirm and characterize the presence of MPs. TGA was performed using a TA Waters Discovery TGA 5500, with a resolution of 0.008 μg and operated with TRIOS software. Samples were heated under a nitrogen atmosphere using a programmed temperature ramp of 15°C per minute up to 800°C, with a purge rate of 15 mL/min. A transfer line, heated to 300°C, was used to transfer gases that the sample generated during TGA into the FTIR spectroscopy. Prior to each run, the system was purged with nitrogen at 40 mL/min for 3 minutes to minimize atmospheric interference, and at the end of each run, the system was held at the maximum temperature and purged again to remove residual evolved gases. This controlled thermal pyrolytic decomposition enabled quantification and partial identification of polymers based on characteristic degradation temperature ranges.

FTIR spectroscopy was conducted of the evolved gases generated during the TGA run using a Thermo Scientific Nicolet™ iS™50 spectrometer to complement TGA measurements and verify the partial TGA identification. Spectra were collected during the mid-infrared range (4000–400 cm^{-1}) at a spectral resolution of 4 cm^{-1} , with 32 scans averaged per scan interval to improve signal-to-noise ratio. In addition, 64 background spectra consisting only of nitrogen purge gas were collected prior to each sample run. These measurements provided information on functional groups and characteristic absorption bands, supporting polymer identification and validation of TGA results. Standardized thermal degradation profiles and spectral libraries were used to ensure consistent identification of recovered MP polymers.

Field Sampling and Data Analysis

Field sampling was conducted at a single rural roadway site in Palmyra, Virginia, with two primary sampling locations: the drainage outfall and the ditch (Figure 2). Although urban areas are often associated with elevated MP concentrations because of higher population densities and traffic volumes, roadway-related MP sources are not limited to urban environments. This rural site was selected because it contained documented erosion control netting, a plastic-based infrastructure material that was a potential source of MPs through ultraviolet-induced degradation and subsequent transport to adjacent sediment and stormwater runoff. Erosion control netting (type 2) was installed along the ditch line depicted in Figure 2 in 2017 following the completion of the roundabout construction. By focusing on a site with a known plastic infrastructure component, this study sought to evaluate whether roadway-associated MP generation can occur even in lower-traffic rural environments. The site was also approximately 23 miles from the research team, enabling repeated field sampling and efficient site access throughout the study period.

The site's traffic characteristics included an annual average daily traffic volume of 8,000 vehicles and an annual average daily truck traffic percentage of 10%, representative of moderate rural roadway conditions (VDOT, 2024).

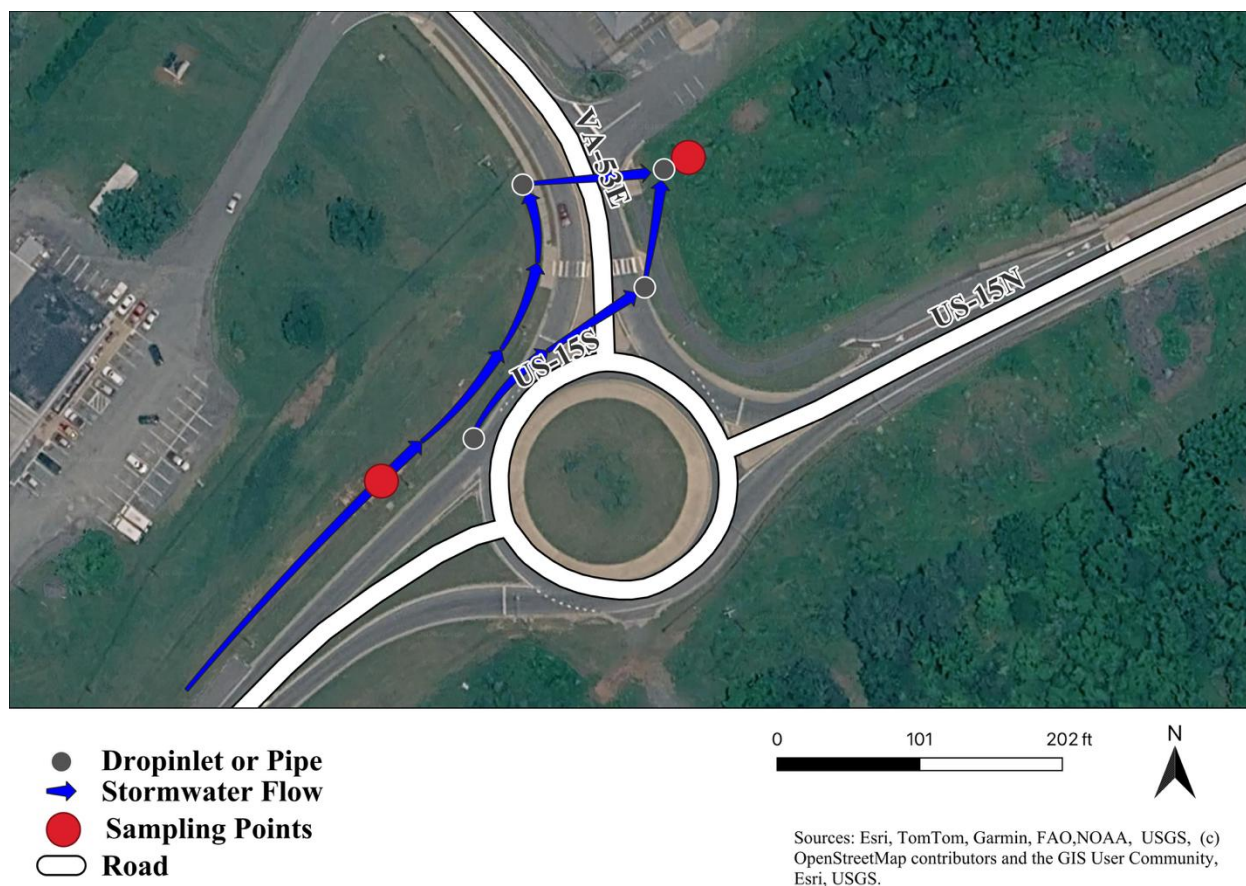


Figure 2. Field Sampling Site in Palmyra, Virginia. Red circles denote locations where stormwater and sediment samples were collected.

Sampling Design

Stormwater samples were collected as grab samples during discrete rainfall events between August 2025 and January 2026, resulting in seven samples collected across the two primary sampling locations over time. This temporal, event-based approach was used to capture runoff conditions associated with episodic MP mobilization rather than continuous loading. Grab sampling was selected for stormwater collection because of time and logistical constraints associated with field deployment, while still enabling rapid collection immediately following rainfall events and capturing peak runoff conditions relevant to MP transport. Stormwater samples were collected and stored in 5-gallon glass jars and retrieved between 24 and 72 hours after collection.

Sediment samples were collected at the same two primary sampling locations (outfall and ditch), with five sampling events carried out between August 2025 and January 2026. At each event, sediment was collected in triplicate to account for spatial heterogeneity within depositional zones and to improve representativeness of the solid-phase MP fraction, resulting in 18 sediment samples. Stainless steel tools and precleaned glass containers were used for collection.

Sample Preparation and Microplastic Extraction

All sample preparation and MP extraction were performed in the Water Quality Laboratory in the University of Virginia's Civil and Environmental Engineering Department. For oxidative digestion, samples were treated with 30% hydrogen peroxide to remove organic matter. For density separation, MPs were isolated using ZnCl₂ combined with centrifugation, identified during laboratory method validation as the most effective approach for sediment and water samples.

Subsampling for Microplastic Analysis

Because of variability in the mass recovered from each extraction, field samples were subdivided into multiple analytical subsamples prior to TGA-FTIR evaluation. This subsampling approach was necessary to meet TGA sample size requirements, which typically involve milligram-scale quantities (< 50 mg per run). The number of subsamples varied depending on the total mass recovered following density separation, ranging from one to seven subsamples per field sample. Samples yielding higher recovered masses were analyzed using multiple subsamples to improve representativeness and capture within-sample variability, whereas samples with less recovered mass were analyzed using fewer subsamples. Each subsample was treated as an independent analytical replicate for TGA-FTIR evaluation.

Microplastic Analysis

MP analysis was carried out at the VTRC Environmental Laboratory. All extracted MPs were analyzed using TGA-FTIR spectroscopy to identify polymer types and confirm the presence of MPs. The same instrument parameters described in the Method Development and Validation section of this report were also utilized for all analyses.

RESULTS AND DISCUSSION

Literature Review: Methods for Microplastics Analysis

This report's Appendix summarizes research efforts conducted to date related to the identification and evaluation of MPs within the roadway sector. Particular emphasis was on runoff and sediment, with potential contributors to MP pollution being the transportation infrastructure (e.g., road markings or erosion control netting) and vehicles using the transportation infrastructure, where pollutants arise from tire wear and brake wear. Accordingly, research efforts have developed diverse methodologies for analyzing MPs in various environmental matrices. Cowger et al. (2020) asserted that this analysis has resulted in a broad spectrum of techniques that has led to inconsistencies that complicate cross-study comparisons and large-scale synthesis of findings.

Several formalized methods recently developed directly address longstanding inconsistencies in sampling, preparation, and polymer identification. In particular, the complementary ASTM standards D8333-20 and D8401-24 together outline a structured

workflow for preparing and analyzing MPs. ASTM D8333-20 provides a standardized digestion and cleanup procedure for samples with high, medium, or low suspended solids, enabling the removal of interfering organic matter and thereby rendering a sample suitable for particle and fiber characterization and identification using spectroscopic or pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) techniques. Building on this process, ASTM D8401-24 establishes a validated Py-GC-MS method that standardizes the identification and simultaneous quantification of organic polymer particles and fibers (ASTM International, 2020, 2024).

Together, these standards formalize the fundamental sequence illustrated in Figure 3. 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.

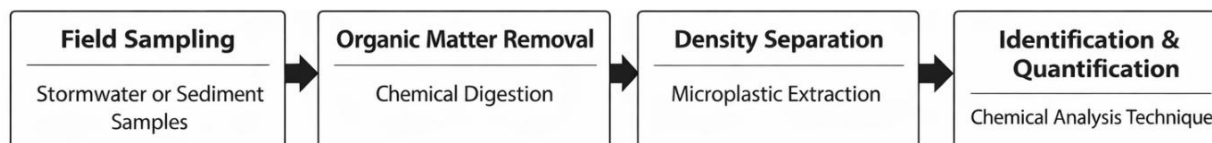


Figure 3. Microplastic Analysis Process Flowchart (adapted from Halle et al., 2020)

Field Sampling

Analysis of MPs in roadway environments begins with collecting 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) (Prata et al., 2019).

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, which improves sample representativeness and minimizes labor and human error (Geosyntec Consultants and Wright Water Engineers, Inc., 2009). In a study by Järnskog et al. (2020), 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 subsamples when flow rates exceeded 5 L/s. Because of fluctuating flow conditions, the autosamplers were later adjusted to collect samples when water levels in the 47-inch diameter pipe rose above 3 inches. This threshold was selected to exclude minor rainfall events less than 0.12 inch and to ensure adequate sample volumes were collected during significant storm events; a tipping bucket rain gauge with 0.0079-inch tipping volume was used to monitor rainfall. Several other studies have also used automated, composite flow-weighted sampling in their MP research (Sanchez Garcia et al., 2025; Smyth et al., 2021).

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 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 (Mansa and Zou, 2021). When using instruments such as FTIR spectroscopy, organic residues can mask or overlap polymer-specific absorption bands, making it harder to correctly identify the polymer type (Xu et al., 2019). When using techniques like Py-GC-MS, some constituents of organic matter may release the same or similar pyrolysis products as the targeted polymers, leading to potential MP overestimation (Bouزيد et al., 2022). 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 (Rani et al., 2023). 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 (Emam and Jung, 2025; Huang et al., 2025; Karimi Estahbanati et al., 2023). To enhance digestion efficiency, these agents are applied in varying concentrations and at different temperatures (Table 1).

Table 1. Characteristics of Common Chemical Digestion Agents in the Removal of Organic Matter

Digestion Agent	Concentration	Temperature	Digestion Time	Citations
Hydrogen Peroxide (H ₂ O ₂)	30%	< 75°C	Variable (until no organic matter is visible)	Huang et al., 2025; Masura et al., 2015
Fenton's Reagent (H ₂ O ₂ + Fe ²⁺)	30% H ₂ O ₂ + 0.05M FeSO ₄	Room temperature to 50°C	24 hours	Löder et al., 2017; Tan et al., 2022
Potassium Hydroxide	10%	45°C	24 hours	Tan et al., 2022
Potassium Hydroxide	1–10%	Room temperature to 60°C	24 hours	Huang et al., 2025; Tan et al., 2022
Nitric Acid (HNO ₃)	65%	Room temperature	24 hours	Claessens et al., 2013; Tan et al., 2022
Enzymatic Digestion	Proteinase (2000U/L), Lipase (2500U/L), Cellulase (200U/L)	Proteinase 50°C, Lipase 40°C, Cellulase 50°C	24 hours per enzyme	Löder et al., 2017; Tan et al., 2022
Sodium Hydroxide (NaOH)	10M	45°C–60°C	24–48 hours	Rani et al., 2023; Tan et al., 2022
Mixed Acid, e.g., Nitric Acid: Perchloric Acid (HNO ₃ :HClO ₄)	Variable	Room temperature	24 hours	Tan et al., 2022

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. Because the density of plastic (~ 0.8–1.6 g/cm⁻³) is much less than that of sediment (~ 2.7

g/cm⁻³), this difference can be used to segregate MPs from sediment. Solutions with a density greater than 1.4 g/cm⁻³ are commonly used to segregate MPs from sediment (Tirkey and Upadhyay, 2021). The density separation process involves mixing the collected sample with a chosen density solution, allowing time for separation and then collecting floating plastics. 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 NaCl, sodium bromide (NaBr), sodium iodide (NaI), calcium chloride (CaCl₂), and ZnCl₂, 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, PP, and polystyrene, whereas denser solutions are needed to recover higher-density polymers such as polyethylene terephthalate, polyvinyl chloride, or polytetrafluoroethylene (Frias et al., 2018). 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 (Liebezeit and Dubaish, 2012). Therefore, the selection of a density separation solution must be carefully matched to the target polymer to avoid material alteration. In addition, the organic matter content in samples influences the effectiveness of density separation. 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 because it can be adjusted to achieve high recovery rates with simple handling (Liu et al., 2019; Schütze et al., 2022). NaBr has high MP recovery, primarily due to 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 2 compares commonly used density separation salt solutions in MPs research.

Table 2. Commonly Used Density Separation Salt Solutions for MP Research

Separation Solution and Typical Concentration	Polymers Recovered	Typical Recovery Rate	Citations
NaCl > 99%	PE and PP (mainly low-density polymers)	60–80%	Claessens et al., 2013; Frias et al., 2018; Schütze et al., 2022
CaCl ₂ ≥ 94%	PE, PP, and PS (partially PET, limited PVC)	70–90%	Duong et al., 2022; Gran et al., 2025; Liu et al., 2019
NaBr 99%	PE, PP, PS, and high-density polymers: PET, PVC, PTFE	85–95%	Frias et al., 2018; Schütze et al., 2022
ZnCl ₂ 98%	Almost all common MPs (PE, PP, PS, PET, PVC, etc.)	80–98%	Crutchett and Bornt, 2024; Duong et al., 2022; Imhof et al., 2012; Ponti et al., 2025
NaI 99%	Most common MPs, including PVC and PET	> 95%	Claessens et al., 2013; Katsumi et al., 2022; Nava and Leoni, 2021; Quinn et al., 2017

MP = microplastic; PE = polyethylene; PET = polyethylene terephthalate; PP = polypropylene; PS = polystyrene; PTFE = polytetrafluoroethylene; PVC = polyvinyl chloride.

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 multiple separation cycles, combining different density solutions and

replacing manual stirring with other techniques such as aeration, ultrasonication, and centrifugation (Mohamed Nor and Obbard, 2014; Pfohl et al., 2024).

Oil-based separation methods have also been explored because of 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. (2012) tested pine oil combined with a froth conditioner to facilitate the release of MPs from sediment. This approach yielded relatively low recovery rates (55%), especially for high-density MPs. In contrast, when Lechthaler et al. (2020) experimented with canola oil, it demonstrated higher efficiency, achieving a recovery rate of more than 90%, with a minimal retention of organic matter. A different study by Karlsson et al. (2017) added a drop of olive oil to salt-saturated solutions. This method improved MP recovery rate from 64 to 82% (Karlsson et al., 2017). Although oil-based methods may require an additional detergent cleaning step and have some limitations, they can be effectively combined with saturated salt solutions to improve overall MP recovery.

Identification and Quantification

Identification and quantification of MPs is the succeeding step after sampling, chemical digestion, and density separation procedures. This step confirms that the separated particles are 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 provides more comprehensive and reliable data. MP analysis methods are generally categorized into four main groups: visual, spectroscopic, thermal, and combined techniques.

Visual Analysis Techniques

Visual methods are used as preliminary screening tools to estimate MP abundance and assess physical characteristics such as size, shape, and color. Early MP studies relied heavily on microscopy-based identification (Dris et al., 2015), but these methods are now mainly used as a first step before chemical confirmation (Sanchez Garcia et al., 2025). Light microscopy is commonly applied for particles larger than approximately 50 μm but is limited by subjectivity and low chemical specificity (Huang et al., 2022). Fluorescence microscopy (e.g., Nile Red staining) improves detection of hydrophobic particles, although false positives require confirmatory chemical analysis (Shamim, 2024; Shruti et al., 2021). Overall, visual methods are useful for screening but are not sufficient for definitive MP identification.

Spectroscopic Techniques

Spectroscopic methods identify MPs based on molecular vibrational signatures that produce polymer-specific spectral fingerprints (Ivleva, 2021). FTIR, including attenuated total reflection-FTIR, identifies polymers through infrared absorption patterns. Attenuated total reflection-FTIR is particularly suitable for irregular or larger particles ($> 300 \mu\text{m}$), in which samples are directly pressed against a crystal (e.g., diamond or ZnSe) for surface analysis (Liu et al., 2019; Othman et al., 2023). FTIR-based methods are effective for particles more than or

equal to 20 μm and supported by spectral libraries for polymer identification (Xu et al., 2019). Raman spectroscopy is another commonly used spectroscopic technique that provides higher spatial resolution ($\sim 1 \mu\text{m}$) but can be affected by fluorescence interference and weathered plastics (Yang et al., 2023). These techniques are primarily used for polymer identification but are less effective for mass-based quantification.

Thermal Techniques

Thermal analysis evaluates polymer behavior under controlled heating conditions. TGA measures changes in sample mass as a function of temperature and provides indirect information on polymer composition and thermal stability (Majewsky et al., 2016). However, standalone thermal methods do not provide direct polymer identification or particle morphology.

Combined and Advanced Analytical Techniques

Combined analytical techniques integrate multiple analytical principles to improve the reliability and robustness of MP identification and characterization. Within broader literature, commonly used methods include μ -FTIR imaging, TGA-FTIR, Py-GC-MS, and thermal extraction desorption-GC-MS, each offering different strengths in polymer detection and quantification. Two promising methods (Table 3) include TGA-FTIR and Py-GC-MS:

- TGA-FTIR simultaneously determines the thermal decomposition behavior of a sample (TGA) and the chemical composition of the evolved gases (FTIR) (Mansa and Zou, 2021). 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 method allows researchers to not only identify the types of polymers present but also detect associated additives and understand their thermal decomposition patterns (Prezgot et al., 2025).
- Py-GC-MS is widely recognized for its ability to provide detailed polymer identification and mass-based quantification of MPs (Prata et al., 2019). In Py-GC-MS, MPs are thermally decomposed under inert conditions at temperatures ranging from 500°C to 800°C (Nandikes et al., 2024). 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 column and subsequently analyzed by a mass spectrometer, which identifies the decomposition products by ionizing individual molecules (Prata et al., 2019). 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 degradation by-products, providing essential data for accurate environmental and human health risk assessments (Ivleva, 2021).

Table 3. Promising Analytical Techniques

Method	Advantages	Disadvantages	Detection Limits	Citations
TGA-FTIR	- Provides both degradation profile and gas composition. - Commonly accessible. - Rapid analysis.	- Identification is limited to polymers with unique absorption bands. - Preconcentration of samples.	Does not provide particle size	Mansa and Zou, 2021
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 by-products.	0.06–0.0002 µg	Nandikes et al., 2024; Prata et al., 2019; Zhou et al., 2025

MPs = microplastics; Py-GC-MS = pyrolysis-gas chromatography-mass spectrometry; TGA-FTIR = thermogravimetric analysis-Fourier transform infrared spectroscopy.

Key Insights

The field of MP analysis has seen some standardization; examples are ASTM D8333-20 for sample preparation and D8401-24 for validated Py-GC-MS polymer identification and quantification (ASTM International, 2020, 2024). Although these standards can improve consistency across laboratories, they have not been widely adopted, and they further represent only a portion of the workflow given in Figure 3. Not surprisingly, broader literature exposes persistent limitations that affect reproducibility, comparability, and accurate quantification. In short, no universally validated method has been adopted across the field that is a reproducible approach. This lack of standardization affects the four major elements of Figure 3.

- *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*, although essential for removing organic matter, relies on diverse reagents and temperatures, risks altering polymer integrity or incomplete removal of organics, leading to interference with subsequent chemical analysis.
- *Density separation methods* also show contradictions. For example, although NaCl is widely used for its low cost, its recovery efficiency is limited for high-density polymers, whereas denser solutions like ZnCl₂ or NaI offer higher recoveries 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, or nanoplastic particles; and thermal and combined techniques provide chemical composition and additive profiling but ignore particle morphology and require costly, complex instrumentation.

Collectively, these methodological inconsistencies reveal a field still constrained by non-uniform approaches. As a result, reproducible and comparable MP data across environmental studies still depend on the broader implementation of these standardized methods.

In its quest to develop a reproducible method, the research team sought to strike a balance between adopting promising methods outright to reduce study time and costs and investigating two or more promising methods to ascertain the best approach. Of the four elements in Figure 3, the area of greatest uncertainty was density separation, thus an experiment to this end was derived. For two elements (field sampling strategies and chemical digestion), expediency drove the research team's decision. Although flow-weighted approaches are preferable in theory, grab-bag sampling was used herein because of the availability of the equipment. For chemical digestion, a 30% hydrogen peroxide solution was used because this method was shown to have promise. For one element from Figure 3 (identification and quantification), the research team utilized TGA-FTIR because of equipment availability and prior experience. However, based on the characteristics in Table 3, further investigation of Py-GC-MS could be valuable.

Method Development and Validation

Density Separation Results

Three density separation approaches were systematically evaluated (Table 4), with each method performed in triplicate ($n = 3$). Recovery efficiencies were calculated for each replicate, and results are reported as mean values. Methods 1 and 2 yielded apparent recoveries exceeding 100% in nearly all cases because of the extraction of non-target particles or residual sediment components. The sequential separation steps in methods 1 and 2 appear to increase the likelihood of including extraneous material, thereby producing variable and unreliable recovery efficiencies. These results highlight the limitations of these methods for accurate MP quantification in environmental samples. In contrast, the superior performance of Method 3, with a mean recovery percentage of 99.87, could be attributed to improved density separation and reduced particle loss provided by the centrifugation and limited need for sample transfers, particularly for smaller MP fractions. Based on these findings, Method 3 was selected as the optimized density separation technique for subsequent field-based analyses.

Table 4. Recovery Rate Efficiencies of Different Density Separation Methods Performed in Triplicate

Method	Solution	Initial Mass of PP Added (mg)	Final Mass of Recovered Sample (mg)	PP Recovery Efficiency (%)	Mean Recovery (%)
1	NaCl + ZnCl ₂	32.7	336.1	1,027.8	536.6
		19.5	13.0	66.7	
		20.2	104.0	514.9	
2	2 x ZnCl ₂	34.8	104.8	301.2	252.9
		198.1	209.0	105.5	
		10.4	36.6	351.9	
3	ZnCl ₂ + centrifugation	142.2	141.9	99.8	99.9
		83.2	83.1	99.9	
		201.9	201.8	99.9	

PP = polypropylene.

Thermogravimetric Analysis Results

The effectiveness of Method 3 MP density separation was further verified using TGA-FTIR evaluation. The same three independent PP-spiked sediment samples used in Method 3 density separation experiments were analyzed, and the thermal datasets were used for statistical evaluation. TGA confirmed that the recovered material consisted predominantly of PP, providing strong evidence that Method 3 (ZnCl_2 density separation combined with centrifugation) is effective for isolating MPs from roadway samples. Figure 4 shows representative TGA mass loss profiles, illustrating the characteristic thermal degradation behavior of PP.

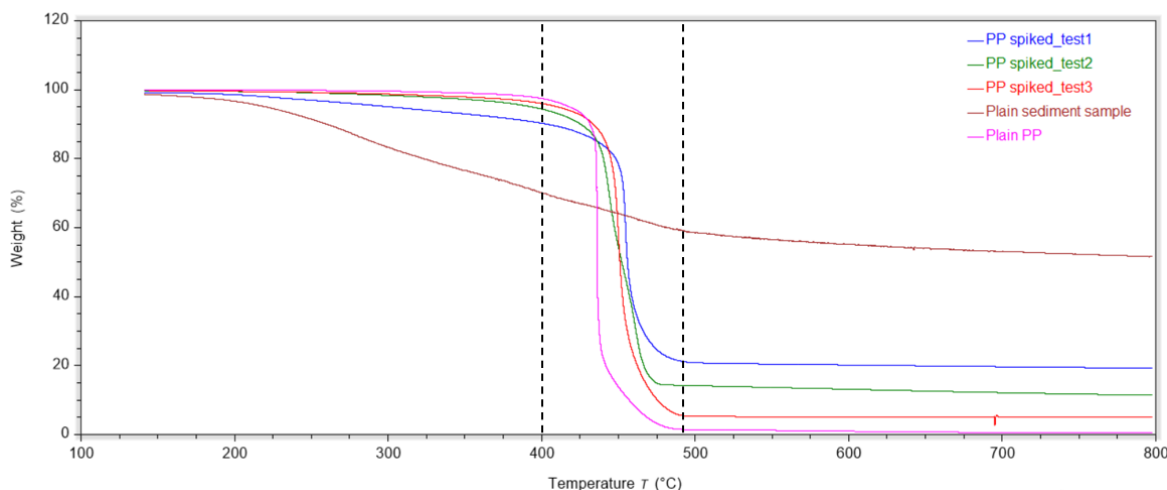


Figure 4. Representative Thermogravimetric Analysis Mass Loss Profiles of PP-Spiked Sediment Samples. The first four curves were obtained using Method 3 density separation. The last thermogram, or plain PP, illustrates the typical thermal degradation behavior of PP. PP = polypropylene.

The three spiked sediment samples exhibited degradation within a very similar temperature range of 444–455°C, consistent with the characteristic thermal degradation range of PP found in the literature (400–480°C) (Sorolla-Rosario et al., 2023; Yu et al., 2019). Notably, the degradation temperatures of the spiked sediment samples closely overlapped with those of the plain PP reference material, further confirming the successful recovery and identification of PP following density separation, as depicted in Figure 4 and Table 5. By comparison, the plain sediment sample, containing no added PP, showed no degradation within this characteristic temperature range. Instead, it exhibited a minor thermal event at approximately 276°C, which is not consistent with PP and is likely attributable to the decomposition of other non-polymeric constituents within the sediment matrix. The amount of material pyrolyzed at this temperature was too low (3.7 mg) to reliably characterize its composition via FTIR.

The relatively low residual masses observed following TGA (Table 5) indicate that only limited non-polymeric or inorganic material remained associated with the recovered PP following density separation, suggesting that Method 3 effectively isolated PP from the sediment sample and produced comparatively clean recovered fractions for thermal analysis. Moreover, the observed slight differences in both mass loss temperature and residual mass likely reflect variations in the distribution of spiked PP within the sediment, inherent sample heterogeneity, or minor experimental variability during handling and weighing, which could have subtly

influenced the onset of thermal degradation and the residual mass. Because PP was successfully identified using TGA based on its known degradation temperature range of 444–455°C, this approach demonstrates that the analytical technique can be reliably applied to identify common roadway MP sources at the field site. This approach is particularly effective when characteristic degradation temperatures are used as the primary indicator, while acknowledging that residual mass may vary because of sample and experimental factors.

Table 5. Thermogravimetric Analysis Results of PP-Spiked Sediment and Control Samples

Sample ID	Sediment Mass (mg)	Spiked PP Mass (mg)	Mass Loss Temperature (°C)	Mass Loss (mg)	% Mass Loss	Residual Mass (mg)	Calculated PP Mass (mg)	Recovery Efficiency
1	3,517.8	83.2	451	27.99	95	1.484	81.82	98%
2	10,094.4	142.2	449	1.037	4.5	1.258	140.64	99%
3	10,203	201.9	443	22.92	94	1.343	200.46	99%
Plain PP	NA	3.91	457	3.85	98	0.06	NA	NA
Plain Sediment	12.14	NA	276	3.72	23	8.40	NA	NA

NA = not applicable; PP = polypropylene.

The calculated polymer mass and corresponding recovery efficiencies further demonstrated the effectiveness of Method 3 density separation (Table 5). The recovered PP values reported represent the amount of PP quantified through TGA following density separation and thermal characterization. Recovery efficiency was calculated by comparing the TGA-quantified PP mass to the known amount of PP initially spiked into each sediment sample, thereby reflecting the overall method performance, including both density separation and analytical identification steps. Recovery efficiencies ranged from 98 to 99%, indicating minimal polymer loss during sample processing and strong agreement between the spiked and TGA-identified PP masses. These findings further support the reliability of the ZnCl₂ and centrifugation density separation method and TGA workflow for the recovery, preliminary identification, and quantification of PP in roadway environmental samples.

Fourier Transform Infrared Spectroscopy Results

FTIR spectra also showed distinct absorption bands corresponding to PP functional groups (Figure 5). These bands include peaks at 2,960 to 2,980 cm⁻¹ associated with methylene and methyl (CH₃), 1,455 to 1,470 associated with alkanes, and 1,375 to 1,470 associated with CH₃ and highly characteristic of the pyrolysis of PP (Lloyd and Habbouche, 2026).

Overall, an effective workflow comprising hydrogen peroxide digestion, ZnCl₂ density separation with centrifugation (Method 3), and TGA-FTIR analysis was developed and validated for the isolation and identification of roadway-derived MPs. The results suggest that this integrated pretreatment and analytical approach is capable of recovering and confirming MPs from complex roadway matrices. Chemical analysis verified that the recovered particles were PP, indicating that the workflow preserved polymer identity throughout processing.

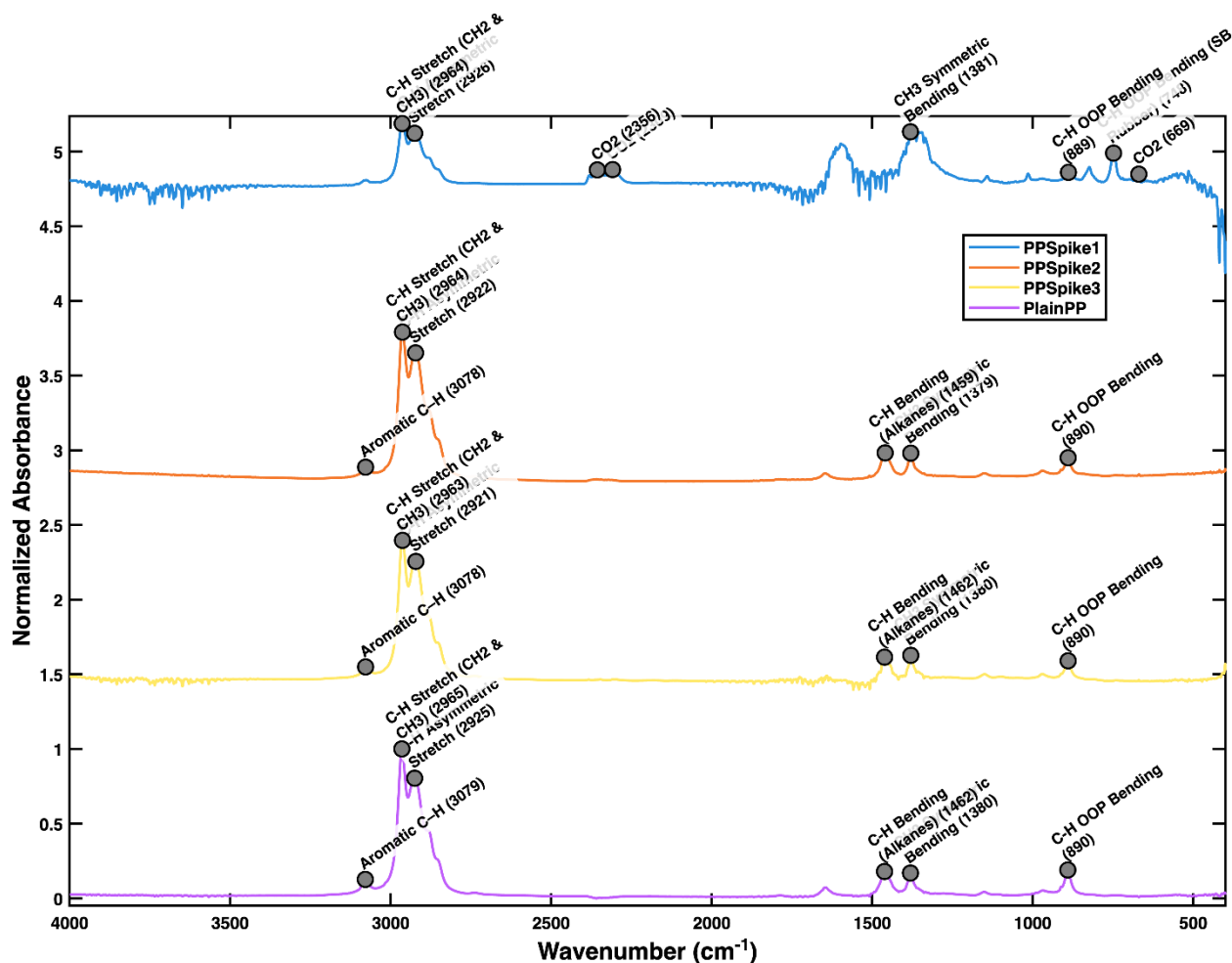


Figure 5. Normalized FTIR Spectra of Recovered PP Using Method 3 for Density Separation, Showing Characteristic Functional Groups Indicative of PP (aromatic C-H bend between 675 and 660 cm^{-1} , CH_3 symmetric bending vibration between 1,375 and 1,385 cm^{-1} , C-H stretch between 2,960 and 2,870 cm^{-1} , and aromatic C-H stretch between 3,100 and 3,075 cm^{-1}) (Lloyd and Habbouche, 2026; Socrates, 2002). FTIR spectra were normalized to the maximum absorbance and baseline corrected using the following regions: 4,000–3,100 cm^{-1} , 2,700–2,400 cm^{-1} , and 600–400 cm^{-1} . FTIR = Fourier transform infrared; PP = polypropylene.

Representative Field Sampling and Data Analysis

Reference Samples

To support the interpretation of MP analysis results, a set of reference materials representing common roadway-related MP sources was analyzed using TGA-FTIR. The reference materials included tire wear particles, road marking materials (yellow road marking was used for this study), and erosion control netting, all collected directly from the study site. Tire wear particles were obtained by identifying large pieces of tire found on the shoulder, road marking materials were obtained by using a knife to extract a small sample from the yellow road marking line, and erosion control netting was extracted from an adjacent ditch line. These reference materials were analyzed under the same instrumental conditions applied to field-collected samples to ensure methodological consistency and comparability. The resulting data

were used to establish reference thermal and spectral profiles for each material type, which serve as a basis for comparison with environmental samples in subsequent sections.

For TGA, characteristic parameters extracted from the thermograms included onset, midpoint, and endpoint temperatures of mass loss (Table 6).

Table 6. Thermogravimetric Analysis Degradation Temperatures of Reference MP Sources

Reference MP source	Onset (°C)	Midpoint (°C)	Endpoint (°C)
Tire wear	336.71 ± 2.01	403.81 ± 2.25	469.44 ± 2.43
Road markings	371.02 ± 10.05	393.44 ± 3.29	416.21 ± 4.07
Erosion control netting	415.81 ± 26.13	442.39 ± 19.81	469.56 ± 13.73

MP = microplastic.

For FTIR analysis, functional group signatures associated with each reference material type were identified and used to develop a comparative reference library (Table 7). Because several absorption bands overlap among roadway-related polymers and additives, material identification was not based on isolated peaks alone. Instead, interpretation relied on combinations of characteristic absorption bands and overall spectral profiles. Emphasis was placed on diagnostic functional groups that showed greater specificity for individual reference materials, thereby improving differentiation between potential MP sources in field-collected samples.

Table 7. Diagnostic Fourier Transform Infrared Functional Group Assignments for Reference Microplastic Sources

Material	Dominant Polymer/Additive	Diagnostic Functional Groups	Wavelength Number/Regions (cm ⁻¹)	Citations
Tire wear	Styrene-butadiene	• C = C stretching vibration. • CH out of plane vibration.	• 1,640 • 965 • 910	Kang et al., 2000; Socrates, 2002
	Alkanes	C-H stretching and bending vibrations	• 2,750–3,100 • 1,300–1,470	Bai et al., 2023
Road markings	Styrene	Aromatic = C-H Stretching	3,075–3,100	Grand View Research, Inc., 2016; Nel et al., 2021; Socrates 2002
	Acrylics	• C = O. • C = C. • C-O bonds.	• 1,750 • 1,649 • 1,308	
	Polyester	C = O and C-O associated bands	• 1,700–1,800 • 1,000–1,300	
	Urethane	• C = O. • C-O-C. • CO₂. • C-H peaks.	• 1,767 • 1,154 and 1,065 • 2,356 and 2,320 • 2,981 and 2,892	
Erosion control netting	Polypropylene	CH ₃ symmetric bending	1,375–1,385	Kärman et al., 2016; Park and Kim, 2023

The reference thermal and spectral profiles presented in Tables 6 and 7 are used as a comparative framework for the interpretation of field-collected stormwater and road sediment samples in the following results sections. Characteristic absorption peaks identified for tire wear,

road marking material, and erosion control netting, collected directly from the Palmyra field site, represent the key spectral features targeted during interpretation of field sample FTIR spectra. The literature sources summarized in Table 7 informed the functional group assignments associated with these peaks (Figure 6).

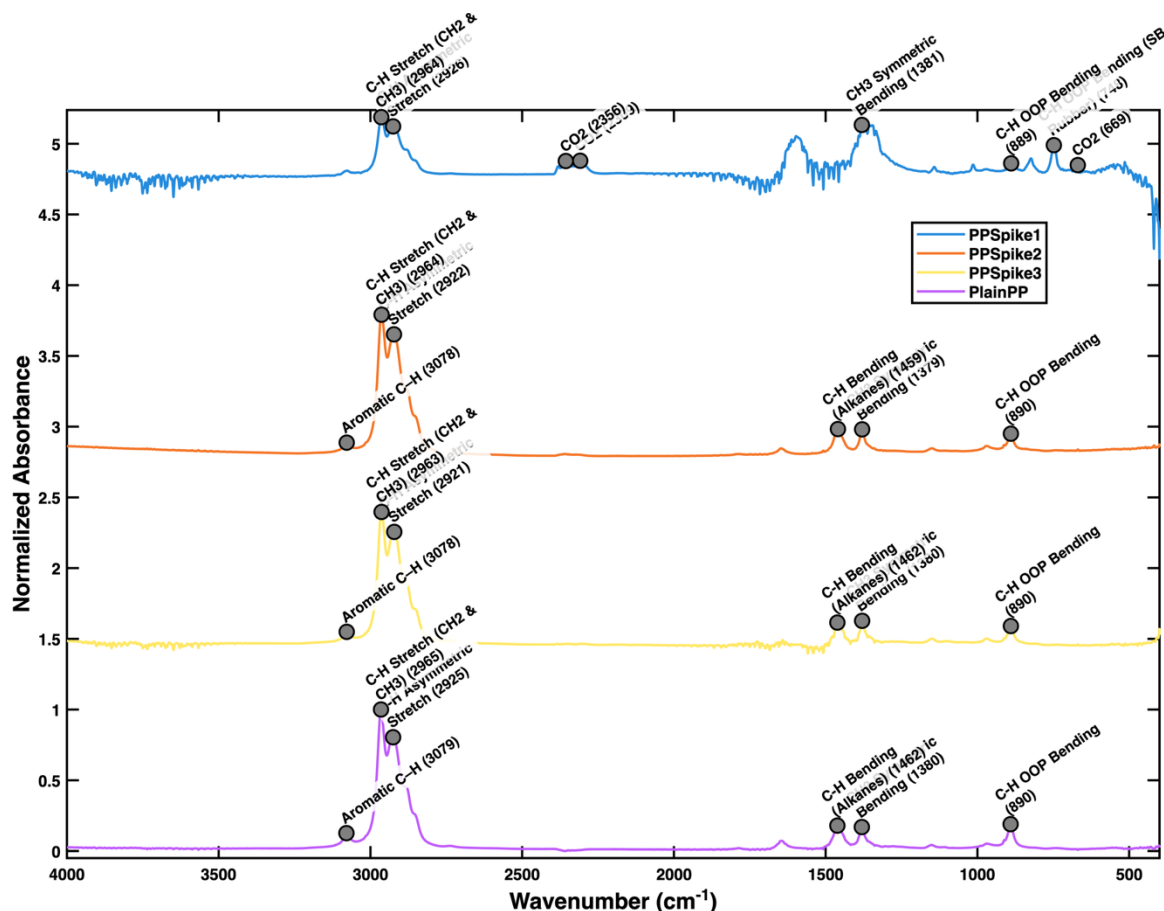


Figure 6. Normalized FTIR Spectra of Reference Material Collected at the Palmyra Field Site. FTIR spectra were normalized to the maximum absorbance and baseline corrected using the following regions: 4,000–3,100 cm^{-1} , 2,700–2,400 cm^{-1} , and 600–400 cm^{-1} . FTIR = Fourier transform infrared; PP = polypropylene.

Field Samples

Table 8 summarizes all field samples analyzed in this study. The dataset comprises 12 environmental samples collected from the Palmyra site, including both stormwater and road sediment. Samples were labeled A through L to maintain consistent tracking throughout thermal and spectroscopic analyses. The reported mean sample mass, shown in the rightmost column of Table 6, represents the average mass of the extracted MP fraction obtained after sample pretreatment (chemical digestion and density separation). This portion is the fraction that was subjected to TGA-FTIR evaluation, and it reflects the chemically analyzed material rather than the original bulk environmental sample. The use of mean values accounts for multiple subsamples analyzed per field sample, providing a representative mass for each sample type.

Table 8. Road Sediment and Stormwater Samples Collected from the Palmyra Site

Sample ID	Number of Replicates	Sample Type	Initial Mean Sample Mass (mg)	Recovered Mean Sample Mass (mg) ^a
A	4	Sediment	32,570	46.00
B	3	Sediment	37,670	11.22
C	1	Stormwater	12,400	12.83
D	1	Stormwater	910	3.13
E	4	Sediment	35,770	4.22
F	3	Sediment	41,970	4.37
G	4	Sediment	34,530	4.44
H	1	Stormwater	4,560	7.98
I	1	Stormwater	110	0.60
J	1	Stormwater	10,240	4.10
K	1	Stormwater	190	0.05
L	1	Stormwater	5,730	5.42

^a This portion was analyzed via thermogravimetric analysis-Fourier transform infrared spectroscopy following sample pretreatment.

Thermogravimetric Analysis Results

TGA of extracted stormwater and road sediment samples from the Palmyra site revealed thermal events that occurred across a broad range of temperatures. Most mass-loss transitions occurred within temperature regions commonly associated with thermal degradation of common roadway-associated MPs and as defined by reference materials (Table 7), although these thermal events were variable among samples.

Figure 7 shows the average and standard deviation of midpoint temperatures of the reference materials collected at each site, depicted respectively as dotted lines and shaded regions. For example, the average midpoint degradation for erosion control netting is 448°C, with a standard deviation of 15°C, thus the range from 433°C to 463°C is shaded blue. The standard deviation for tire rubber and yellow road marking material is considerably smaller at roughly 2°C.

To evaluate potential relationships between field samples and roadway-derived MPs, Figure 7 also shows the mean midpoint degradation temperatures calculated from all available TGA subsamples for each sample. Box plots are shown for each sample, for which the box gives the 25th, 50th, and 75th percentile values, and the highest and lowest values are shown outside the box. For example, considering Sample A with five subsamples, one subsample had a high midpoint of 425°C, one had a low midpoint of 280°C, and the median midpoint was 380°C. The low midpoint of 280°C is shown as a dot because it is an outlier (much larger than the difference between the 25th and 75th percentile values), and in practice, it shows a high degree of variability in the sample. Because none of these midpoint temperatures overlap the blue shading associated with erosion control netting, Sample A does not have MPs sourced from erosion control netting.

The box plots demonstrated substantial variability among the Palmyra site stormwater and road sediment samples, with thermal events distributed from approximately 293 to 442°C. Several sample groups exhibited midpoint temperatures near or overlapping the reference materials associated with tire rubber and road markings (~ 393–404°C), including Samples C, E,

F, G, and H. This result suggests the potential contributions from these roadway-derived reference materials.

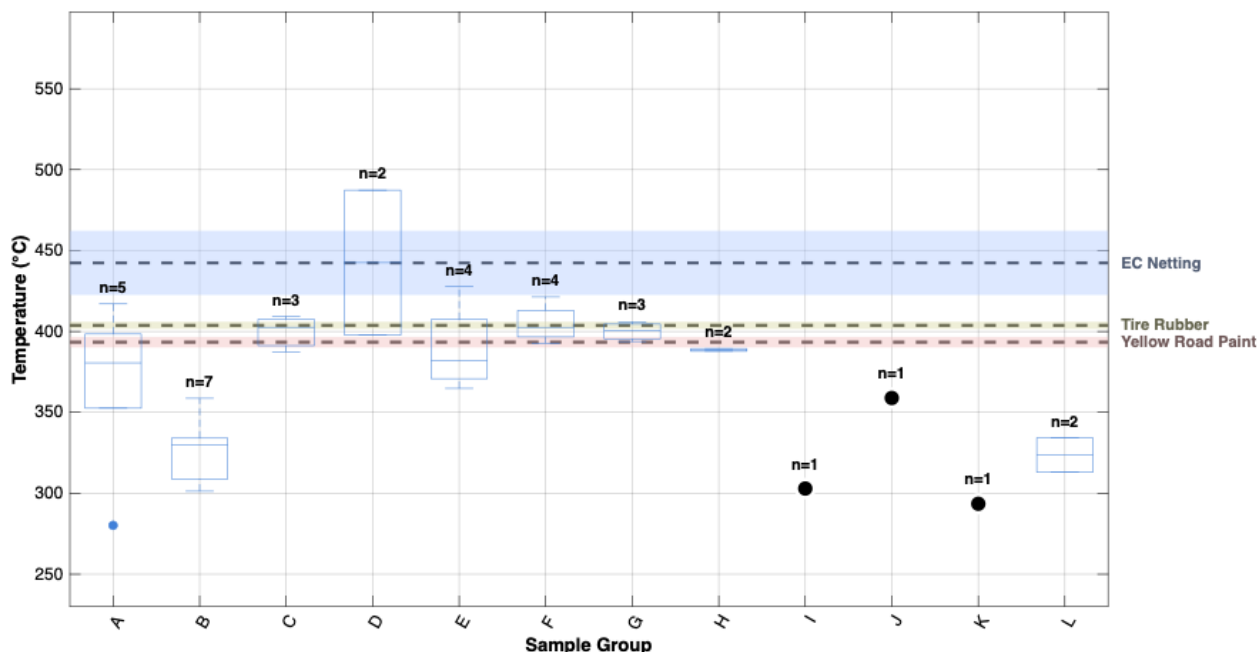


Figure 7. Box Plots Depicting Thermogravimetric Analysis Midpoint Mass Loss Temperatures of Field Samples. Dotted lines reflect the average midpoint temperature of each reference material with the associated shaded regions denoting their standard deviations. Between one and seven subsamples were included per field sample, depending on the recovered mass.

Sample D displayed the greatest variability (398–487°C) and the highest midpoint temperatures, with values extending into the range associated with erosion control netting. In contrast, Samples B, I, J, K, and L exhibited lower midpoint temperatures, generally below the reference material ranges, likely suggesting thermal events not clearly associated with the roadway-related reference MPs evaluated in this study. Sample A showed relatively broad variability, with some overlap near the tire rubber and road marking reference regions but also lower-temperature transitions.

Factors that may explain the observed variability and limited thermal resolution of some field samples may include the relatively low concentration of MPs within recovered stormwater and sediment fractions, which may result in polymer-associated thermal degradation events that are insufficiently pronounced to produce distinct or reproducible mass-loss transitions. In addition, samples from roadway environments are inherently heterogeneous, and the milligram-scale subsampling required for TGA may introduce sampling bias, thereby reducing the likelihood of capturing representative MP particles.

Overall, although several field samples exhibited partial overlap with site-specific reference materials, the thermal responses were often variable, highlighting the complexity of interpreting TGA signatures in heterogeneous roadway samples and reinforcing the need for further confirmation. For this reason, the FTIR analysis was performed on all samples and reference materials.

Fourier Transform Infrared Spectroscopy Results

FTIR was used to provide complementary chemical confirmation of polymer identities in all field samples. Spectral interpretation was based on comparison with characteristic absorption bands of site-specific reference materials, with an accepted variability of approximately $\pm 20\text{ cm}^{-1}$ to account for minor shifts in peak position due to environmental degradation, matrix effects, and instrument conditions. Several field samples exhibited spectral features corresponding to more than one reference material, indicating potential co-occurrence of multiple roadway-derived MP sources within individual samples.

Distinct spectral features consistent with yellow road markings were observed across Samples A, C, E, F, G, and H. This assignment was based on the presence of key absorption bands near 1750 , 1460 , 1310 , and 1170 cm^{-1} , corresponding to C = O stretch, C-H bending (alkanes), C-O (polyester), and C-O-C (urethane), respectively, which represent paint-related polymeric binders and additives. Figure 8 presents representative spectra showing this correspondence between a field sample (Sample E) and the yellow road marking reference material.

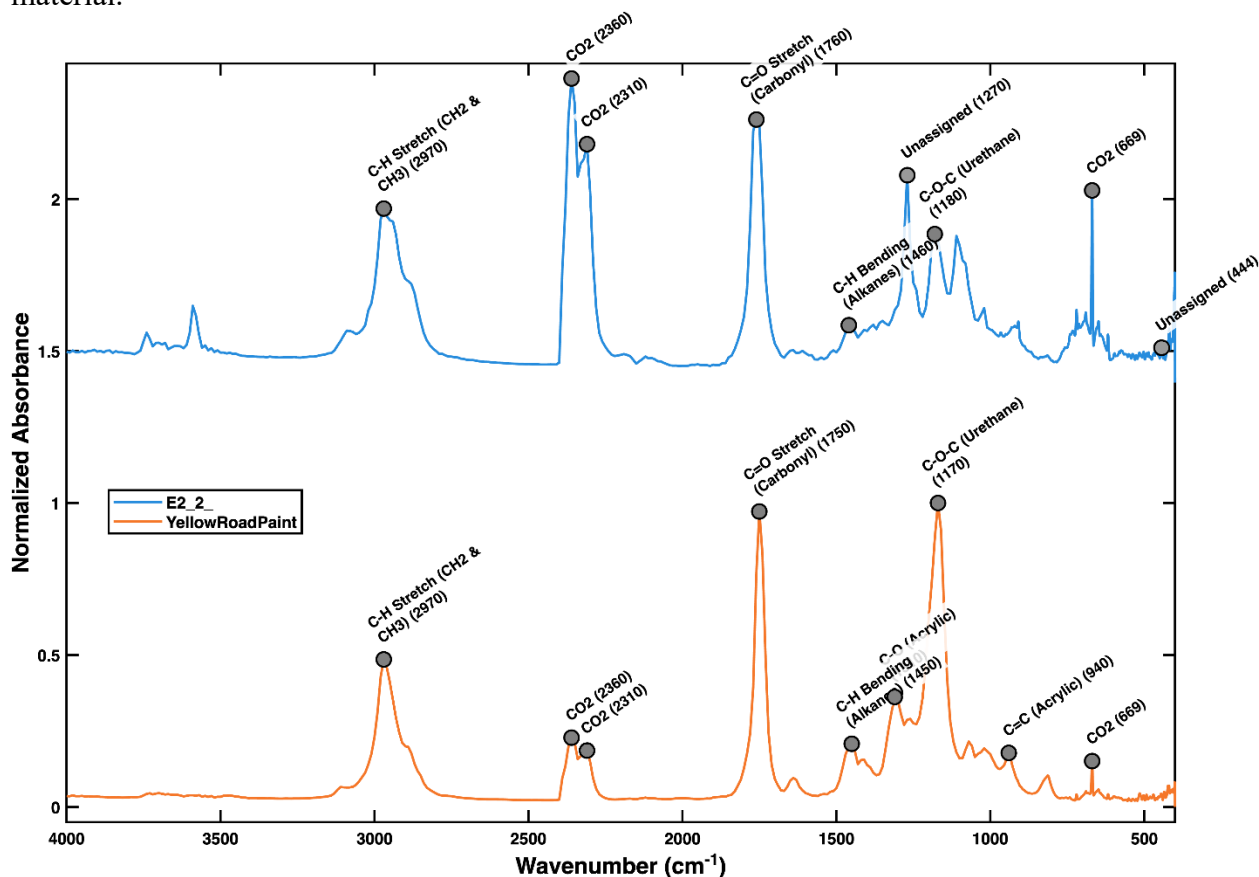


Figure 8. Normalized FTIR Spectra of Sample E. The spectra show characteristic functional groups indicative of acrylic road markings. Peaks corresponding to C = O, C-H, C-O, and C-O-C bonds were observed at 1750 , 1460 , 1310 , and 1170 cm^{-1} , respectively, consistent with acrylic-based materials (Grand View Research, Inc., 2016; Nel et al., 2021; Socrates 2002). FTIR spectra were normalized to the maximum absorbance and baseline corrected using the following regions: $4,000\text{--}3,100\text{ cm}^{-1}$, $2,700\text{--}2,400\text{ cm}^{-1}$, and $600\text{--}400\text{ cm}^{-1}$. FTIR = Fourier transform infrared.

Evidence of tire wear material was also identified in Samples F, D, G, H, and J, primarily through the co-occurrence of absorption bands near 1460, 1380, and 889 cm^{-1} . These peaks correspond to C-H bending (alkanes), CH_3 symmetric bending, and C-H out of plane bending, respectively, commonly associated with tire wear compounds. Figure 9 shows a representative comparison between a field sample and the tire rubber reference spectrum, illustrating strong alignment in the diagnostic peak regions.

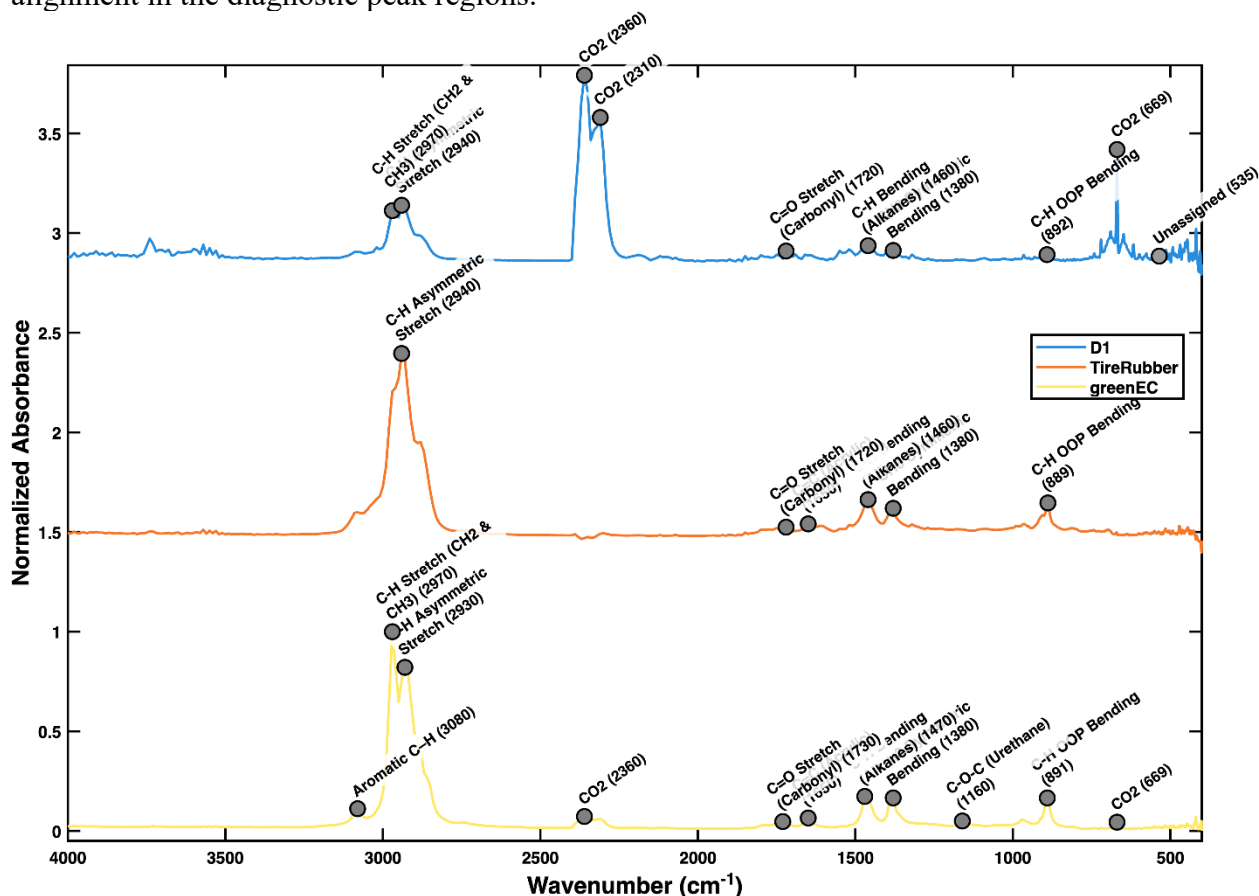


Figure 9. Fourier Transform Infrared Spectra Comparison of Sample D with Reference Spectra for Tire Rubber and EC Netting. Sample D shows overlapping diagnostic absorption bands characteristic of both materials, including peaks near 1,460, 1,380, and 889 cm^{-1} (tire wear) and 1,470 and 1,380 cm^{-1} (EC netting), indicating the co-occurrence of multiple roadway-derived polymeric materials within a single environmental sample. EC = erosion control; OOP = out of plane.

In addition, erosion control netting was suspected to be present in Sample D, based on absorption bands near 1,470 and 1,380 cm^{-1} corresponding to C-H bending (alkenes) and CH_3 symmetric bending, respectively. However, the absorbance intensity of these peaks is admittedly low, indicating that a very small amount of netting was present. The presence of both erosion control netting and tire wear signatures in Sample D suggests a mixed polymer composition within this sample, likely reflecting the heterogeneous nature of roadway-derived particulate inputs.

Overall, FTIR analysis supports the presence of multiple roadway-associated polymeric materials within the Palmyra samples, most notably yellow road markings and tire wear particles, with more limited evidence for erosion control netting. These results indicate that

roadway surfaces and adjacent infrastructure contribute a heterogeneous mixture of polymer types to stormwater and sediment in roadway environments.

Table 9 presents the quantitative estimation of MP concentration within the extracted stormwater and road sediment samples collected from the Palmyra site. Table 9 summarizes the calculated mass-based concentrations derived from the recovered fractions following laboratory processing and analytical identification of polymeric materials. These values provide an estimate of the relative loading of MPs across the different field samples.

Table 9. Summary of TGA-FTIR MP Detection in Field Samples from the Palmyra Site

Sample ID	FTIR Confirmation	TGA-Quantified MP Mass (mg)	Initial Mean Sample Mass (g)	MP Concentration (mg/g)
A	road markings	16.41	32.57	0.50
B	none	*	*	*
C	road markings, tire wear	9.27	12.4	0.75
D	tire wear, erosion control netting	1.34	0.91	1.47
E	road markings	4.85	35.77	0.14
F	road markings, tire wear	45.73	41.97	1.09
G	road markings, tire wear	11.06	34.53	0.32
H	road markings, tire wear	7.99	4.56	1.75
I	none	*	*	*
J	road markings, tire wear	10.65	10.24	1.04
K	none	*	*	*
L	none	*	*	*

MP = microplastic; TGA-FTIR = thermogravimetric analysis-Fourier transform infrared spectroscopy; * = value not attributable to MPs.

Applicability of the Proposed Method to Practice

The TGA-FTIR analysis provided complementary evidence supporting the presence of roadway-derived MPs within stormwater and road sediment samples collected from the Palmyra site. TGA results revealed variable thermal degradation behavior among field samples, with several exhibiting characteristic thermal degradation temperatures overlapping with site-specific reference materials associated with tire wear, road markings, and erosion control netting. However, substantial variability among subsamples highlighted the limitations of relying solely on bulk thermal methods for polymer identification in heterogeneous environmental samples. FTIR analysis provided confirmation and refinement of this preliminary thermal evaluation, identifying characteristic functional groups associated with yellow road markings and tire wear particles in seven of the 12 samples, with additional tentative evidence of erosion control netting in Sample D. Quantitative estimates of MP mass indicated varying levels of MP concentrations across samples, reinforcing the variability of roadway-associated MP occurrence.

Although the combined use of TGA and FTIR provided valuable preliminary insight into roadway-derived MPs, the observed variability and analytical limitations suggest that future studies would benefit from the adoption of other analytical techniques, such as Py-GC-MS. Compared with TGA-based techniques, which rely on degradation temperatures to separate components of a sample, Py-GC-MS utilizes the components' volatility and polarity for separation. This process offers greater sensitivity and polymer-specific chemical characterization, enabling more definitive identification and quantification of complex and

mixed polymer compositions within heterogeneous environmental samples (Nandikes et al., 2024). The incorporation of Py-GC-MS in future roadway MP investigations could therefore provide a more comprehensive understanding of the sources, composition, and environmental distribution of roadway-generated MPs. However, even with advanced instrumentation, challenges associated with environmental heterogeneity are expected to persist, emphasizing the continued importance of improved sample preparation and homogenization procedures to enhance representativeness and reduce analytical uncertainty.

These findings highlight the need for advanced analytical techniques, such as Py-GC-MS, to further differentiate polymer sources and quantify trace-level contributions. At the same time, the results point to the need for targeted future investigations using more representative sampling approaches, including ditch-line coring, to better capture potentially buried, degraded, or spatially variable MP sources. Expanding sampling across additional roadway sites may also provide a clearer understanding of how differing roadway materials, infrastructure characteristics, and environmental conditions influence MP occurrence and composition. As another example, automated sampling, as suggested by Geosyntec Consultants and Wright Water Engineers, Inc. (2009), may help reduce variability in stormwater MP analysis because such sampling provides time or flow-weighted integration during the full duration of storm events.

CONCLUSIONS

- *A sequential three-step method (hydrogen peroxide digestion, zinc chloride density separation with centrifugation, and TGA-FTIR analysis) for identifying roadside MPs was successfully developed.* The results of the first two steps recovered up to 99% of MPs, and the third step confirmed that the recovered materials were indeed MPs during spike recovery testing.
- *In field samples, the sequential three-step method can quantify MPs attributed to some but not all sources because of different materials having overlapping temperature mass loss curves (for TGA) and overlapping infrared spectra (for FTIR).* The field study site identified acrylic-based road markings and tire wear particles as the predominant roadway-derived MP sources with concentrations ranging from 0.135 mg/g to 1.75 mg/g. However, at the same site, erosion control netting was suspected to be present in one sample but could not be individually quantified because of overlapping thermal and infrared characteristics.
- *The three-step method cannot identify MPs in samples containing an unknown mixture of polymer types.* Because of the limitations noted in the previous conclusion (overlapping thermal degradation temperatures and infrared spectra), TGA-FTIR cannot separate discrete components in a sample. For site monitoring, this occurrence is not a limitation if one needs only to quantify total MPs, but it is a limitation if one needs to determine the sources of these MPs.

RECOMMENDATIONS

1. *VDOT should monitor emerging regulatory requirements related to MPs in stormwater runoff and in sediment or debris removed from stormwater infrastructure.* If new regulations require the assessment or management of MPs, VDOT should develop appropriate mitigation and management procedures to comply with those requirements. In such cases, VDOT may also utilize the sample preparation and analysis methods described in this report to measure total MPs in the material.
2. *VDOT should conduct a follow-up study to apply the methodologies described in this report to a rigorous field sampling program across Virginia, including sites where recycled plastic-modified asphalt has been used.* To better determine the sources of MPs detected in field samples, this study should also adapt the sample preparation methods for more advanced analytical techniques, such as pyrolysis gas chromatography-mass spectrometry. The objective of this work should include (1) further verification of these methodologies and (2) collecting baseline data on MPs concentrations in stormwater runoff and soils within VDOT right-of-way and select stormwater best management practices operated by VDOT.

IMPLEMENTATION AND BENEFITS

The researcher and the technical review panel (listed in the Acknowledgments) for the project collaborate to craft a plan to implement the study recommendations and determine the benefits of doing so. This process is to ensure that the implementation plan is developed and approved with the participation and support of those involved with VDOT operations. The implementation plan and the accompanying benefits are provided here.

Implementation

Regarding Recommendation 1, VDOT's Environmental Division will, with support from the appropriate Divisions (likely Maintenance, Materials, and Location and Design), develop appropriate mitigation and management guidance and procedures if regulations are established. If no relevant regulations are established within 3 years, implementation of this recommendation will be considered complete.

Regarding Recommendation 2, VTRC research scientists will initiate a follow-up research study within 3 months of publication of this report. The duration of this study will be limited to 2 years.

Benefits

This study provides methodologies for evaluating MPs in stormwater and roadside soils and presents preliminary evidence of their presence in stormwater and in the sediment and debris that accumulate within stormwater infrastructure. Although no regulations currently exist for this emerging pollutant, increasing attention from regulatory agencies and growing documentation of

its prevalence in environmental samples elsewhere may accelerate the development of future requirements.

Given these factors, this information offers important context for VDOT Environmental, Maintenance, Location and Design, and Materials Division staff. It enables them to (1) proactively evaluate existing maintenance and disposal practices and make any needed adjustments, (2) develop effective strategies to mitigate MPs releases, and (3) identify alternative materials in advance of, or in response to, potential regulatory action. These methodologies also provide a foundation for conducting a rigorous field sampling campaign to further improve the understanding of the fate and transport of MPs in the roadway environment—an area where knowledge remains limited.

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APPENDIX

Literature Review

Sources of Microplastics in Roadway Environments

Roadway environments serve as contributors of microplastic (MP) pollution due to the continuous mechanical abrasion and environmental degradation of materials used in transportation infrastructure and vehicle components. Figure A1 summarizes the primary and emerging sources of MP generation in roadway environments.

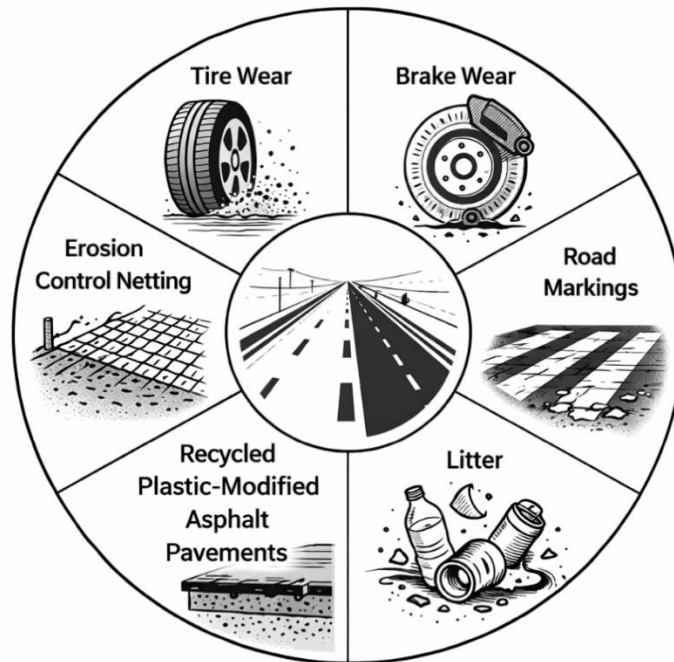


Figure A1. Sources of Roadway Microplastics

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, natural rubber, polyethylene (PE), polyethylene terephthalate, polypropylene, and a range of chemicals (Halsband et al., 2024; Knight et al., 2020; Roychand and Pramanik, 2020; Yang et al., 2023). Through several computational estimates, the wear of tires on roads has been identified as the largest source of MP pollution in the environment (Kole et al., 2017; Setälä et al., 2017). Meng et al. (2025) reported that the average known TWP emissions on a global scale are 0.81 per kilogram, amounting to approximately 6.1 million tons per capita (approximately 1.8% of total plastic production). Notably, the United States is estimated to have the highest per capita release of TWPs at 4.70 kg per year, primarily because of its extensive road network and the highest per capita number of automobiles (Kole et al., 2017).

TWPs are generated through the friction between tires and the road surface. This friction results in abrasion that generates both shear forces and heat, contributing to the formation of TWPs. Shear forces primarily produce relatively larger coarse-size fraction MP fragments ($> 20 \mu\text{m}$), 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 ($< 2.5 \mu\text{m}$), capable of long-range atmospheric transport (Grigoratos and Martini, 2014; Kreider et al., 2010; Wagner et al., 2018; Wang et al., 2022).

Factors such as traffic intensity, vehicle weight, distance traveled, driving speed, and climatic conditions largely influence TWP emissions. For example, a study by Mierzyńska et al. (2024) aimed at investigating traffic intensity as a factor influencing MP and TWP pollution on urban roads found that high traffic roads tend to produce more TWPs. They recorded statistically significant differences between the average values of the TWP concentration on low, medium, and heavy traffic roads, amounting to 62.32 pcs/L, 335.97 pcs/L, and 792.76 pcs/L, respectively. Moreover, heavy-duty vehicles such as trailer trucks have been reported to emit approximately 10 times more TWPs than light-duty vehicles and passenger cars. Hillenbrand et al. (2005) reported the following median TWP emission values for different vehicles: passenger cars at 90 mg/km; trucks at 700 mg/km; and trailer trucks at 1200 mg/km.

Distance traveled is another major factor influencing TWP and MP generation. Based on empirical and extrapolated data compiled by Kole et al. (2017), country-specific annual mileage has a linear relationship with annual TWP emissions. For example, cars and four-wheeled light vehicles in India have an estimated annual mileage of approximately 10,000 km and annual TWP emissions of approximately 52,000 metric tons per year. By comparison, the same vehicle class in the United States has an estimated annual mileage of approximately 18,000 km and annual TWP emissions of 587,000 metric tons per year, with the higher U.S. values largely reflecting longer per-capita annual vehicle travel distances. Another study by Kwak et al. (2013) aimed at characterizing TWPs (and roadway particles) from on-road driving and laboratory experiments showed a linear correlation between speed and TWPs. During constant speed conditions, the average PM_{10} and $\text{PM}_{2.5}$ concentrations of TWPs increased with increasing speed: 50km/h at 13 PM_{10} and 20 $\text{PM}_{2.5}$; 80km/h at 25 PM_{10} and 32 $\text{PM}_{2.5}$; 110km/h at 26 PM_{10} and 33 $\text{PM}_{2.5}$; and 140km/h at 29 PM_{10} and 36 $\text{PM}_{2.5}$. These results indicate that higher driving speeds substantially elevate emissions from tire wear.

Climatic conditions can significantly influence TWP emissions. In cold regions, road safety measures such as the use of studded tires are common. Although studded tires improve traction on snow and ice, the metal studs embedded in the tread intensify mechanical abrasion between the tire and pavement, accelerating TWP generation (Järnlskog et al., 2020; Olofsson et al., 2025). Using a mobile laboratory vehicle to directly measure emissions, Kupiainen and Pirjola (2011) found that studded tires produced significantly higher PM_{10} road dust emissions than non-studded tires at speeds above 50 km h^{-1} , with tires containing 110 heavy studs generating 2.4 to 2.8 times more PM_{10} at 60 km h^{-1} and 2.3 to 3.3 times more PM_{10} between 70 and 90 km h^{-1} . Winter maintenance activities, such as snow plowing, also contribute to the

redistribution of TWP already accumulated in roadway environments. For example, Vijayan et al. (2022) quantified tire and road wear particles in roadside snowbanks in two Swedish municipalities and found average concentrations of $20,000 \pm 48,000$ particles L^{-1} , with peak concentrations reaching 197,000 particles L^{-1} . The smallest size fraction (50–100 μm), which is readily generated and mobilized by snow plowing, comprised approximately 80% of all particles. The study concluded that snow plowing mechanically scours pavement surfaces, transferring tire and road wear particles into roadside snowbanks that subsequently release accumulated MPs during snowmelt. In addition, 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 (Kole et al., 2017). Field measurements by Kang and Kim (2023) showed that concentrations of tire and road wear particles collected from roadside environments were approximately 7.6 to 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 (Weyrauch et al., 2023). 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.

Brake Wear

Vehicle components such as brake wear particles (BWPs) are recognized as another significant source of MPs in roadway environments. Evangelidou et al. (2020) 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 (Chan and Stachowiak, 2004), 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 because of 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. (2000), approximately 80% of a brake's friction material is typically lost during its lifetime. Based on this percentage and accounting for vehicle weight, they concluded that brake wear emissions are estimated at 18 to 29 mg per vehicle-mile for passenger cars and about 47 mg per vehicle-mile for large pickup trucks. Vehicle speed also has a direct effect 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. (2023) experimentally demonstrated that increasing vehicle speed by 12.5 mi/h can raise BWP concentrations by several tens of percent. Testing four different brake pads, they found that speed had the strongest influence on $PM_{2.5}$ particles, with average concentrations rising from 4 to 45, 348, and 851 $\mu g/m^3$ at 12.5, 25, 37, and 50 mi/h, respectively.

Finally, conditions such as brake temperature and humidity significantly influence BWP release. Li et al. (2025) 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 (2017) 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-metallic brake material, average wear decreased from 0.06 to 0.05 and 0.02 g at 50, 65, and 80% relative humidity, respectively, whereas 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 (2017) attribute approximately 7% of MP emissions to road markings, whereas other studies report ranges from 0.7% (Wang et al., 2019) to 19% (Ryberg et al., 2018). State transportation agencies, such as VDOT, employ a diverse set of marking materials (Table A1), 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 A1. Virginia Department of Transportation Road Marking Materials List (VDOT, 2019)

Label	Material
Type A	Paint (latex based or waterborne, with glass beads or other material added for retro reflectivity)
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. (2015) ranked the average durability of road marking systems as follows:

1. Road marking tapes—superior durability compared with other systems.
2. Epoxy and 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 (2020) reported that water-based paints typically have short lifespans of approximately 6 to 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 can wear off in as little as 6 months in high-traffic freeways (VDOT, 2019) and are likely to result in higher annualized MP emissions (Andersson-Sköld et al., 2020).

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. (2019) 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. Therefore, these findings highlight that the interplay between material properties, durability, and region-specific operational stressors governs MP emissions from road markings, reinforcing the need for differentiated analyses rather than aggregated emission estimates when evaluating the 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 (Mohammadi and Ameri, 2024). Commonly incorporated plastics include PE, polypropylene, polystyrene, and polyethylene terephthalate (Ma et al., 2021; Xu et al., 2022). Two techniques of incorporating plastic into asphalt have been explored—the wet method, in which the recycled plastics are first blended with hot bitumen before the plastic-modified bitumen is added to the hot aggregates, and the dry method, in which recycled plastics are used as aggregate substitutes and mixed with the aggregates before adding hot bitumen (Ma et al., 2021).

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. Enfrin et al. (2022) developed a laboratory-based procedure 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 PE added to the mix at rates of 1 to 6% by weight of binder. The dry mixes contained either recycled polyethylene terephthalate or recycled acrylonitrile butadiene styrene added to the mix at rates of 0.5 to 4% by weight of the total mix. Both mix types had a binder content of 5%. Considering this proportion, the wet mixes contained only 0.3% at most, more than 16 times less than that of the dry mixes (4% maximum). Despite this significant difference, the study found that the wet mixes released MPs faster than the dry mixes (0.048 g/m²/min versus 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 discharge of MPs released from the low-density PE mixes by nearly three times compared with 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.

Smyth et al. (2025) carried out a 2-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 study's findings 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 compared with 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 = 5,504 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 TWPs, litter, 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. Therefore, the study emphasized the need for the thorough evaluation of novel RPM pavement materials prior to large-scale implementation.

Lloyd et al. (2026) performed another study aimed at assessing RPM asphalt pavements constructed in Virginia that incorporated a PE-based additive via the dry method at 5% by weight of asphalt binder (equating to 0.25% of the total mixture). The study utilized the Cantabro mass loss test to generate abraded material representative of field conditions. Material abraded from samples during the test was collected, and solvent was extracted to remove the binder present in the material. Following solvent extraction, the recovered particulates were sieved into various particle sizes and analyzed via thermogravimetric analysis-Fourier transform infrared spectroscopy. The results revealed distinct MP particles present in the material abraded from PE-based RPM asphalt samples with median MP concentrations ranging from 1.60 ± 4.5 mg/g to 7.25 ± 6.9 mg/g. This amount represents one of the first studies to quantify MPs concentrations on a mass basis rather than simply based on particle counts. However, the authors note that the Cantabro test is intended to compare the durability of an asphalt mix relative to others, not during a specified period of time. Therefore, the rate at which MPs could be released from the material could not be determined. The study's authors recommended that further efforts be made to conduct long-term field monitoring of the RPM asphalt site to better understand the rate of MPs generated from the material under real-world conditions.

In 2024, Duan et al. (2024) 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. Hamburg Wheel-Track Testing was used to simulate extreme pavement degradation under heavy loading and moisture (American Association of State Highway and Transportation

Officials, 2022), whereas the permeability test assessed MPs leaching from crack surfaces (Florida Department of Transportation, 2015). Results showed that although RPM asphalt pavements have the potential to release MPs, the estimated emissions were about three orders of magnitude less than those generated by tire wear on pavement surfaces. However, the authors noted that long-term field validation of these methods is still needed.

Erosion Control Netting

Erosion control netting has been used in road construction to stabilize soil, support vegetation growth, and reduce sediment runoff (U.S. Environmental Protection Agency, 1995). 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 (VDOT, 2025). 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 deterioration (Rivas, 2006). Many commercially available erosion control netting products incorporate plastic components that are designed to degrade and fragment under ultraviolet exposure and are often marketed as “biodegradable.” However, many materials labeled as biodegradable rely on sunlight to facilitate degradation; once vegetation establishes and shades the netting, this process is inhibited, and the material may persist in the environment without degrading as intended (U.S. Geological Survey, 2016).

A review by Kärman et al. (2016) further highlighted that plastic-based components commonly used in erosion control netting can lead to long-term environmental challenges. In cases when these materials undergo breakdown through ultraviolet exposure, weathering, and mechanical stress, they fragment into smaller particles that are released into the environment as buoyant MPs. These particles can subsequently be transported via stormwater runoff, contributing to broader environmental dispersion (Whitman et al., 2025). Although erosion control netting has proven to be an effective environmental management tool, its pollution potential arising from the breakdown of plastic netting has not yet been comprehensively studied.

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 (Premarathna et al., 2025).

Key Insights

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 because of 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 by nearly a factor of 10. 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 methods for incorporating recycled plastic strongly influence MP emissions. Similarly, erosion control netting remains underrepresented in quantitative assessments, despite its potential for long-term MP release through ultraviolet exposure, weathering, and mechanical wear. Overall, although 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. These limitations highlight the critical need for field-based studies, particularly on emerging sources such as RPM asphalt pavements and erosion control netting, to generate accurate, real-world 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 transporting MPs from roadway environments into aquatic ecosystems (Fang et al., 2021; Shafi et al., 2024; Shruti et al., 2021). According to Premarathna et al. (2025), initially, TWPs 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 concentrations of between 66 particles per liter and as high as 4,400 particles per liter in stormwater samples (Järlskog et al., 2022; Järlskog et al., 2020; Piñon-Colin et al., 2020).

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 because of their low density (polypropylene, a common roadway MP polymer, has a density of about 0.9 g/cm³) compared with water (1 g/cm³), heavy rainfall and resulting turbulent flows are likely to remobilize and transport them into surface waters (Hoellein et al., 2019; Maddah, 2016). Therefore, rainfall intensity and flow rate play a crucial role in generating stormwater runoff and serve as key drivers for the transport of MPs in urban environments (Xia et al., 2021). A study by Treilles et al. (2021) investigated MPs in stormwater during four rain events. The highest MP concentrations (~ 129 particles/L) were observed in two of the rain events and at the beginning of both rain events, whereas the lowest MP concentrations were observed at the end of the rain events (~ 3 particles/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 (Barrows et al., 2018; Lee et al., 2002; Wang et al., 2017).

Atmospheric Transport

Because of their low density and size, MPs in roadways can be airborne when exposed to mechanisms such as vehicle-induced turbulence, shear stress, or wind (Kupiainen, 2007). These processes also affect the movement and distribution patterns of MP pollution, shaping source-sink dynamics in both terrestrial and marine ecosystems (Bank and Hansson, 2019). 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 (Zhang et al., 2020). The Interstate Technology and Regulatory Council (2023) explains how MPs transported in the atmosphere may vary by location; that is, smaller MPs tend to be found in remote areas, and larger MPs tend to be found in urban areas. According to Allen et al. (2019), the transmission distance of MPs in the atmosphere is approximately 19 km per month. Another study by Evangelidou et al. (2020) 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.

Key Insights

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 versus composite), event-based versus time-integrated monitoring, inconsistent reporting units (particles/L versus mass-based metrics), and analytical detection limits related to polymer identification techniques. These inconsistencies hinder cross-study comparability and limit the ability to derive representative MP transport coefficients. In contrast, the atmospheric transport pathway is less characterized, with empirical data comparatively sparse. A common assertion is that smaller MPs are transported to remote areas, and 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, although 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 adopting standardized and comprehensive approaches to accurately quantify MP transport in roadway environments.