THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Tyre Wear Particles: Emissions and Distribution in Soil and Stormwater Systems in Near Road Environments

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ABSTRACT

Tyre wear particles (TWP) are a major source of microplastic pollution in road environments, yet their emissions, distribution, and environmental fate remain insufficiently characterised. This thesis presents a multi-scale investigation of TWP emissions in Sweden, their occurrence and distribution in two roadside ditches and one stormwater system, and the effectiveness of selected mitigation strategies. A detailed methodology was developed to estimate national TWP emissions using vehicle-specific emission factors and mileage data. Passenger cars were identified as the largest contributors (55%), followed by heavy-duty vehicles (31%), with rural roads accounting for the highest emissions. Field studies confirmed the occurrence of TWP in stormwater components such as gully pots, wells, and receiving waters. Fine particles 1.6–20 µm constituted a substantial portion of the total TWP load in both water and sediment samples. In roadside soils, TWP <500 µm were quantified at all depths, with concentrations decreasing with distance from the road. Laboratory column experiments demonstrated high retention efficiencies (93–99%) for TWP, particularly in fine-grained soils amended with biochar. Vegetation influenced TWP mobility by creating preferential flow paths, especially during dry periods, while drought conditions reduced retention. Co-transport of TWP with metals and tyre-derived chemicals (TDC) was observed primarily in the water phase. Strong correlations between TWP and total metals were found in effluent samples, but not in soil mixtures. Fourteen TDC were analysed, with particulate-bound forms such as 6PPD and 6PPD-Q showing high retention (>97%), while more water-soluble compounds (e.g., HMMM, OHBT, MTBT, BTSA) exhibited variable leaching. The addition of biochar improved the retention of TWP, TDC and metals in fine, non-vegetative soils, and may contribute to climate mitigation by offsetting carbon emissions from construction materials such as concrete and steel. The thesis also evaluated mitigation strategies, including stormwater systems, road ditches, and bioretention filters. Bioretention filters with the addition of sorption materials demonstrated high removal efficiencies (97–100%) for TWP even under cold and high-flow conditions. The findings in this thesis contribute to improved understanding of TWP transport and retention and support the development of targeted measures to reduce microplastic pollution from road traffic.

Keywords*: Tire wear particles, microplastics, stormwater, roadside soil, biochar, bioretention, metals, tyre-derived chemicals, transport, retention*

SAMMANFATTNING

Däckslitagepartiklar (TWP) utgör en av de mest betydande källorna till mikroplastföroreningar i vägmiljöer, men trots detta är kunskapen om deras emissioner och spridningsvägar i naturmiljön fortfarande begränsad. I denna avhandling presenteras en omfattande undersökning av TWP-emissioner i Sverige, deras förekomst och spridning i två vägdiken och i ett dagvattensystem, samt utvärdera effektiviteten hos olika åtgärdsstrategier. En detaljerad metodik har utvecklats för att uppskatta de nationella TWP-emissionerna, baserat på fordonspecifika emissionsfaktorer och körsträcksdata. Personbilar identifierades som den största utsläppskällan (55 %), följt av tunga fordon (31 %), där landsvägar stod för de högsta emissionerna. Fältstudier bekräftade förekomsten av TWP i dagvattenkomponenter såsom rännstensbrunnar och sedimentationsbrunnar, men visade också på förekomst i närliggande recipient. Fina partiklar (1.6–20 µm) utgjorde en betydande andel av den totala TWP-belastningen i både vatten- och sedimentprover. I jordprover nära vägkanten påträffades TWP (<500 µm) på samtliga djup, med koncentrationer som minskade med avståndet från vägen. Kolonnförsök i laboratoriemiljö med blandade jordar visade på hög retention (93–99 %) för TWP, särskilt i finkorniga jordar med tillsatts av biokol. Vegetation påverkade mobiliteten av TWP genom att skapa preferentiella flödesvägar, särskilt under torra perioder, medan torka minskade retentionen. Samtransport av TWP med metaller och däckrelaterade kemikalier (TDC) observerades främst i vattenfasen. Starka korrelationer mellan TWP och totala metallhalter kunde visas i vattnet i utloppsprover från kolonnerna, men inte i jordblandningarna. Fjorton TDC analyserades, där partikelbundna former av 6PPD och 6PPD-Q visade hög retention (>97 %), medan mer vattenlösliga föreningar (t.ex. HMMM, OHBT, MTBT, BTA) kunde lakas ut från kolonnerna. Tillsatsen av biokol förbättrade retentionen av TWP, TCD och metaller i fina icke-vegetativa jordar, och kan också bidra till klimatbegränsningar genom att kompensera för koldioxidutsläpp från byggmaterial som t ex betong och stål. Avhandlingen omfattar även en utvärdering av olika åtgärdsstrategier, inklusive dagvattensystem, vägdiken och bioretentionsfilter. Bioretentionsfilter med tillsats av sorbentmaterial uppvisade hög avskiljningsförmåga/retention (97–100 %) för TWP även under förhållande med kyla och höga vattenflöden. Sammantaget bidrar resultaten i denna avhandling till en fördjupad förståelse för hur TWP transporteras från vägar, i diken via dagvattensystem och vidare till recipienter och stödjer också utvecklingen av effektiva och riktade åtgärder för att minska mikroplastföroreningar från vägtrafik.

LIST OF PUBLICATIONS

This thesis is based on the work from the following papers:

I. **Polukarova, M.,** Hjort, M., Gustafsson, M. 2024. Comprehensive approach to national tyre wear emissions: Challenges and implications. *Science of The Total Environment*, Volume 924, 171391, https://doi.org/10.1016/j.scitotenv.2024.171391

II. Gaggini, E.L., **Polukarova, M.,** Bondelind, M., Rødland, E., Strömvall, A-M., Andersson-Sköld, Y., Sokolova, E., 2024. Assessment of fine and coarse tyre wear particles along a highway stormwater system and in receiving waters: Occurrence and transport. *Journal of Environmental Management,* 367, 121989. https://doi.org/10.1016/J.JENVMAN.2024.121989

III. **Polukarova, M.,** Gaggini, E.L., Rødland, E., Sokolova, E., Bondelind, M., Gustafsson, M., Strömvall, A-M., Andersson-Sköld, Y., 2025. Tyre wear particles and metals in highway roadside ditches: Occurrence and potential transport pathways. *Environmental Pollution,* 125971. https://doi.org/10.1016/J.ENVPOL.2025.125971

IV. **Polukarova**, **M.,** Johansson, G., Rødland, R., Strömvall, A-M., Andersson-Sköld, Y., 2025. Transport of TWP, tyre-derived chemicals and metals in road ditch soil with and without the addition of biochar. *In prep*.

V. Johansson, G., **Polukarova**, **M.,** Karlfeldt Fedje, K., Modin, O., Andersson-Sköld, Y., Strömvall, A-M. 2025. Removal of microplastics, organic pollutants and metals from stormwater in bioretention filters with added sorbent materials during simulated extreme rainfall events under winter conditions with dormant plants. *Journal of Hazardous Materials*, 496, 138868.https://doi.org/10.1016/j.jhazmat.2025.138868

The author has contributed in the following ways to the journal articles included in the thesis:

Paper I: Analysis and assessment of the data. Creation of illustrations for the draft. Writing the original draft and editing and reviewing the text after consultation with co-authors and external review.

Paper II: Reviewing and editing the manuscript text, assisting with the methodology and investigation.

Paper III: Planning and performing the study, procurement of field tools, performing all field measurements, sample collection and sample pre-treatment. Performed laboratory analysis. Analysis and assessment of the data, statistical analysis of data and creation of illustrations for the draft. Writing of the original draft, editing and reviewing of text after consultation with co-authors and external review.

Paper IV: Planning and performing the study, procurement of laboratory equipment, performing sample collection and sample pre-treatment. Performed laboratory analysis (LOI, Turbidity, conductivity). Analysis and assessment of the data, statistical analysis of data and creation of illustrations for the draft. Writing of the original draft and editing and reviewing of text after consultation with co-authors.

Paper V: Planning and performing the study. Evaluation of data and creation of illustrations for the draft. Writing, editing and reviewing of text after consultation with co-authors and external review.

The author has contributed to the following research and publications, which are not appended to this thesis. Participation in these works supported the development of broader expertise in stormwater

pollution, mitigation strategies, and field sampling methodologies. A list of the publications is provided below.

Journal Articles:

Järlskog, I., Strömvall, A-M., Magnusson, K., Galfi, H., Björklund, K., **Polukarova, M.**, Garção, R., Markiewicz, A., Aronsson, M., Gustafsson, M., Norin, M., Blom, L., & Andersson-Sköld, Y. (2021). Traffic-related microplastic particles, metals, and organic pollutants in an urban area under reconstruction. *Science of the Total Environment, 774*, 145503. https://doi.org/10.1016/j.scitotenv.2021.145503

Järlskog, I., Strömvall, A-M., Magnusson, K., Gustafsson, M., **Polukarova, M.**, Galfi, H., Aronsson, M., & Andersson-Sköld, Y. (2020). Occurrence of tire and bitumen wear microplastics on urban streets and in sweepsand and washwater. *Science of the Total Environment, 729*, 138950. https://doi.org/10.1016/j.scitotenv.2020.138950

Polukarova, M., Markiewicz, A., Björklund, K., Strömvall, A-M., Galfi, H., Andersson-Sköld, Y., Gustafsson, M., Järlskog, I., & Aronsson, M. (2020). Organic pollutants, nano- and microparticles in street sweeping road dust and washwater. *Environment International, 135*, 105337. https://doi.org/10.1016/j.envint.2019.105337

Reports and Institutional Publications:

Blomqvist, G., Järlskog, I., Gustafsson, M., **Polukarova, M.**, & Andersson-Sköld, Y. (2023). *Microplastics in snow in urban traffic environments*. Statens väg- och transportforskningsinstitut. https://urn.kb.se/resolve?urn=urn:nbn:se:vti:diva-19712

Gustafsson, M., **Polukarova, M.**, Blomqvist, G., Järlskog, I., & Andersson-Sköld, Y. (2023). *Street sweeping: A source to, or measure against, microplastic emissions?* Statens väg- och transportforskningsinstitut. https://urn.kb.se/resolve?urn=urn:nbn:se:vti:diva-19697

Andersson-Sköld, Y., Johannesson, M., Gustafsson, M., Järlskog, I., Lithner, D., **Polukarova, M.**, & Strömvall, A-M. (2020). *Microplastics from tyre and road wear: A literature review*. Statens väg- och transportforskningsinstitut. https://urn.kb.se/resolve?urn=urn:nbn:se:vti:diva-15243

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1. INTRODUCTION

Road traffic is a major source of environmental pollution in urban areas, contributing to a complex mixture of contaminants that affect air, soil, and water quality. Among the most concerning pollutants are metals (e.g., lead, zinc, copper, nickel, cadmium, chromium), organic compounds such as aliphatic hydrocarbons, polycyclic aromatic hydrocarbons (PAH), phthalates, and airborne particulate matter (PM_{10} and $PM_{2.5}$), originating from both exhaust and non-exhaust sources such as fuel combustion, tyre and brake wear, and road dust resuspension (Markiewicz et al., 2017; Health Effect Institute, 2022). These pollutants pose ecological and health risks, including respiratory and cardiovascular diseases, soil degradation, and aquatic toxicity. In response, the European Union has implemented increasingly stringent regulations, such as the Euro 7 standards, to reduce air pollution from vehicles (European Parliament and Council of the European Union, 2024).

In recent years, tyre wear particles (TWP) have emerged as a particularly concerning type of traffic-related pollutants. Generated through the friction between vehicle tyres and road surfaces, TWP are now recognised as a significant source of microplastic pollution (Giechaskiel et al., 2024; Fussel et al., 2022; Kole et al., 2017; Wagner et al., 2018; Baensch-Baltruschat et al., 2021). Research has intensified to map their occurrence, understand their environmental fate, and assess their toxicity to both terrestrial and aquatic organisms (Wagner et al., 2018; Knight et al., 2020; Baensch-Baltruschat et al., 2020; 2021). Their widespread occurrence across environmental matrices, such as air, water, soil, sediments, and snow, suggests high exposure potential, exacerbated by increasing traffic volumes and vehicle weights (Baensch-Baltruschat et al., 2020; Gaggini et al., 2025a,b; Järlskog et al., 2022a; Khan et al., 2024; Rødland et al., 2022a, 2023a; Wang et al., 2024; Ertel et al., 2023).

Despite their suggested widespread presence, monitoring TWP remains challenging due to their small size, complex chemical composition, and the lack of standardised analytical methods (Rødland et al., 2023b). Although several studies have reported TWP concentrations in various environmental matrices, significant knowledge gaps remain. These include the extent of their accumulation across different road types and countries, average tyre wear per kilometre, and the relative contributions of different vehicle types to TWP emissions. Roadside soils, in particular, remain poorly studied due to their analytical complexity, with only a few investigations addressing TWP occurrence in these environments (Müller et al., 2022; Rødland et al., 2023a). Further research is essential to understand their distribution and transport, which is critical for assessing environmental risks and developing effective mitigation strategies.

‘

1.1. Research aim and objectives

This project aimed to increase knowledge and understanding of the occurrence, distribution and spread of TWP from roads to the surrounding areas, as well as to investigate the effectiveness and assess the benefits of measures to reduce the spread.

The research questions of the thesis were:

1) How to develop a detailed and locally adapted method to estimate national TWP emissions? What are the quantities of national tyre wear emissions occurring in urban versus non-urban environments in Sweden, and which vehicle categories and tyre types are the primary contributors?

2) What is the occurrence and the spatial distribution of TWP in stormwater systems?

3) What is the occurrence and spatial distribution of TWP in roadside ditches?

4) What are the key controlling factors for retention of TWP in the soil and bioretention filter?

5) Are TWP, tyre-derived chemicals, and metals co-transported in soil and bioretention filter with added sorption materials?

To achieve the overarching aim, the specific objectives of this research included:

- Develop a robust and detailed methodology for estimating national TWP emissions. Apply this method to Sweden, ensuring differentiation by road type (urban, rural, motorway) and quantification of the contribution from each vehicle and tyre category to the total emissions (Paper I).
- Investigate the occurrence and distribution of TWP in different matrices such as road runoff, gully pot water, sediments, as well as in receiving waters (Paper II).
- Investigate the occurrence and distribution of TWP and metals in roadside soils (Paper III).
- Enhance understanding of the various factors that influence soil transport, such as filtration, and leaching of tyre wear particles, tyre wear-derived chemicals and metals in different types of soil materials with and without biochar and vegetation (Paper IV).
- Examine the effect on bioretention in filters containing various sorption materials, such as biochar, ash and peat in combination with cold weather and dormant plants in the filters (Paper V).

1.2. Thesis outline

The overall aim of this project is to increase knowledge and understanding of the occurrence and transport patterns of TWP, to support environmental risk assessments. The thesis is structured around a series of research questions that progress from broader national-scale assessments to more detailed investigations of environmental occurrence, transport mechanisms, and mitigation strategies. To create a coherent structure, the articles are arranged according to the research questions they address, starting with the most comprehensive, system-level analysis and gradually narrowing down to specific environmental compartments and

processes. This progression reflects a deliberate strategy to build understanding step by step, from identifying major sources of TWP emissions to exploring their fate and potential mitigation. An overview of the research papers included in the thesis is presented in Table 1.

The first part of the thesis develops a detailed methodology for estimating national TWP emissions, applied to Sweden. This includes quantifying emissions across different road types (urban, rural, motorway) and assessing contributions from various vehicle and tyre categories (Paper I). Subsequent sections investigate the occurrence and distribution of TWP in stormwater systems and roadside ditch soils, presenting measured concentrations in near-road environments (Papers II and III). These are followed by studies on transport patterns and retention processes in soil systems, including co-transport of TWP with tyre-derived chemicals and metals (Papers IV and V). Finally, the thesis evaluates selected mitigation strategies, focusing on source reduction and stormwater management, contributing to a more comprehensive understanding of the environmental risks posed by TWP and informing future mitigation efforts.

Table 1. Overview of the research papers included in the work.

Paper	Knowledge gap	Research question	Methods	Key findings	Scientific novelty
I	Lack of reliable **methods** to assess the total **national TWP emissions** and their **distribution** in the **environment**	How to assess total national TWP emissions and their distribution in the environment? What are the national emissions in Sweden? How much TWP are accumulated alongside different types of roads (urban, rural, motorway)?	Literature study, Swedish statistics summary, and field measurements of emission factors	A detailed method to assess national TWP emissions 11,040-12,560 tonnes in total, only 1/3 are alongside urban roads, which may have stormwater management, 2/3 are along roads with no/little stormwater management. Approximately 30% of emissions originate from heavy-duty traffic, which predominantly operates in non-urban or interurban areas, rather than within city environments.	Field-measured, well-documented and robust/reliable emission factors for passenger cars and light-duty vehicles. Detailed and adapted to local conditions, emission factors and emissions for HDV. A detailed methodology to assess total national TWP emissions and their distribution in the environment based on field data
II	**TWP quantification** in **stormwater** has only been found sporadically in the literature **TWP spread** and concentrations **through** a **stormwater system**	What is the occurrence, characteristics and spatial distribution of TWP in the near-road environment of a highway stormwater system? What is the distribution of small and larger TWP?	Field sampling, chemical analysis with PYR-GC/MS. Monte-Carlo simulations, correlations	TWP concentration is similar to that reported in other studies and quantified in natural waters. In the water and sediment samples, TWP in the size fraction 1.6–20 μm accounted for a significant mass proportion. Sediment samples from the recipient Lillån contained somewhat higher median TWP concentrations than the road ditch soil samples at depths of 0.1–0.5 m.	Measurements of TWP were done along a stormwater system at different locations simultaneously. In addition, including measuring TWP in stormwater in the small size fraction 1.6–20 μm.

III	**TWP quantification** in **road ditch soil** has only been found sporadically in the literature	What is the occurrence and distribution of TWP and metals in roadside soils, and what are the correlations between these contaminants?	Field sampling of road ditch soil, sample preparation, PYR-GC/MS, Monte-Carlo simulations, correlation analysis	TWP were found at all soil depths. TWP concentration decreased with distance from the road. Traffic-related metals were the most abundant. Varying correlations between metals of different types and TWP.	A detailed transect and depth-resolved analysis of TWP in two different types of road ditches: one receiving runoff from the adjacent highway, and the other primarily from a stormwater outlet. Small TWP particles were included in the size fraction analysed of <500 µm.
IV	**Transport** and **accumulation** of **TWP** and **tyre-derived chemicals** through different types of **soil**	Which factors influence the transport of tyre wear particles, tyre-derived chemicals, and associated metals in various soil types, both with and without biochar and vegetation?	Laboratory column study, irrigation and collection of leachates, sample preparation, PYR-GC/MS, UPLC MS/MS, Monte-Carlo simulations, correlation analysis	Vegetation influenced TWP transport by creating preferential flow paths through root systems, particularly during dry periods when soil cracking enhanced vertical movement. Biochar amendment improved TWP retention and vegetation growth in fine-grained soils, though its effectiveness declined under drought conditions, which warrants further long-term evaluation. Soil moisture is an important factor for TWP retention, especially in fine-grained (clayey and silty) soil covered with vegetation. Metal concentrations, as for example, Zn, Cu, and Cr, increased alongside TWP in topsoil, but correlations between metals and TWP were generally absent in the soil mixtures. Strong correlations were observed between TWP and total metals in effluent waters, but not with dissolved metals, supporting the co-transport of TWP and metals in particle form. Several TDC were efficiently retained as particulate-bound forms; some TDC in filtrated water exhibited significant leaching or variability between columns.	Investigating TWP transport and 14 tyre-related chemicals in road ditch materials simultaneously. In addition, including measuring TWP in the small size fraction 1.6-500 µm for water and 0.3-500 µm for soil samples. The results show that several tyre-related chemicals, including HMMM, OHBT, MTBT and BTSA are leaching from soil irrigated with polluted runoff, indicating low or even negative removal efficiency.
V	**Bioretention** with the addition of sorption materials for the **removal of TWP** during **cold weather** and **high runoff volumes**	How do high volumes of stormwater, in combination with cold weather and dormant plants, affect the removal and transport processes of TWP in bioretention filters with added sorption materials?	Field sampling, irrigation and collection of leachates, sample preparation, chemical analysis, correlation analysis	TWP > 10 µm were removed efficiently even during colder temperatures (above 0 °C) and at higher runoff volumes, showing that bioretention filters have high potential to be used in urban areas with moderately cold winters and high (50-year rainfall event) precipitation volumes.	First-time evaluation of bioretention filters with the addition of sorbent materials under winter conditions and high runoff volumes. Multi-pollutant removal performance.

2. THEORETICAL BACKGROUND

This chapter will summarise the research regarding the environmental distribution, occurrence, fate, and transport pathways of TWP, highlighting their growing significance in the context of urban pollution and evolving regulatory frameworks. The sub-sections will primarily focus on TWP in stormwater, runoff, and roadside ditches, as these systems represent the initial and most influential pathways for TWP mobilisation from road surfaces, offer practical opportunities for mitigation through infrastructure design and maintenance, and provide critical data for modelling contaminant transport and informing regulatory strategies. Finally, the TWP complex chemical composition, size, morphology, and elemental content will be examined to illustrate their potential environmental and human health risks. The tyre-derived chemicals studied in this thesis are also introduced in this chapter.

2.1. Estimated emissions

Tyre wear particles (TWP), generated through the mechanical abrasion between vehicle tyres and road surfaces, represent a significant and growing source of microplastic pollution (Kole et al., 2017; Wagner et al., 2018; Baensch-Baltruschat et al., 2021). In the European Union alone, it is estimated that approximately 1.3 million tonnes of TWP are emitted annually (Wagner et al., 2018). The contribution of TWP to total microplastic emissions varies significantly across countries. For instance, TWP account for approximately 24–30% of microplastic emissions in Germany (Baensch-Baltruschat et al., 2021), 54% in China (Wang et al., 2019), 56% in Denmark (Lassen et al., 2015), and between 61% and 79% in Sweden (Magnusson et al., 2016). Notably, in Switzerland, TWP have been estimated to contribute as much as 94% of total microplastic emissions (Sieber et al., 2020). In terms of absolute quantities, the emissions in Sweden are? estimated at 12,350 tonnes (Magnusson et al., 2016) of TWP annually, while in the United Kingdom, the emissions are approximately 42,000–84,000 tonnes (Kole et al., 2017).

To compare national TWP emissions between different countries, per capita emissions can be used as a relevant indicator. Baensch-Baltruschat et al. (2021) compiled estimations from different regions, and emissions range from 0.2 kg/capita per year in India to 3–5.5 kg/capita per year in the United States, thus reflecting car use relative to the population. The mean value for European countries is 1.17 kg/capita per year, with values varying from 0.6 for France to 1.8 for Norway. The calculations in this study show that the tyre wear emissions are approximately 1.06 kg/capita per year in Sweden (based on 10.4 million inhabitants in 2021), placing it in the lower half of the European range. A similar method used for South Korea by Lee et al. (2020) yielded a mean of 1.03 kg/capita (based on 51.7 million inhabitants in 2021).

Once generated and accumulated on the road surface, the environmental fate of TWP is influenced by local infrastructure and environmental conditions. In Germany, it is estimated that 12–20% of TWP reach surface waters, 2–3% are deposited in agricultural areas, and 66–76% accumulate in roadside soils such as ditches (Baensch-Baltruschat et al., 2021). In the UK, the distribution differs: 5% is emitted into the atmosphere, 36% enters surface water, and 24% enters soil (Zheng et al., 2025). Field measurements by Järlskog et al. (2022a) in a highway environment showed that approximately 4% of TWP are emitted directly to the air. In dense urban environments with dry climates and high traffic, the airborne fraction may be higher, leading to higher human health risks.

The distribution of TWP emissions across different road types depends on the national road network and the emission rate per vehicle-kilometre, which varies by road type. Urban areas typically exhibit higher tyre wear due to frequent braking and turning, while highways, especially in rural areas, may also show elevated wear rates due to higher vehicle speeds. A widely used method for estimating national and road-type-specific TWP emissions is the mileage-based approach. This method calculates emissions using emission factors (EFs) expressed as tyre wear per vehicle kilometre, combined with traffic activity data. It has been applied in several countries, including the Netherlands (Verschoor et al., 2016), Norway (Sundt et al., 2014), Sweden (Magnusson et al., 2016), and South Korea (Lee et al., 2020).

The mileage approach enables detailed assessments of emissions by vehicle type and road category (urban, rural, motorway), and supports the evaluation of regulatory measures such as the Euro 7 emission standard. However, the accuracy of this approach is limited by the quality and relevance of the emission factors used. Tyre wear is influenced by numerous factors, including climate, road surface properties, topography, and driving behaviour, all of which vary geographically. As highlighted by Mennekes and Nowack (2022), many studies rely on outdated or poorly justified emission factors, often derived from earlier literature rather than direct measurements. Of the few studies that conducted their own measurements, half date back to the 1970s and with a limited scope, some focus solely on light-duty vehicles or buses. Only three non-peer-reviewed studies were deemed to provide reliable data, and these were infrequently cited.

Furthermore, country-specific parameters such as the use of winter tyres, which have different wear characteristics compared to summer tyres (e.g., ADAC, 2021), and differences in vehicle fleet composition, weight, and regulatory practices, limit the transferability of emission factors across regions. These uncertainties highlight the need for updated, locally adapted, and vehicle-specific emission factors that reflect current traffic conditions and vehicle technologies. Road-type and vehicle-type-specific TWP emission data are critical for accurate quantification, risk assessment, and mitigation. Identifying high-emission sources enables targeted improvements in vehicle design, such as reduced weight and optimised tyre recipes. Furthermore, spatially resolved emission data support the optimisation of stormwater infrastructure, e.g., piped systems, roadside ditches, and infiltration ponds, by aligning and optimising treatment capacity with emission hotspots, thereby reducing environmental spread.

2.2. Reported occurrence in road environments

In Table 2, a summary of studies addressing TWP mass quantification in road runoff, rural stormwater, gully pot sediments and road ditch samples, and the retention efficiencies of bioretention filters are presented. The reported TWP concentration in stormwater ranges from just above zero to several hundred mg/L. The number of studies of the occurrence of tyre wear particles in gully pots remains limited, and existing research generally lacks critical details. In particular, there is a lack of data on the temporal variability of TWP accumulation, the particle size distribution, and the effects of chemical ageing and degradation on quantification accuracy. Moreover, the potential influence of gully pot design and maintenance practices on TWP retention and transport is rarely addressed. These gaps highlight the need for more comprehensive and systematic investigations to better understand the role of gully pots in the fate and mobility of TWP within urban drainage systems. Of particular interest is identifying which particle sizes of TWP are effectively retained by gully pots, and how this aligns with the

design specifications intended to target specific size ranges. Additionally, exploring the interactions between TWP and other traffic-related pollutants could provide valuable insights into the behaviour of pollutants and potential synergistic effects.

Table 2 shows that TWP have been quantified in road ditch soils at concentrations ranging from below the limit of quantification (<LoQ) to 15.5 g/kg, depending on the analytical method and particle size investigated. Techniques employed include stereomicroscopy combined with automated image analysis, Thermal Extraction Desorption coupled with Gas Chromatography/Mass Spectrometry (TED-GC/MS), and Pyrolysis coupled with Gas Chromatography/Mass Spectrometry (PYR-GC/MS). The studied ditches encompassed a variety of soil types. For instance, Müller et al. (2022) reported soils containing 11–40% fine particles (<100 µm) and 1.8–4.4% organic matter. Rødland et al. (2023a) examined soils from agricultural land, topsoil, marshland, and mixed compositions (e.g., silt/clay, gravel, sand), with organic matter content averaging 14 ± 16%. However, vegetation layers were not explicitly addressed in these studies, leaving uncertainty about their inclusion in sampling. In another study, a bioretention swale adjacent to a highway was analysed, consisting of sandy soil (2.1% sand, 18% silt, 9.7% clay), where runoff infiltrated through the soil to a subsurface drain (Beaurepaire et al., 2025). Samples were collected using a hand drill, while Müller et al. (2022) and Rødland et al. (2023a) used manual tools, such as shovels and spades. The annual average daily traffic (AADT) at the sampling sites varied widely, from 650 to 34,000 vehicles. Overall, data on TWP accumulation in road ditch soils remain limited. Existing studies often lack detailed characterisation of ditch design parameters, such as slope, depth, soil composition, and maintenance regimes, which are critical for understanding pollutant retention and transport. Sampling typically focuses on surface layers, with deeper profiles rarely investigated. Vegetation management during sampling is also frequently omitted or undocumented, despite its potential impact on contaminant dynamics. These gaps, combined with regional variability (e.g., precipitation, ditch geometry, road age) and methodological differences, hinder cross-study comparisons and complicate the development of predictive models for contaminant transport and environmental risk assessment.

As demonstrated by Han et al. (2025), who reviewed studies on microplastic removal from stormwater runoff using bioretention cells, research specifically targeting the removal of TWP remains limited, with most studies still focusing on microplastics in general (Table 3). The available studies (e.g., Smyth et al., 2021; Werbowski et al., 2021; Lange et al., 2021) have employed analytical techniques other than PYR-GC/MS. Nevertheless, bioretention cells have shown high removal efficiencies for TWP, ranging from 84% to 100%.

Table 2: Summary of studies addressing TWP mass-quantification in runoff, stormwater, gully pot sediments and road ditch soil.

Study	Sample matrix	Size fraction	Analysis method	TWP concentrations
Stormwater/runoff samples				
Dröge & Tromp, 2019	Runoff from the highway roadside	Not reported	TED-GC/MS	51–59 mg/L
Parker-Jurd et al., 2021	Rural and roadside runoff		PYR-GC/MS (benzothiazole, a molecular marker for tyres)	average 2.5±1 mg/L
Lindfors et al., 2025	Road runoff	10–500 µm	PYR-GC/MS (Styrene Butadiene rubber (SBR) and Butadiene Rubber (BR) with markers 4-vinylcyclohexene)	0.71 mg/L min-max: 0.19-1.04 mg/L
	Parking lot runoff			median 0.17 mg/L; 0.07-2.26 mg/L
Rødland et al., 2022a	Untreated tunnel wash water	>1.6 µm	PYR-GC/MS (selected markers for SBR and BR consisted of m/z 78 Da for benzene, m/z 118 Da for α-methylstyrene, m/z 117 Da for ethylstyrene and m/z 91 Da for butadiene trimer)	14.5–47.8 mg/L
Stormwater infrastructure				
Rauert et al., 2022	Stormwater drainage	>1 µm	PYR-GC/MS (following the ISO methods, the pyrolysis product 4-vinylcyclohexene (VCH), a dimer of both SBR and BR.)	231–665 µg/L
Rauert et al., 2022	Retention pond water	>1 µm	PYR-GC/MS (following the ISO methods, the pyrolysis product VCH)	72–236 µg/L
Rasmussen et al., 2024	Stormwater ponds	>10 µm	PYR-GC/MS (SBR and BR with marker VCH)	0-22 µg/L
Johansson et al., 2024	Stormwater from a sedimentation chamber	10-1000 µm	PYR-GC/MS (marker ion m/z 93 (limonene) for polyisoprene (PI) and marker ion m/z 79 (4-vinylcyclohexene) for polybutadiene (PB)/BR and SBR)	PI: 147 µg/L PB: 59 µg/L
Sediment samples				
Mengistu et al., 2021	Urban gully pot	<5 mm	STA-FTIR + PARAFAC	0.8–149.6 mg/g sediment d.w.
Rødland et al., 2022a	Gully pots in the road tunnel	< 1 mm	PYR-GC/MS (selected markers for SBR and BR consisted of m/z 78 Da for benzene, m/z 118 Da for α-methylstyrene, m/z 117 Da for ethylstyrene and m/z 91 Da for butadiene trimer)	4.75–53.1 mg/g
Öborn et al., 2024	Stormwater ponds	20–450 µm	PYR-GC/MS	n.d. –0.0693 mg/g
Johansson et al., 2024	Sediment from the sedimentation chamber	27-1000 µm	PYR-GC/MS (marker ion m/z 93 (limonene) for PI and marker ion m/z 79 (4-vinylcyclohexene) for PB/BR and SBR)	PB: 11 500 µg/kg PI: 142 000 µg/kg

Soil samples				
Müller et al., 2022	German highway roadside soil AADT: 34,000 cars and 2,000 trucks 0.3–5 m from road edge, Depths: 0–0.20 m	<50 µm, 50–100 µm, 100–500 µm, 500–1000 µm	TED-GC/MS (cyclo-hexenyl benzene as a marker for SBR, TWP estimated based on: 11.3% SBR content in tyres)	0.116–15.898 g/kg (based on SBR mass content)
			ICP-OES for estimation based on zinc 11.9 g/kg zinc in tyre powder	0.413– 44.812 g/kg (based on zinc mass content)
Rødland et al., 2023a	16 sites in Norway, Rural roads with vegetation and low traffic, AADT 650–14,250 0 m, 3 m, 5 m, >6 m from road edge Depths: 0.0–0.1 m, 0.1–0.2 m,0.1–0.3 m.	<500 µm	PYR-GC/MS (selected markers for SBR and BR consisted of m/z 78 Da for benzene, m/z 118 Da for α-methylstyrene, m/z 117 Da for ethylstyrene and m/z 91 Da for butadiene trimer)	2.0–26.4 g/kg (mean 11.4 g/kg)
Beaurepaire et al., 2025	Biofiltration lane at the side of the 2x2 lanes highway, Paris AADT: 11,000 in both directions, 50% HDV Depths: 0–0.05 m, 0.05–0.15 m, 0.15–0.25 m, 0.25–0.35 m	<500 µm	PYR-GC/MS (VCH and 4-phenylcyclohexene markers for the combined identification and quantification of SBR and BR)	0–15 g/kg

Table 3. Summary of studies addressing the efficiency of various soils to remove TWP.

Study	**Site**	**Bio retention filter**	**Particle size**	**Analysis method**	**Removal efficiency (%)**
Smyth et al., 2025	Canada	62% sand, 38% silt and clay	106 µm to >1 mm	Stereomicroscopy supported by manual classification based on morphology, colour, texture, and comparison with known anthropogenic characteristics from previous studies	84
Werbowski et al., 2021	USA	70 % sandy loam, 10 % clay, 20 % compost		FTIR for >500 µm and Raman spectroscopy for all others	95
Lange et al., 2021	Sweden	Vegetative sand-based filters		Stereoscopic microscope	97.8
		Non-vegetated sand-based filters			96.9
Johansson et al., 2024	Sweden	Four different types of filters, including materials such as biochar, peat, ash, and sandy loam	10–1000 µm	PYR-GC/MS	99–100

2.3. Environmental effects

2.3.1. Composition and characterisations of TWP

The potential environmental risks associated with TWP are linked to their complex chemical composition, additives, size, morphology, and elemental content, as already mentioned in the introduction. Although the exact formulations of commercial tyres are proprietary, they are generally composed of approximately 50% natural and synthetic rubber, 30% fillers (e.g., carbon black, silica, chalk), 15% oils and resins, and 5% vulcanising agents such as sulphur and zinc oxide (Sommer et al., 2018). A key process in tyre production is vulcanisation that cross-links the rubber chains, forming a three-dimensional network, which improves elasticity and tensile strength. The most commonly used chemical activator for vulcanisation is zinc oxide (ZnO) (Schneider et al., 2005). The different types of tyre fillers are used to reduce the rolling resistance of the tyre (Sommer et al., 2018).

Tyre rubber is typically composed of synthetic polymers such as styrene-butadiene rubber (SBR) and butadiene rubber (BR), as well as natural rubber (polyisoprene, NR) (Wagner et al., 2018). The proportion of natural rubber varies depending on the tyre type: truck tyres generally contain around 30% natural rubber, while car tyres contain approximately 15% (British Tyre Manufacturers Association, n.d.). Tyre formulations differ significantly between brands and intended applications, with hundreds of proprietary recipes tailored to performance requirements. For example, winter tyres are generally softer than summer tyres, and manufacturers optimise their products not only to comply with European tyre labelling regulations, covering rolling resistance, wet grip, and noise, but also to meet consumer expectations. The polymer content, particularly in relation to tyre hardness, has been suggested as a key performance parameter. Harder tyres, such as summer variants, are primarily composed of synthetic rubber and show limited variation in rubber blend (natural vs. synthetic elastomers) across brands (Matsson et al., 2023). In contrast, winter tyres exhibit considerable variability in composition between brands, with some dominated by natural rubber and others by synthetic rubber. Furthermore, differences between tyre brands of the same type (e.g., studded vs. studless winter tyres) are often more pronounced than differences within a single brand.

In environmental samples, TWP are often found with mineral and metal encrustations (Järlskog et al., 2022a, b). These metals, originating from brake and road surface wear, can form coatings around TWP, accounting for 10–50% of the particle volume depending on traffic conditions such as speed and flow (Sommer et al., 2018). Metals are primarily derived from rubber wheels, vehicle components and road abrasion. Several of these metals, such as Cd, Pb, and Zn, are assumed to have moderate to high bioaccessibility, which is usually affected by factors such as pH, hardness, dissolved organic carbon (DOC)/organic matter, and redox conditions. Once exposed, metals have varying acute and chronic effects on humans. Lead and Hg have been shown to negatively impact the nervous, digestive, and reproductive systems (Mashyanov et al., 2017; Pratush et al., 2018; Vöröš et al., 2018). Cadmium, Cu, and Cr are associated with harmful effects on the intestinal tract, circulatory system, and lungs (Izah et al., 2016; Nordberg et al., 2018). Meanwhile, exposure to Zn, Ni, and As can result in damage to the cardiovascular system, liver, and genetic material (Xu et al., 2017; Sanchez et al., 2018; Stefanowicz et al., 2020).

Particle size distributions of TWP have primarily been studied through laboratory-based road simulation experiments. These distributions are typically categorised by number, volume, or

mass, depending on the study's focus. For health-related assessments, particle number may often be more relevant, as smaller particles can penetrate biological tissues such as the lungs and plant surfaces. Their high surface area-to-volume ratio also increases their potential to act as vectors for other pollutants. In contrast, for environmental impact assessments, particularly when chemical toxicity is a concern, mass-based distributions may be more informative. Environmental degradation processes can further alter particle size, potentially increasing their mobility and bioavailability. Thus, TWP pose environmental risks due to both their complex chemical composition (discussed in the next chapter) and their small particle sizes.

Previous studies have shown that TWP mass size distributions often follow a bimodal pattern (Beddows et al., 2023; Fauser et al., 2002), with particles smaller than 1 μm accounting for more than 90% of the total mass (Fauser et al., 2002). Mass peaks have been observed at 0.1–0.6 μm and 1.0–15 μm (Beji et al., 2021; Kwak et al., 2014), while number peaks typically occur at <0.03 μm and 0.05–0.30 μm. A recent study found that TWP in snow samples may exhibit either single or bimodal mass distribution peaks, with diameters ranging from 0.6 to 4 μm. Variability in particulate wear was also observed across different tyre brands (Zhang et al., 2025).

A recent road-simulator study compared TWP generated by summer, studded, and studless winter tyres. It found that studded tyres produced smaller particles than the other types, although these particles were less elongated than typical TWP (Matsson et al., 2023). The typical size range of simulator-generated tyre road wear particles (TRWP) was smaller than 200 μm. The same study reported that Chinese all-terrain tyres had the highest wear emissions, with particulate matter with a diameter ≤ 2.5 μm and ≤ 10 μm ($PM_{2.5}$ and PM_{10}) levels exceeding those of snow tyres by 1.4 times and all-season tyres by 1.6 times. The authors attributed the larger particle sizes of snow tyre wear to their softer and stickier rubber compounds under laboratory test conditions (Zhang et al., 2025).

The size of TWP is an important factor influencing their transport pathways and eventual accumulation sites, whether through stormwater systems or roadside soils. Despite the importance of this parameter, most studies have been conducted under laboratory conditions. Only a limited number have examined TWP size distributions in runoff, and even fewer have investigated their presence in soil. To our knowledge, no studies have yet assessed TWP size distributions across different locations within stormwater systems.

2.3.2. Tyre-derived chemicals

In addition to the main components of tyres, natural rubber and synthetic rubber polymers, tyres also contain tyre-derived chemicals (TDC), also known as tyre-related emerging contaminants (TREC) or additives. These chemicals constitute approximately 5–10% of the total mass (Meland et al., 2024), and are introduced during tyre manufacturing, playingan important role in determining tyre performance and durability (Baensch-Baltruschat, 2020; Wagner et al., 2018; USTMA, n.d.). Tyre-derived chemicals include a wide range of functional additives such as preservatives, antiozonants, antioxidants, desiccants, plasticisers, and processing aids (Ghanadi et al., 2025), which contribute to essential performance characteristics like road grip, fuel and energy efficiency, and noise reduction (USTMA, n.d.)

Tyres typically contain several classes of TDC, including p-phenylenediamines (e.g., 6PPD, 7PPD, IPPD, CPPD, DPPD), benzothiazoles (e.g., ABT, OHBT, MBT, PhBT, BTSA), and

phenylguanidines (e.g., DPG). Other compounds, such as hexamethoxymethylmelamine (HMMM) and quinone derivatives (e.g., TMQ and 6PPDQ), are also commonly present (Meland et al., 2024; Wang et al., 2024) (Table 4). Recent studies found rubber-derived additives and their transformation products in various environmental compartments, including soil, air, and water (Cao et al., 2022; Ghanadi et al., 2025; Kuntz et al., 2024), as well as in snow (Seiwert et al., 2022) and sediments from urban rivers, estuaries, coastal zones, and deep-sea environments (Zeng et al., 2023). Environmental studies investigating the distribution and fate of tyre leachates have primarily focused on a limited number of compounds. Among the most frequently detected TDC are tyre additives such as dibenzylamine, dicyclohexylurea, DPG, diphenylurea, HMMM, 2-mercaptobenzothiazole, and tributylamine, along with known transformation products including benzothiazole-2-sulfonic acid (BTSA), phenylguanidine, and 6PPDQ (Müller et al., 2025). However, recent screening studies of tyre leachates have identified over 150 organic compounds potentially released from tyres, of which approximately 60% remain unidentified. Moreover, environmental ageing of tyre and road wear particles (TRWP) has been shown to significantly alter leachate composition, shifting it from parent compounds to transformation products (Weyrauch et al., 2023). Despite these findings, the identification and environmental monitoring of transformation products remain limited, with most studies focusing on a few well-known compounds such as HMMM, 6PPD, and 6PPDQ (Müller et al., 2025).

The environmental significance of these findings is closely linked to the toxicological properties of TDC and their degradation products. For instance, Wang et al. (2024) recently assessed the ecotoxicity of 18 emerging p-phenylenediamine quinones (PPD-Q) and their parent compounds, finding that several PPD-Q exhibited significantly higher toxicity than the well-studied 6PPD-Q. Bioluminescence inhibition assays revealed effective concentration 50% (EC_{50}) values for PPD-Q ranging from 1.76 to 15.6 mg/L. Additionally, the studied additives were found to be highly toxic to aquatic organisms, with EC_{50} values ranging from 0.02 to 7.07 mg/L. Predicted toxicity profiles for many photolytic phenylenediamine transformation products suggest potential carcinogenicity, immunotoxicity, and other adverse effects, highlighting the need for further research and regulatory attention to mitigate their environmental impact in aquatic systems.

Despite growing awareness, several research gaps remain. These include the long-term effects of chronic exposure to TWP and TDC, their interactions with co-occurring contaminants, and their transformation pathways in various environmental matrices (Ghanadi et al., 2025). Future research should prioritise the development of improved analytical techniques to distinguish between particle-bound and dissolved-phase contaminants, assess cumulative toxicity, and explore mitigation strategies such as optimised tyre formulations and enhanced stormwater treatment technologies. Although soils are likely the largest environmental reservoir for TWP and associated tyre and road wear compounds TDC, most existing studies have focused on their occurrence and effects in aqueous media, airborne dust, and aquatic ecotoxicity. This highlights a critical need for further investigation into the behaviour, fate, and ecological risks of TDC in soil environments. In light of climate change, prolonged droughts followed by intense rainfall events may pose significant risks, as large quantities of accumulated TWP and additives in ditches and bioretention filters could be released into the environment. Addressing these knowledge gaps is essential for advancing risk assessment frameworks and informing regulatory measures aimed at reducing the environmental and human health impacts of tyre-derived pollution.

Table 4. Chemical structures and applications of common tyre-derived compounds (TDC). The chemical structure diagrams were retrieved from PubChem. This table is original and not reproduced from any published source. For a comprehensive review of the characteristics and environmental relevance of recently studied TDC, readers are referred to Ghanadi et al. (2025).

Abbreviation	IUPAC name	Structure	Parent/transformation compound and its use in tyres
6PPD	N^1-(4-Methylpentan-2-yl)-N^4-phenylbenzene-1,4-diamine		Common antiozonat (Antioxidant to prevent tyres from breaking down due to reactions with ozone and other reactive oxygen species in the air)[a,b]
6PPD-Q	2-((4-Methylpentan-2-yl)amino)-5-(phenylamino)cyclohexa-2,5-diene-1,4-dione		An oxidation product of 6PPD (e.g. a reaction with ozone)[b,c]
DPPD	N^1,N^4-Diphenylbenzene-1,4-diamine		Common antiozonat[a]
IPPD	N^1-Phenyl-N^4-(propan-2-yl)benzene-1,4-diamine		Common antiozonat[a]
CPPD	1-N-cyclohexyl-4-N-phenylbenzene-1,4-diamine		Tyre protective additive[e]
7PPD	4-N-(5-methylhexan-2-yl)-1-N-phenylbenzene-1,4-diamine		Common antiozonat[a]
HMMM	N^2,N^2,N^4,N^4,N^6,N^6-Hexakis(methoxymethyl)-1,3,5-triazine-2,4,6-triamine (or Hexamethoxymethylmelamine)		Quality improvement[d]
DPG	N,N′-Diphenylguanidine or (1,3-diphenylguanidine)		Vulcanization accelerator[d]
TMQ	2,2,4-Trimethyl-1,2-dihydroquinoline		Tyre protective additive[d]
MTBT	2-(methylthio)-1,3-benzothiazole		(derivateve of MBT) Vulcanization accelerators[e]
PhBT	2-Phenyl-1,3-benzothiazole		Vulcanization accelerator[f]
MBT	1,3-Benzothiazole-2(3H)-thione (or 2-Mercaptobenzothiazole)		Vulcanization accelerators[e]
BTSA	1,3-Benzothiazole-2-sulfonic acid		Oxidation product of benzothiazole, MBT and OHBT[c]
OHBT	1,3-Benzothiazol-2-ol (or 2-hydroxybenzothiazole)		Vulcanization accelerator[e]

[a] - Wagner et at. 2022; [b] - U.S. Environmental Protection Agency. (n.d.); [c] - Foscari et al., 2024; [d] - Zhang et al., 2023; [e] - Zhang et al., 2018; [f] - Meland et al., 2024

2.4. Potential measures

A variety of measures can contribute to the reduction of the emissions and spread of microplastics from tyre wear (Johannesson & Lithner, 2022; Andersson-Sköld et al., 2020). Broadly, these measures fall into four categories:

1. Source Reduction – aimed at preventing the generation of TWP.
2. Spread Mitigation – focused on limiting the dispersion of particles once generated.
3. Reduction of TWP, effects and persistence
4. Increasing general/public knowledge

According to Johannesson & Lithner (2022), who mapped and prioritized potential policy instruments and measures to address microplastics from tyre and road wear, the most relevant strategies include: reducing road traffic (vehicle-kilometres), promoting eco-friendly driving behaviour, regulating tyre wear propensity maintaining optimal tyre pressure and wheel alignment, regulating of hazardous substances, developing technologies to collect of tyre particles while driving, developing and sustainable manage stormwater from roads, and enhancing knowledge to enable assessment of risks and the need for action.

Due to the high volume of national TWP emissions, regulatory attention is increasing. The European Union's Euro 7 emissions standard, adopted in 2024 and set to take effect between 2025 and 2030, is the first to include non-exhaust emissions such as brake dust and tyre particles under its scope (Regulation (EU) 2024/1257 (European Parliament and Council of the European Union, 2024); LIPPER, 2025). Additionally, the Working Party on Noise and Tyres of the UNECE's World Forum for Harmonization of Vehicle Regulations (WP.29) adopted a proposal to introduce two methods to measure tyre abrasion under UN Regulation No. 117 (UNECE., 2024). These developments mark a significant step toward addressing microplastic pollution from road traffic at both European and international levels. Also, TWP contamination and its associated risks may be directly connected to several United Nations Sustainable Development Goals (SDGs): Sustainable Cities and Communities, Responsible Consumption and Production, Life Below Water. In particular, the Foresight Brief No. 034 titled "Vehicle tyre particles in the environment" identifies TWP as one of the most abundant types of primary microplastics discharged into the environment (United Nations Environment Programme, 2024). They briefly discuss their environmental degradation, chemical release, and relevance to SDG targets, especially those related to water quality and marine pollution. In Sweden, TWP contamination is indirectly addressed through several national environmental quality objectives, including A Good Built Environment, Clean Air, A Non-Toxic Environment, Flourishing Lakes and Streams, Groundwater of good quality, and potentially Balanced Marine Environment, Thriving Coastal and Archipelago Areas and Reduced Climate Impact. These goals may be relevant due to TWP's contribution to urban contamination, marine microplastic contamination, and transport-related environmental impacts.

The measures that would be appropriate for already generated traffic-related TWP vary depending on their transport matrices (air, stormwater, or soil) and environmental pathways. The transport of TWP from their sources to the environment is highly complex and influenced by multiple pathways and environmental conditions (Andersson-Sköld et al., 2020) Tyre wear particles may be transported through surface runoff from impermeable surfaces that may be

directed directly to creeks and recipients without treatment, or to separate stormwater treatment systems such as stormwater ponds, infiltration ditches and bioretentionfilter, and in older parts of larger cities also by combined sewer systems to wastewater treatment plants. Large amounts of the TWP are transported by air and after surface deposition on soils and vegetation, further by runoff as described above. To reduce particle loads entering stormwater treatment systems, improve air quality and urban hygiene, street sweeping is widely practised and evaluated in multiple international studies (Amato et al., 2010; Järlskog et al., 2020; Polukarova et al., 2020; Das and Wiseman et al., 2024; California Department of Transportation, 2025). Furthermore, the proper handling of polluted snow may be relevant since the abundance of MP and TWP has been demonstrated in various studies (Gaggini et al. 2025b; Vijayan et al., 2022; Blomqvist et al., 2023; Rødland et al., 2022b). Another promising approach involves the use of Sustainable Drainage Systems (SuDS), such as bioretention systems (e.g., rain gardens) and filter-based systems, as studied by Neupert et al. (2025) and Vegnhaus et al. (2023). These systems have demonstrated high removal efficiencies for various traffic-related contaminants (e.g., metals, organic pollutants, microplastics, nutrients, and suspended solids) (Biswal et al., 2022; Vijayaraghavan et al., 2021; Johansson et al., 2024; Beryani et al, 2025; Lange et al., 2023; Smyth et al., 2021). Today, the bioretention facilities to retain traffic contaminants have mostly been implemented nearparking lots (double-check). However, the actual removal of TWP in bioretention systems has mostly been evaluated in laboratory settings, controlled test facilities, such as by Johansson et al. (2024) and Lange et al. (2020;2021), or modelling studies. Also, to our knowledge, no studies have examined the performance of bioretention systems under winter weather conditions. This represents a notable gap in the literature, as the sorption behaviour of biofilter materials may vary with seasonal and climatic changes. Field-based studies assessing TWP removal under real-world conditions are still limited and urgently needed to validate their effectiveness in detail. In rural or less-maintained areas, TWP are more likely to spread through: roadside soil and ditches, groundwater infiltration and airborne transport. Here, sedimentation and infiltration ponds are the most commonly used mitigation measures today. However, few studies have specifically evaluated their effectiveness in capturing TWP.

3. METHODS AND MATERIALS

This research has been based on several research methods, including field studies, laboratory experiments and theoretical estimations. The results from the field and laboratory have both qualitative and quantitative character.

3.1. Theoretical estimations of national TWP emissions

To improve the accuracy of TWP emission estimates in Sweden, field measurements were conducted for passenger cars (PC) and light-duty vehicles (LDV), while a literature-based approach was used for heavy-duty vehicles (HDV) and buses (Paper I). Over 1,000 discarded PC and LDV tyres were collected from recycling and tyre replacement stations in/around Stockholm. Most winter tyres were sourced from a major recycling facility covering Mideastern Sweden (Figure 1).

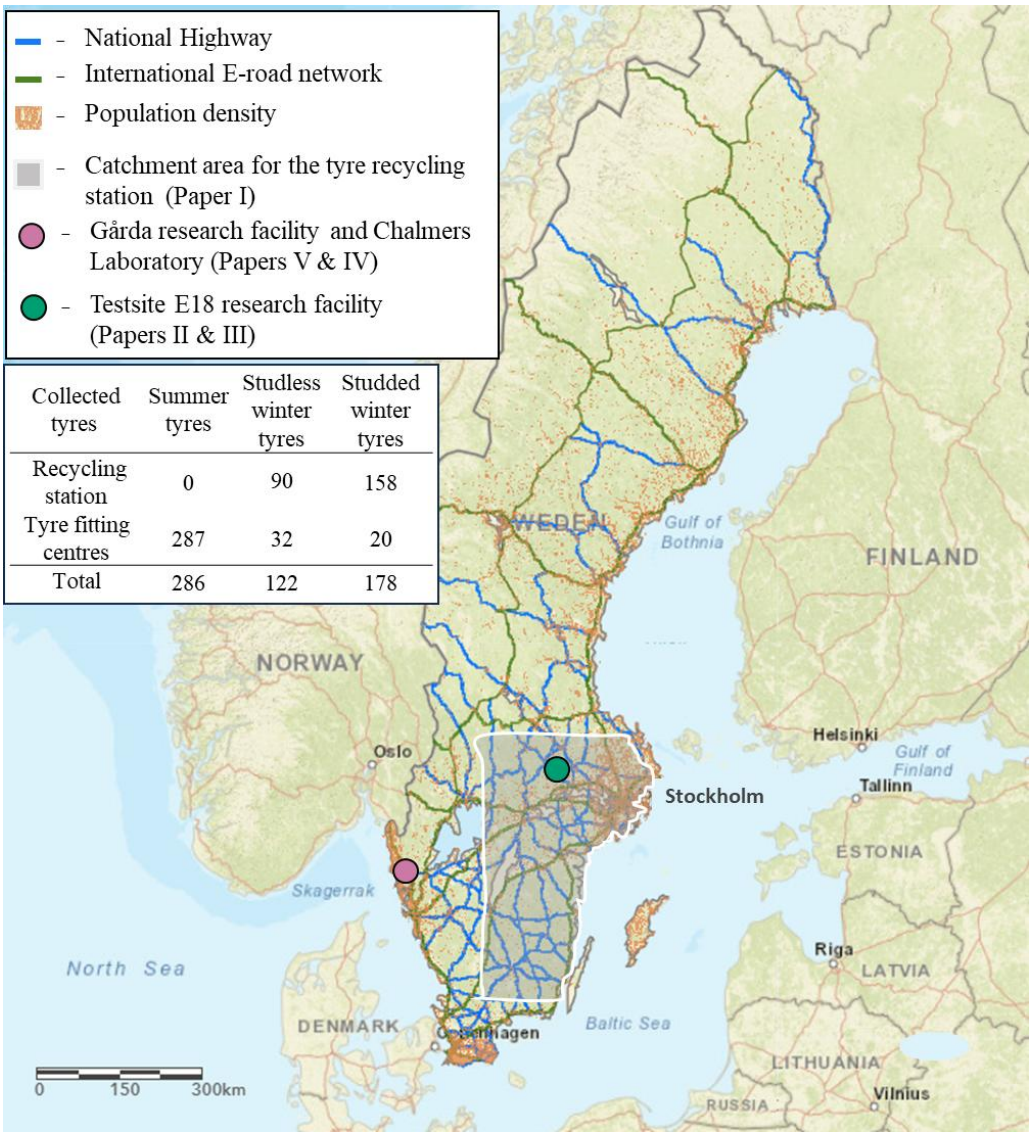


Figure 1. Sampling areas of the measured tyres (Paper I) and field measurement areas Testsite E18 (Papers II and III) and Gårda research facility (Paper V), as well as the Chalmers Laboratory (Gothenburg), where the experiments for Paper IV were conducted. The map layers for population density and road network were derived from Swedish Statistics 2017 and from data from the Swedish Transport Administration (Source: acrgis.com).

Tyre wear was estimated by comparing the measured weight of used tyres to their assumed original weight, and tyre lifespan was approximated based on the assumption that tyres were used until the date of collection. Emission factors derived from these measurements were scaled to different road types using proportional adjustments based on Dutch road-type distributions. For LDV, emission factors were scaled from PC values using the ratio of average curb weights. These adjusted factors were combined with national mileage data using the general equation:

$$E=EF\cdot D\cdot N$$

where:

E = total emission,
EF = emission factor (g/km),
D = average distance travelled per vehicle, and
N = number of vehicles

Further methodological details are provided in Paper I.

Direct measurement of HDV and bus tyre wear was not feasible due to the weight of the tyres and the widespread use of retreading, which complicates the estimation of actual lifespan. In the absence of Swedish-specific data, emission factors from Geilenkirchen et al. (2020) were used and differentiated by road type (urban, rural, highway). These were adjusted to Swedish conditions using national statistics on HDV fleet composition, vehicle types, and gross vehicle weights. While this literature-based approach introduces greater uncertainty compared to direct measurement, it provides a necessary approximation. This highlights the need to develop robust, locally adapted methods for quantifying HDV tyre wear. To validate the national emission estimates, a secondary method, the sales/recycling approach, was applied. This method combines tyre sales or recycling data with average lifetime mass loss per tyre (Blok, 2005), offering a less detailed but useful cross-check of the primary estimates.

3.2. Field sampling areas

The sampling aiming to determine the occurrence and distribution of TWP in stormwater systems and in roadside soil was conducted at Testsite E18 (59°38'01.9"N 16°51'18.7"E), a research facility owned by the Swedish Road Administration alongside the highway E18 (Papers II and III), and at the Gårda sedimentation facility (Paper V), see also Figures 1 and 2. The sampling locations were selected because both facilities have historically served as sites for environmental research (Järlskog et al., 2022a; Svensson et al., 2022; Nielsen et al., 2015; Björklund et al., 2009), offering access to detailed facility drawings and the logistical possibility of temporarily closing road traffic during sampling activities. The contaminant concentration in runoff from the highway adjacent to Testsite E18 is expected to be lower, as its annual average daily traffic (AADT) is several times lower than that of the highway near the Gårda sedimentation facility, which also has an appropriately eight times higher proportion of heavy-duty vehicles contributing to pollutant loads. Testsite E18 research facility has both an area simulating the urban runoff, where the stormwater is collected with gully pots and directed to the wells through an underground pipe system, and an area simulating natural runoff in a non-urban environment, where the stormwater flows directly into road ditches (Figure 3 and 3). The sampling site is described in detail in papers II and III and studies conducted by Gaggini et al. (2025a,b).

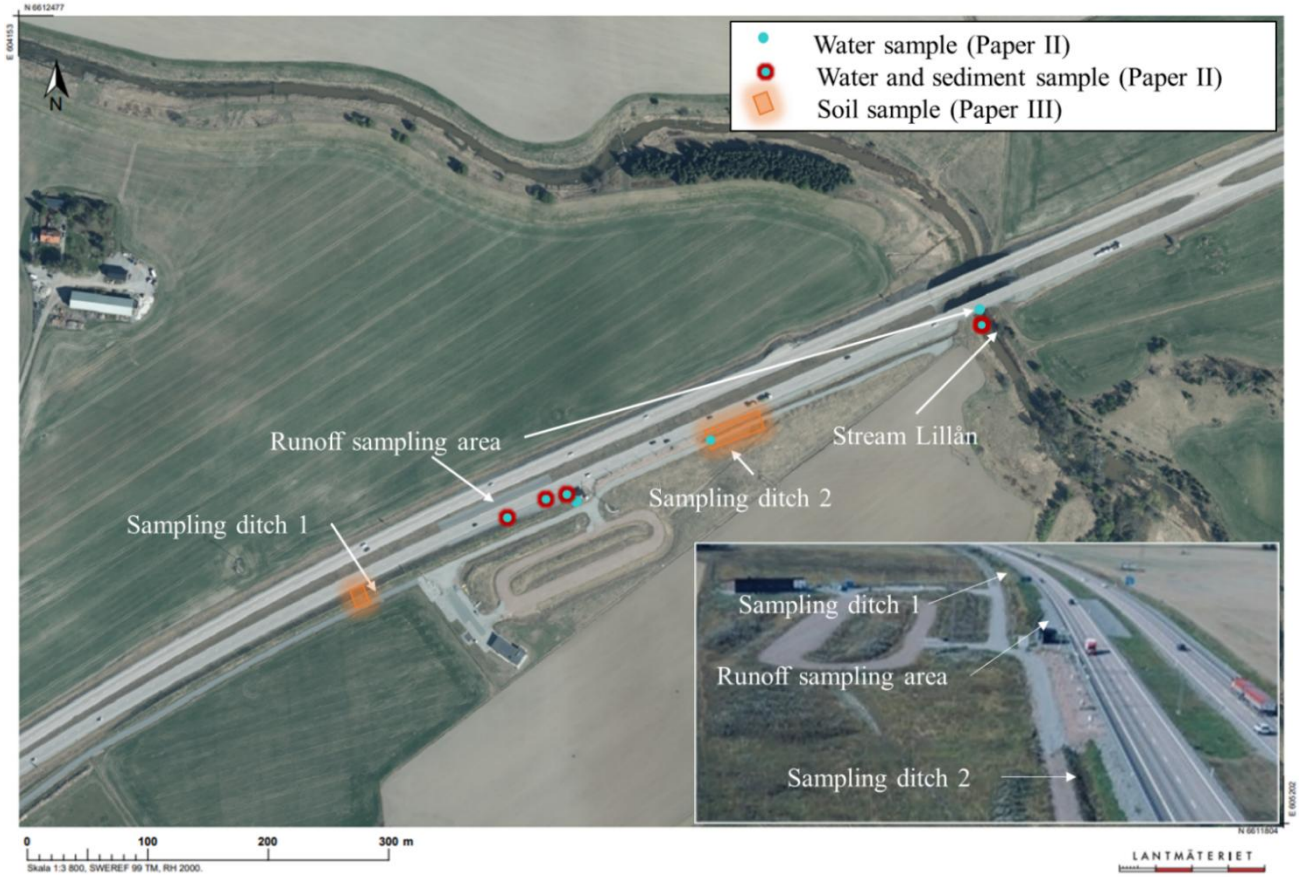


Figure 2. Samples on Testsite E18 collected between November 2022 and June 2023. Map adapted from the Land Survey. The water samples for Paper II were collected in the collecting well and as direct runoff from the opening in the bridge above and in the river Sagån. The sediment samples for Paper II were collected in the gully pots and in the river Sagån.

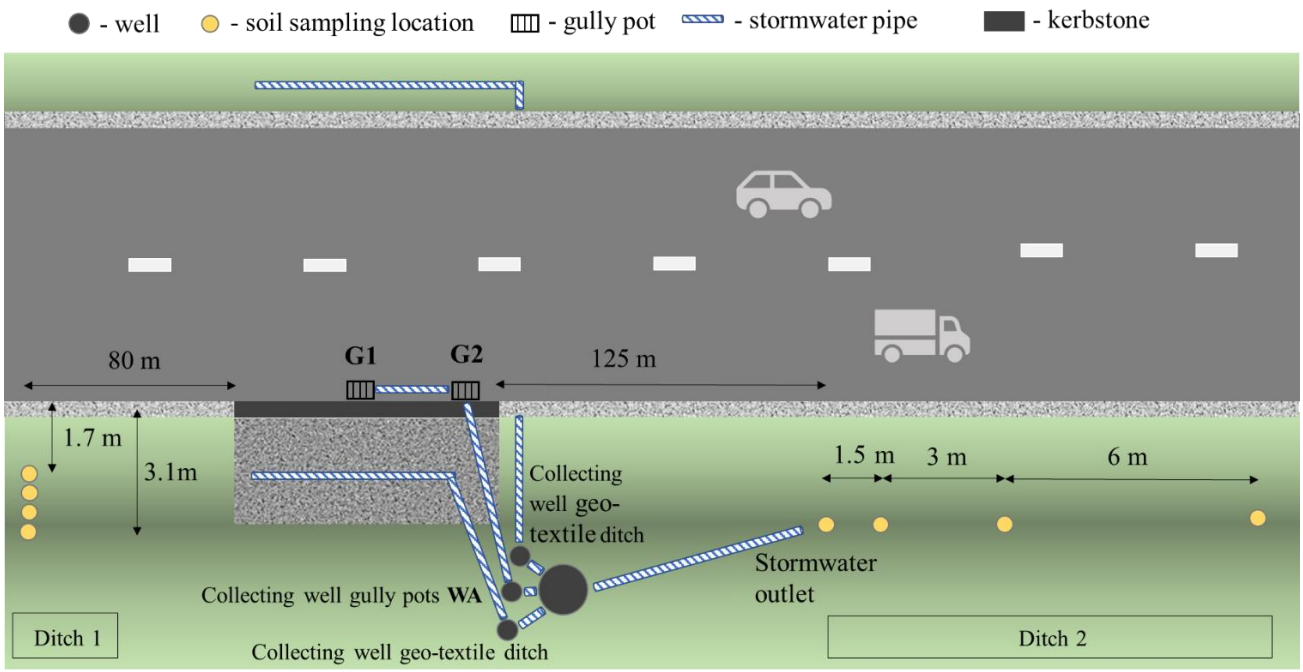


Figure 3. Site description and soil sampling locations at the Highway E18 research station. Soil samples were collected at the sampling points, represented by yellow dots, at four different depths (0.1–0.2m, 0.2–0.3m, 0.3–0.4m and 0.4–0.5m).

Water sampling at Testsite E18 (Paper II): Grab water samples for Paper II were collected from the standing water in the collecting wells, Ditch 2 and the stream, Sagån (Figure 3). Furthermore, a direct runoff sample was collected when a light rain started, placing a bucket under the drainage opening in the bridge above the river Sagån. Grab sampling was considered a suitable and sufficient method for stormwater sampling in this study, as the primary aim was to assess the occurrence of TWP in different parts of the stormwater system. While ISCO samplers may be more appropriate for studies focusing on contaminant concentrations during specific rainfall events or depths, grab sampling was deemed adequate for the qualitative screening approach used in this study.

The sediment samples from Testsite E18 for Paper II from a gully pot and well A were collected using an Ekman sampler. Sediments from the stormwater outlet by Ditch 2 were collected with a metal trowel, and from the Lillån river using a core sampler. These samples were collected to enhance understanding of how TWP are transported, settle and accumulate within different components of the stormwater system.

Soil samples from Testsite E18 for Paper III was collected alongside Ditch 1 as a transect at four different distances from the road edge to the road ditch bottom (1.7 ± 0.1 m, 2.1 ± 0.1 m, 2.5 ± 0.1 m, and 3.1 ± 0.1 m,) and in Ditch 2 at four different distances from the stormwater pipe outlet (0 m, 1.5 m, 3 m, 6 m) along the bottom of the ditch. This was done to determine the TWP spreading in the depth of the ditches and with the distance for Ditch 1 from the road, and Ditch 2 from the stormwater outlet.

At each sampling location, soil samples were collected at four depth intervals: 0.1–0.2 m, 0.2–0.3 m, 0.3–0.4 m, and 0.4–0.5 m. Sampling was primarily carried out using a motorised auger drilling machine, which is capable of penetrating a wide range of soil types and reaching greater depths than a manual hand auger. The motorised auger also provides more consistent and

precise sampling due to its uniform power application. However, near the outlet pipe, a hand auger was used to avoid the risk of damaging the surrounding infrastructure. The choice of soil sampling method generally depends on several factors, including the purpose of sampling (environmental or geotechnical), soil type, space constraints, and whether it is acceptable to disturb nearby structures such as roads. In this study, excavating a test pit was not feasible due to potential impacts on road safety, load-bearing capacity, and drainage performance. Instead, a transect sampling approach was adopted to provide an overview of the spatial distribution of contaminants across the road ditch. The soil in the road embankment consisted of dense material built using dry clay sourced from the surrounding area during road construction. Due to its compact nature, sampling with a hand auger was not feasible at deeper depths, making the motorised auger essential for obtaining samples throughout the profile. However, a drawback of the motorised auger in dry soils is its lower sensitivity and control, which increases the risk of material falling off the drill during extraction. This fallen material can mix with deeper layers, potentially contaminating samples from the lowest depth interval (as indicated by potential signs that the deepest sample contained material from upper layers). Further methodological details are provided in Papers I and III.

The Gårda research facility is situated alongside a stretch of the E6 highway (AADT 85,000–100,000, where 11% is heavy-duty vehicles (Swedish Transport Administration) in Gothenburg (Paper V). The runoff sampled was collected (by pumping) from a sedimentation treatment facility receiving runoff from urban catchment areas of 5.1 hectares, 2.1 hectares of which had impervious surfaces made of roads (82%), roofs (6%) and other impervious areas (12%) (Markiewicz et al., 2020a; Björklund et al., 2009). The stormwater treatment facility in Gårda consists of a series of seven sedimentation chambers, with the first chamber being the source of the stormwater used in this study. Contaminant concentrations entering the Gårda sedimentation facility, as well as those reaching the stormwater system and roadside ditches along Testsite E18, were expected to vary depending on the accumulation of pollutants on highway and urban surfaces. This accumulation depends on the deposition rate, the length of the preceding dry period, and processes such as resuspension, aggregation, and re-deposition (Opher and Friedler, 2010). The build-up process is affected by various natural factors, including climate, as well as human-related factors such as traffic volume, congestion, vehicle speed, vehicle types, and land use.

3.3. Laboratory study and pilot facility

Experiments to investigate the retention and transport of TWP through different soil types were conducted at two scales: in a controlled laboratory setting using ten soil-filled columns (Paper IV), and at a larger scale in a rain garden pilot facility (Paper V), located besides the highway E6 and the sedimentation facility mentioned above, and further described in Johansson et al. (2024). The ten soil-filled columns and the rain garden pilot facility are illustrated in Figure 4.

Figure 4. Investigations of the retention and transport of TWP through different soil types were conducted at two scales: at a larger scale in a rain garden pilot facility (Paper V) at Gårda with bioretention filters with different sorption materials, and in a controlled laboratory setting using ten soil-filled columns with and without biochar and grass in the top layer (Paper IV).

The laboratory study aimed to simulate TWP transport through road ditch soils typical of Swedish conditions. In contrast, the rain garden pilot facility experiments (Paper V) focused on evaluating how high volumes of stormwater, in combination with cold weather conditions, influence the removal and mobility of TWP in bioretention filters. These filters incorporated dormant vegetation and various sorption materials to reflect seasonal and functional variability in field conditions. The filling of the bioretention filters in the field was different to the columns in the laboratory, which were filled with less organic soils and with only biochar tested as sorption material. Furthermore, five out of ten columns in the laboratory had grass vegetation using an *Ängsfröblandning*, which is specifically composed to suit the Swedish roadside environment (Vegtech n.d.). In contrast, the bioretention filter columns in the field pilot had dormant plants such as common rush (*Juncus Effusus*), thrift (*Armeria maritima*), sea buckthorn (*Hippophae rhamnoides*) and red fescue (*Festuca rubra*) selected to optimise the pollutant retention, withstand short drought and floodings, and/or improve soil bed substrate conditions for microorganisms (Johansson et al., 2024).

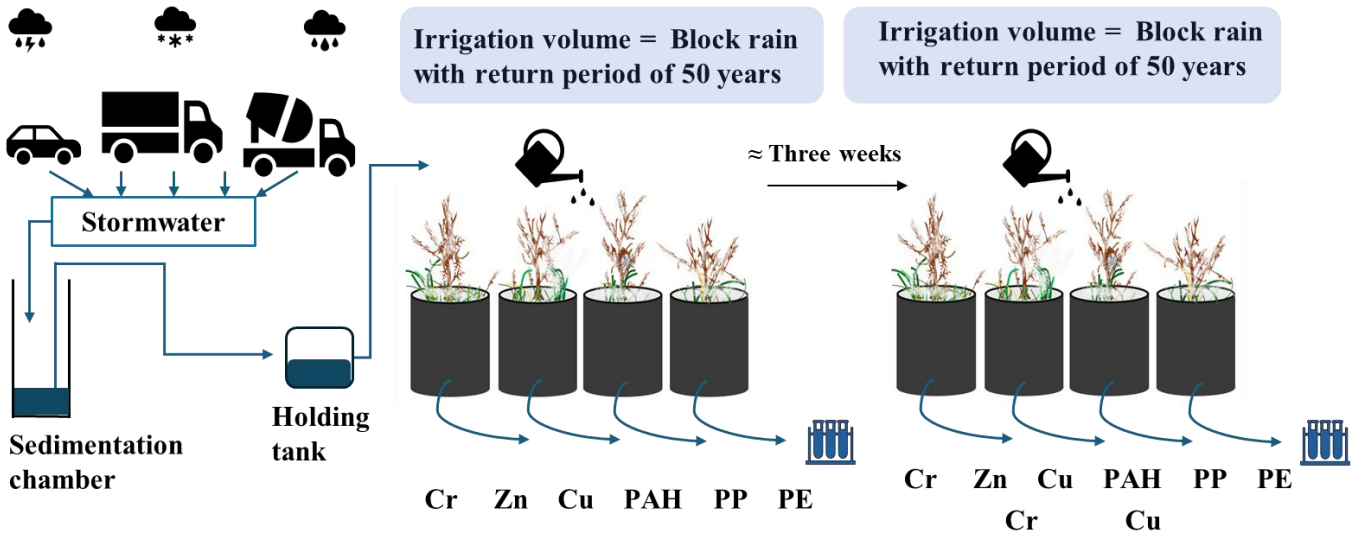


Figure 5. Overview of the rain garden pilot study in Gårda (Paper V). Four different columns (Ash, Biochar, Peat, Control) were irrigated with runoff collected from a nearby sedimentation facility. The irrigations simulated an extreme precipitation event (two 50-year rainfall events) (Paper V).

At the Gårda pilot facility, four bioretention columns with distinct material compositions were studied (Paper V), see Figure 5. The ash column consisted of a mixture containing 50% municipal incinerator bottom ash (MIBA) and 15% compost. The biochar column was filled with a blend of 60% Hekla Regnbädd and 40% biochar, while the peat column contained 60% Hekla Regnbädd and 40% *Sphagnum* peat. The control column was composed of 85% Hekla Regnbädd and 15% compost. These sorption materials were selected based on previous research conducted at Chalmers University and by other research groups, which demonstrated their effectiveness in retaining a wide range of pollutants commonly found in stormwater (Kalmykova et al., 2008; Markiewicz et al., 2020b; Biswal et al., 2022; Silva et al., 2017). In addition to the main bioretention layer, each column was amended with a thin layer of only sorption material placed below it: the biochar column included a biochar layer, the peat column a peat layer, and the ash column was supplemented with both a thin peat layer and a biochar layer. All four types of columns also had a top layer consisting of Hekla Regnbädd soil mixture and four drainage layers. The collected samples included influent and effluent to/from the columns, as well as pore water (>1.2 µm particles) One of the samplers was installed in the soil sorbent mix at 0.45 m depth, and the other below the pure sorbent layer at a depth of 0.85 m. Effluent samples were collected three times for each sampling occasion: the first after the addition of 100 L of stormwater on top of the filters, the second after 360 L, and the final after 500 L. The simulated extreme rainfall event campaign occurred between January 23rd and March 14th, 2023, and selected filters were subjected to two cycles of simulated rainfall, each corresponding to an approximate 50-year rainfall event. According to the Swedish Meteorological and Hydrological Institute (SMHI), precipitation in Sweden is expected to increase on average in the future, and the highest average increase in precipitation is expected during winters (Swedish Meteorological and Hydrological Institute, 2025). Therefore, the campaign period in this study represented multiple conditions that can impact the performance of bioretention filters, such as dormant vegetation, elevated salt ion concentrations from de-

icing salts, increased traffic-related pollutant concentrations due to cold weather and the use of studded tyres.

3.3.1. Column study

The laboratory columns "simulating road ditches" were irrigated with 6 litres of stormwater on 13 occasions over several months, with decreasing frequency over time, see Figure 6. This irrigation volume corresponds to a rainfall depth of approximately 122 mm, based on the column surface area of 0.049 m², representing an extreme precipitation event. The chosen volume was necessary to ensure sufficient outflow for chemical analyses and to allow the irrigation-sampling cycle to be completed within a one-week period.

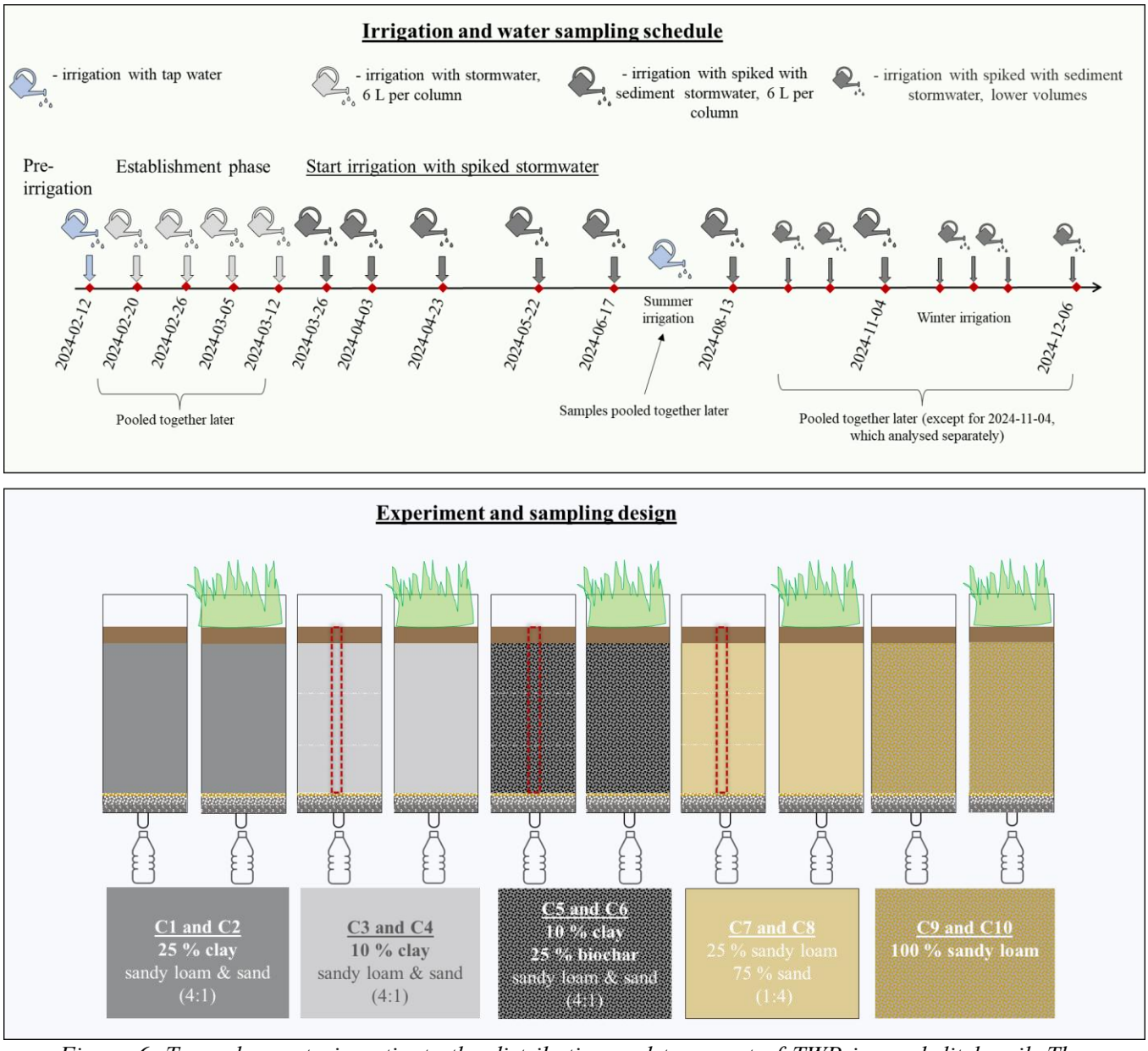


Figure 6. Ten columns to investigate the distribution and transport of TWP in road ditch soil. The experiment lasted from the beginning of 2024 to the end of 2024. Ten columns filled with 5 different types of soil mixtures and covered by a topsoil layer were irrigated with water (blue watering can - tap water; light, grey-coloured watering can - stormwater, dark-coloured grey watering can - stormwater spiked with runoff sediment.

Although all columns had the same filling level, they contained different soil mixtures, which affected their hydraulic properties. Therefore, the irrigation volume was approximated, but equal volumes of stormwater were added to all columns to ensure consistent and adequate outflow across all columns, enabling smooth sampling and analysis. From the fourth event onward, stormwater was spiked with 0.1 litres of sediment from the Gårda sedimentation facility to ensure TWP concentrations remained above the analytical limit of quantification (LoQ). Sediment was collected from the Gårda sedimentation chambers using a grab sampler and mixed into the influent before irrigation. Prior to irrigation with stormwater, each column was flushed with 6 litres of tap water (2024-02-13) to assess potential leaching from the column materials. During the summer period (2024-06-17 to 2024-08-13), columns were maintained with irrigation of 0.5 litres of tap water weekly to support vegetation, referred to as "summer sampling." Between the beginning of September and 2024-12-06, five additional irrigation events were conducted using 0.3–1.2 litres of stormwater spiked with sediment (10% of the stormwater volume). Effluent samples from these events were pooled for analysis and are referred to as "winter sampling." As illustrated in Figure 6, the frequency of irrigation decreased over the study, which was designed to simulate drought periods of different lengths. After each irrigation, the effluent from each column was collected and analysed for the occurrence of TWP, metals, TSS, TOC, DOC, and monitored for different water parameters such as conductivity. Influent samples were analysed for TWP in duplicate due to limited filtered volume, whereas effluent samples were analysed as single replicates for each irrigation event. Winter sampling influent and effluent were analysed for TDC in five non-vegetated columns (C1, C3, C5, C7, C10). These were analysed as single replicates, but TDC were determined for both total and dissolved phases.

Soil samples were collected before and after the experiment from three non-vegetated columns (C3, C5, C7), representing clay-rich soil, biochar-amended clay, and sand. Sampling targeted the top layer and the main layer, which was further divided into three sublayers to assess vertical distribution and mobility of TWP and metals. The top and main layers of these columns were also analysed for TDC (one replicate per sample). Post-experiment soil samples were collected from the top layer (0–0.05 m) and three depths within the main layer (0.05–0.20 m, 0.20–0.35 m, 0.35–0.50 m). Post-experiment soil samples from the top layer were analysed for TWP in triplicate, and the main layer in triplicate as well, with one replicate per sublayer. Pre-experiment soil samples from the top layer were analysed in duplicate, and those from the main layer in triplicate. Soil samples from the top layer were also analysed for metals in triplicate, while the main layer was analysed in triplicate as well, with one replicate per sublayer. In contrast, pre-experiment soil samples were analysed for metals using a single replicate.

Further details on the sampling and analysis methodology are provided in Paper IV.

As illustrated in Figures 5 and 6, experiments designed to investigate the retention and transport of TWP through various soil types or sorbents can be conducted either in controlled laboratory settings or using a pilot-scale facility. Laboratory studies offer easier maintenance and operational control; however, they are limited in their ability to replicate realistic environmental conditions, such as ambient temperature, humidity, precipitation frequency, volume, and water quality. Given Sweden's variable climate, characterised by cold winters, warm summers, and relatively frequent but mild rain events, these factors must be considered not only in the design of bioretention facilities but also in the planning of road ditches. A pilot-scale study offer the advantage of more realistic environmental conditions and enables longer experimental cycles,

as stormwater can be "automatically generated" and irrigation becomes less time-consuming. This setup allows for long-term evaluation of stormwater pollution retention, including the study of clogging, weathering, and ageing of TWP.

3.4. Analytical Techniques and Data Collection

The collected samples underwent pre-treatment at the Water Environment Technology (WET) laboratory at Chalmers University of Technology. The specific procedures applied varied depending on both the sample matrix and the type of analysis intended. This section provides a general overview of the pre-treatment processes and analytical methods used, while further details are available in the corresponding publications and supplementary information. A summary of the analytical techniques employed across the different studies is presented in Table 5. It should be noted that, to our knowledge, only a few existing studies have analysed TWP smaller than 100 µm in environmental samples, and even fewer have addressed particles below 10 µm, see Table 2.

Table 5: Overview of analysis procedures employed on the environmental samples during the thesis work.

Analysis	Matrix	Paper	Size fraction	Method
TWP quantification	Water, Sediments and Soil	II, III, IV and V	<500 µm, 1.6–500 µm, 1.6–20 µm	PYR-GC/MS for SBR+BR quantification + Monte Carlo simulation
TWP quantification	Water Sediment	V V	10–1000 µm 27–1000	PYR-GC/MS by a commercial laboratory, described by Johansson et al. (2024, 2025)
Grain size distribution	Soil	III and IV	< 0.002–2 mm	SS027123 mod and SS027124 mod methods
TSS / suspended solids	Water	II, III, IV	-	SS-EN 872:2005
VSS, volatile suspended solids	Water	II, IV	-	SS 02 81 13
LOI	Sediments, Soil	II, III, IV	-	SS 02 81 13
Total metals (As, Ba, Pb, Cd, Co, Cu, Cr, Hg, Mo, Ni, V and Zn)	Water, Soil	III, IV, V	-	ICP-MS, SS-EN ISO 15587-2:2002 and SS28311:2017mod/SS-EN and ISO 11885:2009 by commercial laboratory
Dissolved metals (As, Ba, Pb, Cd, Co, Cu, Cr, Hg, Mo, Ni, V and Zn)	Water	IV, V	<0.45 µm	ICP-MS, SS-EN ISO 17294-2:2016 by a commercial laboratory
TOC/DOC and TC/DC	Water	IV and V	None/ <0.45 µm	Shimadzu TOC-V CPH total organic carbon analyser
Ions (acetate, chloride, nitrite, bromide, nitrate, phosphate, sulfate, lithium, sodium, ammonium, potassium, magnesium, manganese, calcium)	Water	V	-	Ion chromatography Thermo-Fisher Dionex ICS-900
Grain size distribution	Soil	II	>0.63 µm (sieving) and 0.002–0.063 µm (sedimentation analysis)	SS027123 mod and SS027124 by a commercial laboratory
pH		IV and V	-	pH-meter VWR pH110
Conductivity	Water	IV and V	-	Conductivity meter VWR HCO 304

3.4.1. Sample pre-treatment for TWP analysis

To prepare water samples for TWP analysis via PYR-GC/MS, a two-step filtration process was employed. Initially, samples were sieved through a 500 µm mesh to remove coarse particulate matter. Subsequently, the water was filtered through a 1.6 µm membrane filter. The volume of water filtered was adjusted based on the concentration of total suspended solids (TSS) in each sample. For stormwater samples with TSS concentrations exceeding 70 mg/L, an additional centrifugation step using Falcon tubes was introduced to facilitate filtration, following the protocol proposed by Rødland et al. (2022c). In cases where runoff samples from Testsite E18 (Paper II) were expected to contain elevated concentrations of styrene-butadiene rubber (SBR) and butadiene rubber (BR), the filtered volume was reduced to prevent exceeding the detection limits during pyrolysis. Effluent samples from the laboratory study (Paper IV) differed significantly from the stormwater samples collected at Testsite E18. These effluents contained higher concentrations of organic matter, which frequently clogged the filters and hindered the collection of sufficient sample volume for PYR-GC/MS analysis. To ensure that the pyrolysis cup contained a detectable quantity of SBR and BR, two filters were placed inside the cup, thereby increasing the total analyte mass available for detection.

In Paper V, both influent and effluent samples were analysed for the presence of rubber polymers polybutadiene (PB), polyisoprene (PI), and SBR, using a Pyrolysis-GC/MS method developed by a commercial laboratory. The sample pre-treatment involved extensive steps, including filtration through a 10 µm stainless-steel filter, ultrasonication, alkaline digestion with 10% potassium hydroxide (KOH), decantation, and final filtration on 1.6 µm GF/A filters. Samples with high particle loads underwent additional filtration, ultrasonication, and density separation using calcium chloride ($CaCl_2$; density 1.4 g/mL). Further information on the procedures, including the marker compounds used for polymer identification, is available in the supplementary information of Paper V. Due to the sieving and removal of particles >1000 µm, the analysis results are expected to represent microplastics in the 10–1000 µm size range. However, it is likely that particles larger than 10 µm were also lost due to the ultrasonication and alkaline digestion steps, which may be due to smaller rubber particles clogged to larger asphalt and sand particles were released, or that microplastics were fragmentated into smaller particles that were subsequently removed during decantation and filtration. This effect was observed during laboratory work for Paper II, where ultrasonication applied to water samples increased the TWP content in the 1.6–20 µm size fraction compared to samples that were only shaken, likely due to the release of smaller particles from the matrices or breakdown of TWP particles and their mineral encrustations.

Soil samples presented a more complex matrix due to challenges in achieving homogeneity, particularly in clay-rich soils, and the presence of organic matter, which can interfere with pyrolysis analysis. Samples from Testsite E18 (Paper III) consisted predominantly of clayey soils, which complicated both mixing and sieving. To address these issues, wet sieving was implemented. This method not only facilitated homogenisation but also enabled the removal of coarse material potentially present in the samples. Soil samples from the column study (Paper IV) were expected to contain higher concentrations of organic matter. Therefore, an oxidative pre-treatment step using hydrogen peroxide (H_2O_2) was introduced to remove this material. The method was selected for its mild oxidative strength, effectiveness in terms of both time and chemical use, and minimal loss of sample material. This method was initially developed for

liquid samples containing small amounts of particulate matter and was later applied to soil samples for consistency across the study. Pre-treatment strategies for organic matter removal are continuously evolving. The choice of method should be adapted not only to the sample type (liquid or solid) but also to the specific tyre wear particle markers targeted in subsequent analysis. This is important because different pre-treatment methods can affect TWP markers differently, potentially influencing detection and quantification outcomes. The treatment involved incubation with 30% hydrogen peroxide (H_2O_2), followed by filtration using 13 mm GF-75 glass fibre filters (pore size 0.3µm). The filtered samples were then dried at room temperature prior to analysis. Unlike the clay-rich road ditch soils from Testsite E18, the column study soils contained significantly less clay, making them easier to homogenise. As a result, wet sieving was not required, and dry sieving was employed instead. Although dry sieving may have led to the resuspension of ultrafine particles, it was considerably less time-consuming and eliminated the need for thermal drying of the samples, thereby streamlining the pre-treatment process.

3.4.2. TWP analysis and quantification

Due to the heterogeneity of TWP in terms of size, density, chemical composition, morphology, and texture, a variety of analytical methods have been developed for their characterisation and quantification. These methods are generally categorised into two main groups: single-particle-based and bulk-based approaches (Rødland et al., 2023b). In papers II-IV, a bulk-based method was chosen because it provides mass-based concentration data, which is essential for risk assessment and regulatory purposes. Bulk-based methods estimate the mass concentration of tyre tread using specific markers, which can be classified into three types: elemental composition, organic composition, and thermal decomposition. Among these, thermal gravimetric methods, particularly pyrolysis (PYR) and thermal desorption (TED) methods coupled with gas chromatography mass spectrometry PYR-GC/MS or TED-GC/MS), have become the most widely used in environmental studies (Rødland et al., 2023b), mainly due to the early development of standardised protocols.

These thermal decomposition methods provide an indirect quantification of the total mass of TWP in a sample by monitoring thermal decomposition products of polymers, such as natural rubber (polyisoprene (NR)) and synthetic rubber (styrene butadiene rubber (SBR) and butadiene rubber (BR)), within tyre thread. As highlighted by Rødland et al. (2023b), reviewing available methods for analysing TWP, most previous studies have monitored single markers such as BR dimer (4-vinylcyclohexene, 4-VCH for SBR+BR) and dipentene for NR. These markers are used in ISO Technical Specifications (ISO/TS 20593 and ISO/TS 21396) for monitoring TWP in soil and air, however, recent studies suggested the use of combined multiple markers since they allow for optimising the compromise between higher selectivity and sensitivity. Therefore, all the samples analysed for the occurrence of TWP in Papers II-IV, along with selected samples from Paper V, were assessed using a combination of multiple markers, specifically the sum of benzene, a-methylstyrene, ethylstyrene and butadiene trimer, targeting the rubber polymers SBR + BR. The PYR-GC/MS setting and calibration were the same for all studies and can be found in the respective papers. Since benzene is commonly present in environmental samples, particularly those rich in vegetation and organic matter, it can interfere with benzene coming from tyres. Soil, being a complex matrix with occasionally high organic content, was expected to exhibit such interference. In samples where benzene concentrations were unexpectedly high, it was excluded as a marker for that specific analysis. Instead,

quantification was performed using an alternative marker combination, referred to as combination B. The 4-vinylcyclohexene (4-VCH) marker, indicative of butadiene rubber (SBR+BR), was consistently monitored as a control to ensure reliable detection and quantification.

To translate the measured SBR+BR content in environmental samples (Paper II-V) into total TWP mass, a reference database of polymer composition in Norwegian summer and winter tyres, both studded and non-studded, was utilised. This database, developed by Rødland et al. (2022c), includes data from 18 personal vehicle (PV) tyres and 13 heavy-duty vehicle (HDV) tyres. Considering the substantial variability in SBR+BR content across tyre types (ranging from <0.05% to 28%), relying on a fixed standard ratio as suggested in ISO/TS 21396:2017(E) and ISO/TS 20593:2017(E) may lead to significant underestimation of TWP concentrations, as highlighted by Rauert et al. (2021). Quantification of TWP was performed by integrating the pyrolysis marker data with the compositional database using Equation 6 from Rødland et al. (2022c). To account for uncertainty in polymer content, the SBR+BR input values for PV and HV tyres were modelled as probability distributions. A Monte Carlo simulation (100,000 iterations), implemented using Crystal Ball in Excel (Oracle), was employed to estimate the mean and standard deviation of TWP mass per sample. The local ratio of PV to HV tyre usage was retrieved from regional traffic data to refine the input distribution and improve the accuracy of the model.

The majority of samples analysed for the presence of rubber polymers, polybutadiene (PB), polyisoprene (PI), and styrene-butadiene rubber (SBR), in Paper V were assessed using Pyrolysis-GC/MS with single-marker compounds. For the identification of natural rubber (NR), represented by polyisoprene (PI), the marker ion m/z 93 (limonene) was used. For PB/BR and SBR, the marker ion m/z 79 (4-vinylcyclohexene) was applied. All these sample analyses were carried out by a commercial laboratory, as the study also included the investigation of other polymer types beyond rubber. This allowed for consistent pre-treatment and analytical procedures across all samples, ensuring comparability between different polymer groups. Calibration curves for the rubber components yielded correlation coefficients of $r^2 < 0.98$. Unlike the approach described by Rødland et al. (2022c), which uses SBR1500 as a standard, the commercial laboratory employed a standard mixture supplied by Frontier Labs containing 12 polymers, in addition to pure standards of PB/BR and PIP/NR provided by PSS Polymer. It is known that SBR also contributes to the signal for 4-vinylcyclohexene. To account for this, the laboratory's reporting software includes a correction algorithm that subtracts the contribution from SBR and other polymers, ensuring that PB/BR is only reported when present independently. Consequently, if a sample contains pure SBR, PB/BR will not be reported alongside it. It should be noted that the commercial laboratory does not publicly disclose its detailed analytical protocol, which makes independent validation and verification of the method challenging.

As illustrated above, there are several analytical approaches for quantifying TWP polymers, and even within the same category, such as bulk-based methods using Pyrolysis-GC/MS, variations in instrument settings and laboratory routines are common. Despite this, results are rarely validated across different analytical techniques. To improve comparability between studies, standardisation is needed in sampling procedures, sample preparation, analytical protocols, and data reporting. Consistent use of separation techniques and harmonised definitions of size fractions would enhance reliability. Incorporating local tyre composition data

or establishing a global tyre polymer database could reduce uncertainty in marker-based quantification. Furthermore, a deeper understanding of ageing processes and the influence of non-rubber components is essential for improving mass estimates of TWP and evaluating their environmental fate. As emphasised by Rødland et al. (2023b), adopting validation practices commonly used in environmental chemistry would significantly strengthen the robustness of TWP analytical methods. This step is particularly critical when comparing contamination levels to target values, guideline thresholds, or risk-based criteria.

3.4.3. TDC analysis and quantification

Several sediment and water samples in Paper IV were analysed for the presence of 14 tyre-derived chemical: N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine (6PPD), 6PPD-quinone (6PPD-Q), N,N′-diphenyl-p-phenylenediamine (DPPD), N-isopropyl-N'-phenyl-p-phenylenediamine (IPPD), N-(cyclohexyl)-N'-phenyl-p-phenylenediamine (CPPD), 4-N-(5-methylhexan-2-yl)-1-N-phenylbenzene-1,4-diamine (7PPD), hexamethoxymethylmelamine (HMMM), N,N′-diphenylguanidine (DPG), 2,2,4-trimethyl-1,2-dihydroquinoline (TMQ), 2-(methylthio)-1,3-benzothiazole (MTBT), 2-Phenyl-1,3-benzothiazole (PhBT), 2-mercaptobenzothiazole (MBT), 1,3-benzothiazole-2-sulfonic acid (BTSA), and 2-1,3-benzothiazol-2-ol (OHBT) (Table 4). All these samples were analysed as single replicates. Sample preparation and analysis followed the method described by Meland et al. (2024), with minor modifications. Soil samples (1.0 g) were extracted by shaking for 60 minutes using 7 mL of a 9:1 (v/v) methanol (MeOH)/ethyl acetate (EtAc) mixture. Water samples (50 mL) were centrifuged at 2800 RPM for five minutes. The water phase, including an extra 1 mL MQ wash of the centrifuged particle residue, was loaded onto a 200 mg HLB (Hydrophilic-Lipophilic Balanced) solid-phase extraction cartridge (Waters). After vacuum drying, the cartridge was eluted with 6 mL of 9:1 MeOH/EtAc. The particle residue was extracted separately with 1 mL of the same solvent mixture by shaking for 60 minutes. All extracts were concentrated to 0.5 mL under a gentle nitrogen stream. A 0.3 mL aliquot was transferred to a Spin-X centrifuge tube (Merck), buffered with 0.1 mL of 5 mM ammonium formate in ultra-pure water. The mixture was centrifuged (1 min at 10,000 × g), and the supernatant was transferred to HPLC vials for chemical analysis. Ultra performance liquid chromatography-tandem quadrupole mass spectrometry (UPLC-MSMS) was used for target quantitation of the TDC as described by Meland et al. (2023). The laboratory procedural blank, and samples with known concentrations such as a solvent spike (extraction solvent spiked with 20 ng PPD's/80 ng BT's), a spiked soil sample (blank soil sample spiked with 20 ng PPD/80 ng BT's) and a spiked water sample (tap water spiked with 10 ng PPD/40 ng BT's) were processed along with the batch of samples to control the measured concentrations. Recoveries of the target analytes in spiked samples were in the range from 60 to 120%, and the procedural blank was below LOQ for all analytes.

4. RESULTS AND DISCUSSION

4.1. Emission assessment

4.1.1. Method developed

The proposed framework for national tyre wear emissions represents the most comprehensive and ambitious approach to date. For passenger cars and light-duty vehicles (LDV), vehicles with a gross vehicle weight rating up to 3500 kg intended for transport of goods, the measured emission factors and mileage data used in the mileage approach can be considered robust and, therefore, are a useful tool for the estimation of national tyre wear emissions from these vehicles. The method, which includes weighing scrapped tyres and comparing the results with the weight of new tyres, yields emission factors in accordance with the literature and the latest on-road measurements. The uncertainties found in the tyre wear emission factors for heavy-duty vehicles (HDV), vehicles with a gross vehicle weight rating above 3500 kg and buses, as well as in the data available for the yearly mileage of different vehicle classes, contribute to lower-than-expected accuracy when using the mileage approach to calculate total national emissions from these vehicles. For example, statistical sources for vehicle mileage in Sweden differ by almost 30 %, and there is no obvious way to determine which source is the most reliable. In this study, the most detailed data were chosen.

4.1.2. National estimations

From the results of the calculations in this thesis(Paper I), the national emission of TWP in Sweden is estimated at 11,040 tonnes per year, see Figure 7. This estimate is considered robust, as it aligns closely with both the validation result from the sales-based approach (12,560 tonnes) and the earlier estimate of 12,350 tonnes reported by Magnusson et al. (2016). Passenger cars account for the largest share of total emissions (55%), followed by heavy-duty vehicles (31%), light-duty vehicles (10%), buses (3%), and motorcycles (0.09%) (Figure 7). The highest proportion of these emissions occurs on rural roads, with motorways accounting for the second largest share. While these results reflect Swedish conditions, they also highlight broader concerns regarding the environmental fate of TWP. For example, Zheng et al. (2025) estimated that 18.5% of TWP emissions in the UK end up in swales and ditches. Although this differs from the Swedish distribution, the same study also found that 39% of UK emissions accumulate in swales, ditches, and roadside soils, areas typically lacking controlled runoff treatment. This suggests that a substantial portion of TWP emissions in both countries is deposited in environments where mitigation is limited, highlighting the need for improved stormwater management and infrastructure design.

Although the winter season in Sweden accounts for only one-third of the year, winter tyres contribute approximately 44% of total passenger car tyre emissions (Figure 7). This disproportionate contribution is attributed to the higher emission factors associated with winter tyres compared to summer tyres. These findings are important for the development of targeted emission control measures. For instance, roadside ditches that receive TWP during winter also accumulate road salts, which may influence the transport and fate of TWP in the soil. The combined effect of elevated TWP emissions during winter and altered soil chemistry due to de-icing agents should be considered in the design and maintenance of roadside drainage infrastructure.

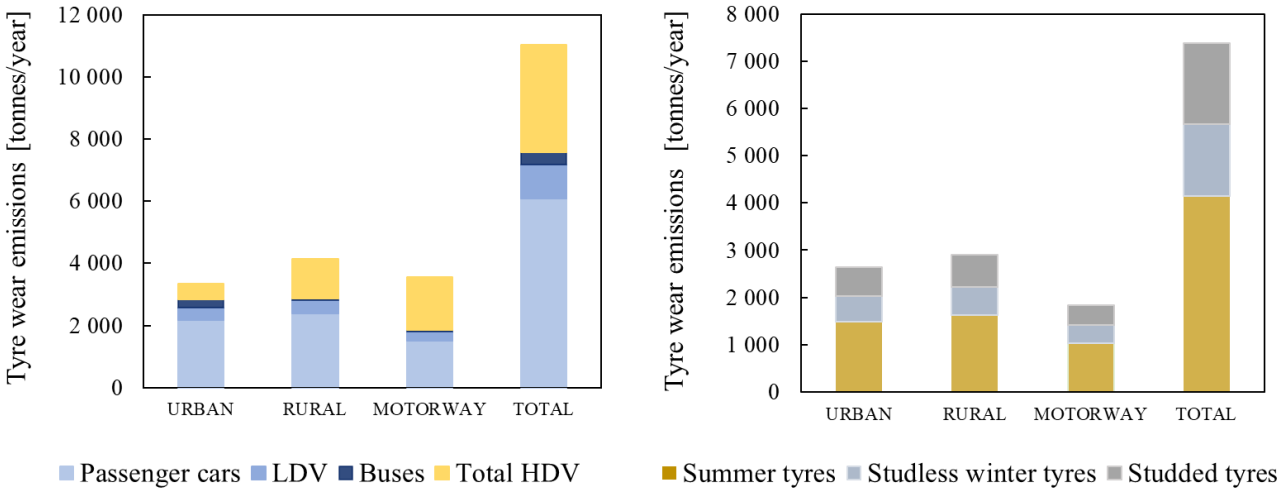


Figure 7. Estimated annual tyre wear emissions (in metric tonnes per year) across different road types in Sweden, urban, rural, motorway, and total, and by various tyre categories. Emissions were calculated using the mileage-based approach, whereby total emissions are correlated with road type length and specific emission factors, which vary depending on the road type and tyre type.

4.2. Measured concentrations of TWP in Various Matrices (Paper I–V)

Figure 8 presents the concentrations of TWP in various environmental matrices, as evaluated in the studies in Papers II and III, included in this thesis. As highlighted in these studies, TWP are abundant in road environments. Although a standardised sampling and analysis protocol for TWP is not yet available, which would facilitate more consistent comparisons, the following discussion presents a valid comparison, as the studies referenced employed the same analytical technique (Pyrolysis-GC/MS). The standing water throughout the stormwater system at Testsite E18 was sampled as grab samples in Paper II, including gully pots, stormwater wells, and the outlet at Ditch 2. The concentrations of TWP (1.6–500 µm) in standing water volumes in two gully pots connected in series G1 and G2, and connected to the well WA, ranged from 0.52–2.9 mg/L and in the outlet at the ditch 0.45–1.7 mg/L, are comparable to previously reported values from stormwater drains and retention ponds (Rauert et al., 2022; see also Table 2). Within the stormwater system studied, TWP concentrations (1.6–500 µm) in the water decreased in concentrations from the gully pots to the collecting well(G1 and G2, with G2 located closer to WA, see Figures 2 and 3). A significant reduction was observed between G2 and WA (linear regression adjusted for triplicates, $p = 0.004$). One explanation for the lower TWP concentration in the water from WA is the larger volume of the well, which could promote sedimentation of the particles and prevent resuspension. The standing water throughout the stormwater system sampled in Paper II exhibited lower TWP concentrations (1.3 ± 0.81 mg/L), with median values 16–42 times lower than those observed during rain events, where runoff was collected using an ISCO sampler from the same highway (Gaggini et al., 2025a). Notably, these concentrations are higher than those reported in other surface waters (see Table 2).

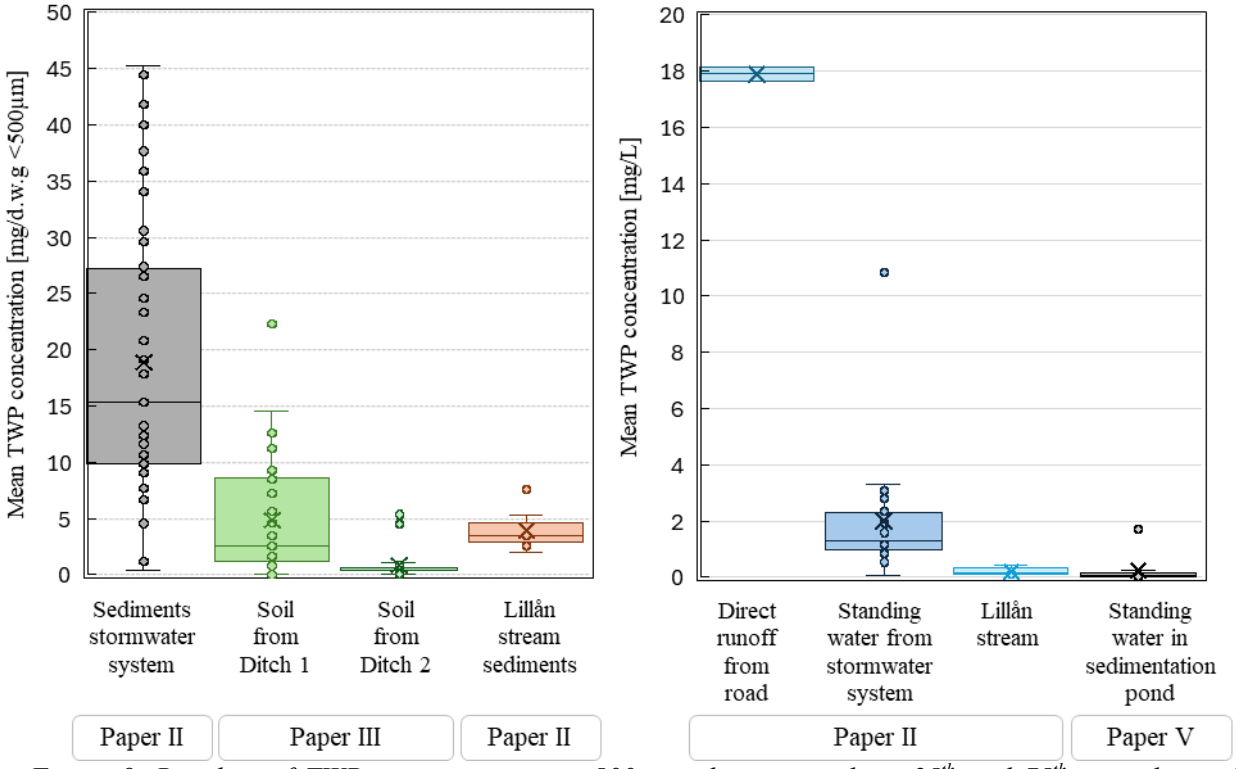


Figure 8. Boxplots of TWP concentrations < 500 µm showing median, 25th and 75th quartiles and whiskers indicating minimum and maximum, along with scatter plots of individual samples.

Comparing TWP concentrations across studies in road ditches and gully pots remains challenging due to limited information on the accumulation period since road construction, as well as variations in maintenance practices and regional and geological differences. Furthermore, the concentrations of TWP observed in the sedimentation pond at Gårda (Paper V) were somewhat lower than those previously reported in the literature, which may be attributed to differences in sampling depth, retention time, or pond design, factors that need further investigation. In addition to water samples, sediment samples collected at Testsite E18 in March 2023 revealed higher TWP concentrations compared to those from November 2022. Moreover, TWP concentrations in sediment increased along the stormwater system, from the gully pots to well WA, and further downstream to the outlet pipe (location D). This pattern may be explained by the preferential retention of coarser particles upstream, particularly in sand traps within the gully pots and well. Since TWP is typically found in finer fractions (?? <500 µm), it is less likely to be retained, resulting in a relative enrichment downstream. Supporting this, only 3–5% of sediment in the outlet pipe exceeded 500 µm (Supplementary material B.10, Paper II).

The concentrations of TWP in the road ditch soil samples (Figure 8) were somewhat lower than those measured in the sediment from the nearby stream. This difference may be explained by two main factors. First, the sampling procedure for the road ditch involved removing the upper 10 cm vegetative layer, where TWP concentrations are typically highest, prior to soil collection. Second, the stream receives direct runoff through drainage openings in the bridge above, likely contributing to the accumulation of TWP in the sediment. In addition, other upstream roads and traffic areas may also discharge into the stream, further increasing TWP inputs. The stream has also been classified as not achieving good chemical status for surface waters due to high concentrations of polybrominated diphenyl ethers (PBDE) and mercury

(Hg), most likely resulting from atmospheric deposition (Water Information System Sweden, n.d.). Notably, the Lillån stream ultimately discharges into Lake Mälaren, which serves as a drinking water source for approximately two million people. Although the distance between the sampling site and the lake is considerable, and natural attenuation processes such as dilution, sedimentation, and degradation are expected to reduce contaminant loads along the way, the findings illustrate the importance of monitoring upstream sources of pollution. This is particularly relevant in cases where streams are intersected by trafficked bridges equipped with stormwater drains that discharge directly into the watercourse. In Sweden, however, there are examples of alternative stormwater management solutions. For instance, runoff from urban bridges, such as the bridge over the Nordre Älv in Kungälv, is directed via pipes to small stormwater ponds, which help reduce the direct input of pollutants into receiving waters.

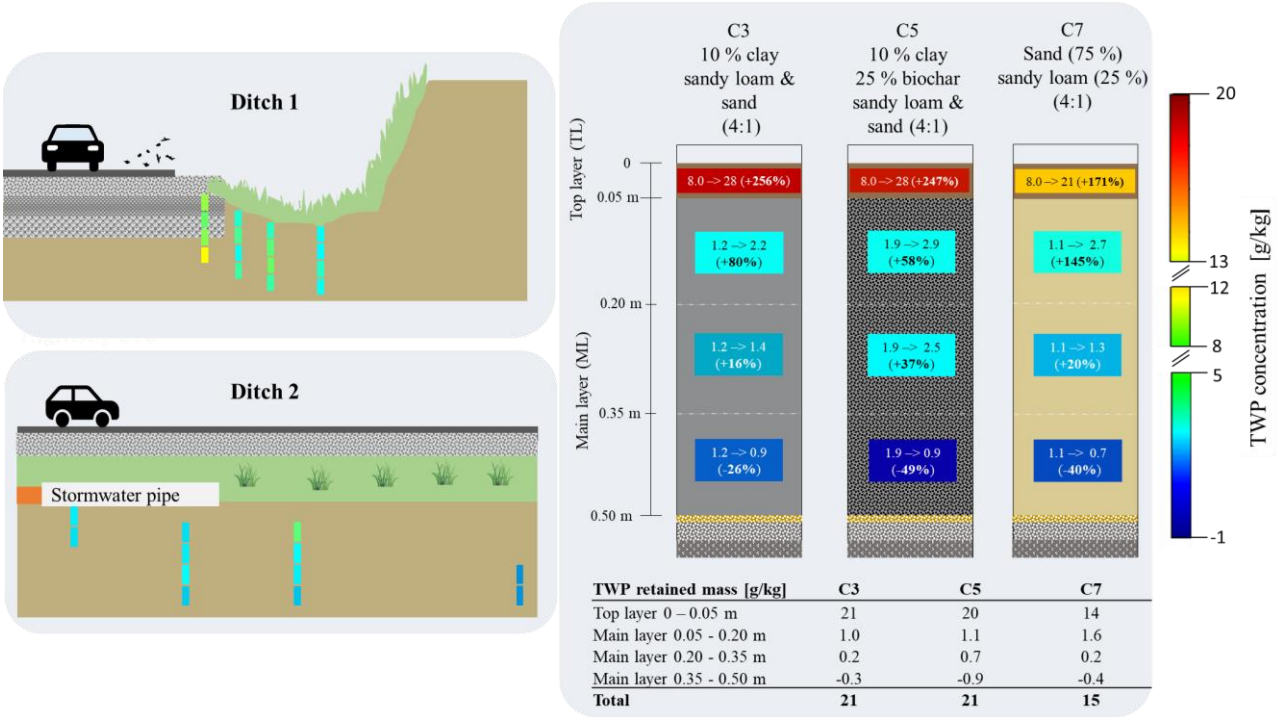
Paper II demonstrates that a significant proportion of TWP 1.6–500 µm in standing water from the stormwater system was present in the fine size fraction (1.6–20 µm). Grab samples collected from standing water within the system showed a high median proportion of fine TWP (78 ± 17%), which is slightly lower than the proportion observed during rainfall events at the same location (89 ± 7–17%), as reported by Gaggini et al. (2025a). These findings suggest that fine particles are highly mobile within the liquid phase and can be easily resuspended during sampling, contributing to their elevated presence in stormwater. The relatively high abundance of TWP in the fine fraction shows the importance of screening stormwater for this size range. Paper II further highlights that ultrasonication during pre-treatment can significantly increase the proportion of fine TWP, from 60% without ultrasonication to 80% with it, emphasising the need for standardised and optimised protocols in TWP analysis. Compared to standing water samples, sediment generally contained lower proportions of TWP in the 1.6–20 µm range, with an average of 32 ± 23% in stormwater system sediments. This is consistent with previous studies on TWP size fractions, which reported modal sizes of 34 µm for TWP from a road simulator (Kovochich et al., 2021) and <20 µm for TWP in tunnel road dust (Klöckner et al., 2021). However, sediments from Lillån exhibited a notably higher abundance of fine TWP, ranging between 65% and 100%. These results from Paper II indicate that gully pots are relatively ineffective at retaining fine TWP in their sediment traps. Similar findings were reported in a recent study conducted in Luleå, Sweden, which investigated particle size distribution in urban gully pots (Wei, 2024). That study found that up to 95% of the retained sediment was in the >2 mm fraction, indicating a strong bias toward capturing coarse material. Moreover, retention of fine particles was notably lower during the winter–spring period compared to the summer–autumn period, suggesting seasonal variability in retention efficiency. These findings highlight the limited capacity of gully pots to reduce finer particle loadings to the sewer system, particularly during periods of increased runoff. In Paper II, high concentrations of TWP (1.6–20 µm) were found downstream from the gully pot in the stormwater system (in outflowing water from well WA). Given that sand traps in gully pots are primarily designed to capture larger particles, this highlights the need to monitor fine particles at the terminal stages of stormwater treatment and transport systems. The mobility of fine TWP in the water phase, along with their tendency to resuspend in standing water, reinforces the importance of developing more effective retention and monitoring strategies. These particles appear to bypass conventional sedimentation mechanisms, further emphasising the need for improved stormwater management approaches.

Overall, the TWP concentrations reported in Paper III, ranging from 0.74 ± 0.20 to 12.40 ± 1.88 mg/g in Ditch 1, and 0.83 ± 0.14 mg/g in Ditch 2, are within the same order of

magnitude as those found in other studies. For example, Rødland et al. (2023a) reported concentrations between 2.0 and 26.4 mg/g, while Beaurepaire et al. (2025) observed concentrations up to 15.5 mg/g (see Table 2). However, direct comparisons across studies are complicated by differences in analytical methods, particle size ranges, traffic intensity (AADT), sampling depth, and road age, parameters that are not consistently reported. These variations highlight the need for standardised methodologies to enable more reliable cross-study evaluations.

4.3. Distribution of TWP in road ditch soil

Results from Paper III showed that in road ditch soils, assessing the distribution of TWP was challenging due to limitations in sampling. The presence of heterogeneous road bank material (comprising mixed soil textures and disturbed layers) made it difficult to obtain representative samples. Despite these challenges, the results indicate that the lowest TWP concentrations in the upper soil layers (0.1–0.3 m) were found furthest away from the road, showing a statistically significant ($p < 0.001$) accumulation gradient, see Figure 9. However, this pattern has been both supported and contradicted by previous studies (e.g. Müller et al., 2022; Rødland et al., 2023a), highlighting the need for more controlled investigations. In the other road ditch (Ditch 2), also studied in Paper III, which consisted of homogeneous clay soil, no clear vertical or horizontal trends in TWP distribution were observed. This was despite noticeable variation in TWP concentrations at different depths and distances from the stormwater pipe outlet, suggesting that TWP may also be mobile within the less permeable soils (Figure 9).



TWP retained mass [g/kg]	C3	C5	C7
Top layer 0 – 0.05 m	21	20	14
Main layer 0.05 - 0.20 m	1.0	1.1	1.6
Main layer 0.20 - 0.35 m	0.2	0.7	0.2
Main layer 0.35 - 0.50 m	-0.3	-0.9	-0.4
Total	**21**	**21**	**15**

Figure 9. Retained concentrations of TWP in Ditches 1 and 2 (Paper III) and in columns C3, C5 and C7 (Paper IV). The numbers within the coloured boxes in the right-hand panels indicate TWP concentrations before and after the experiment, as well as the percentage increase or decrease in each soil layer post-experiment. The colour gradient represents the concentration of TWP across the different layers.

Given these results, future studies should investigate the mobility of the TWP in soil with groundwater. The occurrence of TWP in deeper clay layers, 1.5–3.0 meters away from the stormwater drain, may be attributed to two main mechanisms: vertical transport through soil cracks formed during dry periods, and vertical infiltration during prolonged rainfall events when surface runoff accumulates and remains stagnant. In the absence of forward flow, fine particles such as TWP may have an increased opportunity to settle and penetrate the soil profile. This process is particularly relevant in urban areas where stormwater is discharged directly into natural environments. Therefore, the local topography, both at a large scale (e.g., flat terrain with minimal elevation) and small scale (e.g., shallow depressions or micro-ponds on the soil surface), should be carefully evaluated to identify zones prone to water stagnation and particle accumulation. Understanding these landscape features is essential for developing effective strategies to mitigate the spread and environmental impact of TWP.

Laboratory simulations of TWP transport through stratified soil columns (Paper IV) showed high retention of TWP in the upper soil layers (0–0.05 m) across all three studied columns (C3, C5, and C7), likely due to physical hindrance (i.e., resistance to movement caused by particle shape and size**)**, filtration, and sorption, possibly of TWP or associated metals, to the high organic matter content in the upper soil layer (Figure 9). Similar results were reported by Lange et al. (2022), who studied the vertical distribution of different polymers (MP in fractions 40–5000 µm analysed with µFTIR and ATR-FTIR), including SBR, in several biofilters. As highlighted by Lange et al (2022), this is typical for many other particulates (e.g., Hunt et al., 2012; LeFevre et al., 2015). Also, similar results were reported in a column study conducted by Zhao et al. (2022) used clay loam (29% clay, 44% silt, 27% sand) from farmland, and found that with increasing irrigation runs, microplastic in the topsoil layer (0–2 cm) decreased, while microplastic contents in deeper soil depths increased significantly.

Paper IV also demonstrated that the vertical distribution of TWP varied across the main layers of the soil columns, which included clayey soil, clayey biochar-amended soil, and sand, see Figure 9. In all cases, the highest TWP concentrations were retained within the upper section of the main layer (0.05–0.20 m), with lower, but still substantial retention (14–27 %) also observed in the 0.20–0.35 m depth (Table in Figure 9). In contrast, the lower section of the main layer (0.35–0.50 m) consistently exhibited removal from the soil (28 to 97 %) of TWP across all soil types. That may be due to a combination of particle straining through filtration and possibly sorption in the upper 40 cm. This could cause the observed leaching, due to cleaner water passing the lowest soil layer, and potentially higher water pressure and flow in this layer. However, due to the limited number of samples, this behaviour should be investigated further with greater accuracy and detail.

The diverse distribution patterns of TWP observed in the two studied road ditches highlight the complexity of TWP transport through roadside soils. This complexity is likely influenced by multiple interacting factors, including soil texture, vegetation cover, weather conditions, organic matter content, and soil pH. Additionally, the potential for metals bound to the surface of TWP to facilitate co-transport will be further investigated to better understand the mechanisms governing TWP mobility in terrestrial environments.

4.4. Transport of TWP through soil and its influential factors (Paper III – V)

In Table 6, the total retention efficiency (RE) of TWP (< 500 µm) accumulated in all columns (Paper IV) is presented. Generally, TWP were retained with RE ranging from 93% to 99% across the different soil types used in the experiment. The following chapters will discuss in more detail the parameters influencing the TWP transport.

Table 6. Total mass-based retention efficiency (RE) of TWP accumulated in the different columns. C1and C2=25% clay, C3 and C4 = 10% clay, C5 and C6 = 10% clay + biochar, C7and C8 = 75 % sand, C9 and C10 = 100% sandy loam. C2, C4, C6, C8, and C10 had surfaces covered with grass.

	Total accumulated RE (%) when irrigated with stormwater (based on total mass of TWP)
C1	99%
C2	98%
C3	99%
C4	93%
C5	98%
C6	93%
C7	97%
C8	98%
C9	99 %
C10	97 %

4.4.1. Soil type/texture

Soil texture is one of the key factors determining the transport of TWP through soil. In paper III, it was shown that soil with a coarser grain size, such as that in Ditch 1, exhibits a higher capacity for TWP (<500 µm) transport than soil with a smaller grain size (particle size in Ditch 2 was 95–100 % below 0.063 mm) has reduced transport (Figure 9). This was also seen in Paper IV, where Column C1 (25% clay) retained a similar total mass of TWP compared to C3 (10% clay) and C9 (100% sandy loam), both of which contained similar amounts of fine particles (<0.063 mm) and generally exhibited coarser grain sizes than C1 (Figure 3 and Table 4). This observation does not fully align with previous findings, suggesting that heterogeneous soils with coarser sizes facilitate higher and easier transport of TWP (Polukarova et al., 2024). The total RE of the accumulated TWP in the clay-amended column C3 (99%) was, nevertheless, similar to the total RE in the sand column (C7, 97%) (Table 4). This similarity can be attributed to filtration through the sand (C7) and the transport of TWP via cracks in the clay matrix (C3). The role of microplastic particle size and physical straining within porous soils, such as sand, has also been highlighted by Fan et al. (2025) and Soltani Tehrani et al. (2025). In paper IV, soil particle size did, however, not significantly affect the TWP retention in columns without vegetation. No significant correlation was found between the proportion of fine soil particles (<63 µm) and the amount of TWP in the effluent of these columns. While this may be partly due to the limited dataset, it also suggests that other TWP characteristics, such as particle density and chemical processes, may play a more influential role. Since TWP generally has a lower density than clay, silt, and fine-to-medium sand particles, it may remain suspended for a longer period or settle more slowly.

When amended with biochar, the retention efficiency (RE) of fine-grained non-vegetated soils remained high. For example, column C5 (10% clay + biochar) achieved an RE of 98%, which is comparable to column C3 (99%) that contained 10% clay without biochar (Table 6). Post-experiment analysis of the soil mixtures also showed that the biochar-amended column retained TWP effectively down to a depth of 0.3 meters (Figure 9). In addition, biochar contributed to improved vegetation establishment and growth. As a soil remediation material, biochar has demonstrated the ability to enhance soil quality by promoting plant development, alleviating drought and salinity stress, and interacting with organic pollutants and heavy metals (Gua et al., 2019; Qiu et al., 2022). In addition to its soil remediation properties, biochar contributes to climate change mitigation by acting as a stable carbon sink, sequestering carbon over long time scales and reducing greenhouse gas emissions (USDA Forest Service, 2023; Salma et al., 2024). These results suggest that biochar amendment may be a valuable approach worth further investigation for reducing the spread of TWP in and from roadside ditches. Although the biochar-amended, vegetated clay column (C6) exhibited high RE, it also showed increased TWP leaching following a drought period, indicating that its effectiveness may be more suitable for wetter regions. This observation aligns with previous findings, such as those by Rullander et al. (2025), which showed that prolonged drying may alter biochar structures, creating temporary pathways that facilitate microplastic transport. Therefore, the long-term relevance of biochar application in near-road environments requires further study, particularly under varying weather conditions and over extended time scales.

4.4.2. Vegetation

Paper IV demonstrated that soils covered with grass vegetation tend to facilitate greater transport of both water and TWP (Figure 10, Table 6), primarily due to the formation of continuous macropores created by plant root systems. These root-induced channels promote preferential flow, allowing water and TWP to bypass finer soil matrices and move more rapidly through the soil profile. Several of these columns (C6, C8, C10) also exhibited higher saturated hydraulic conductivity at the end of the experiment, when vegetation was fully developed, highlighting the positive effect of vegetation on water transport through soil. These findings are consistent with previous studies, such as those by Kuoppamäkki et al. (2021), which emphasise the importance of preferential pathways in facilitating microplastic movement through soil. However, if plants develop dense and fibrous root systems, they may possibly form shallow micropores that trap TWP near the surface. The enriched organic layer in vegetated soils may enhance sorption, water retention, and microbial activity, thereby reducing TWP mobility and increasing residence time. Thus, while grass vegetation can enhance vertical transport via root channels, it may also introduce mechanisms, particularly through organic matter, that limit TWP migration and promote surface retention. These dual effects show the complex role of vegetation in regulating microplastic behaviour in soils.

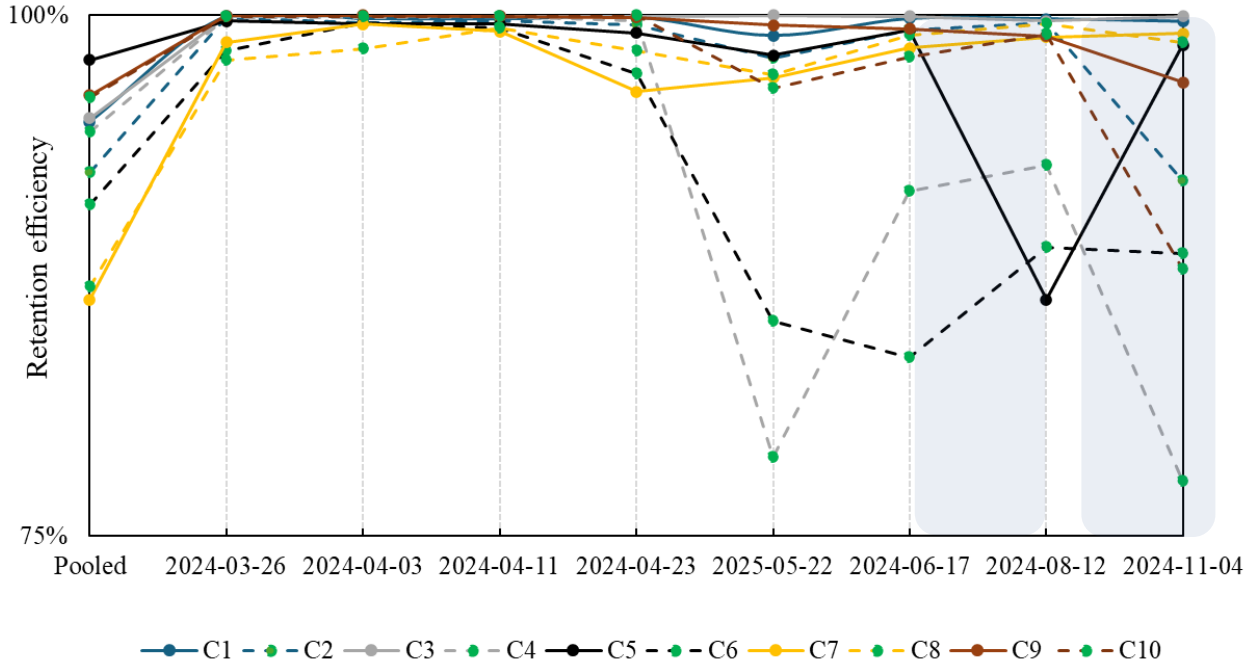


Figure 10. Retention efficiency ((mass TWP influent – mass TWP effluent)/mass TWP influent) of TWP in columns during the experiment. C1and C2=25% clay, C3 and C4 = 10% clay, C5 and C6 = 10% clay + biochar, C7and C8 = 75 % sand, C9 and C10 = 100% sandy loam. C2, C4, C6, C8, and C10 had surfaces covered with grass. The shaded area indicates periods of low-volume irrigation. During the summer months (June–August), irrigation was performed using tap water: 0.3–1.2 L per week for vegetated columns and 0.1–0.3 L for non-vegetated columns. In the autumn and winter months (September–December), all columns were irrigated six times with runoff water spiked with TWP, using volumes of 0.3–0.6 L per event.

4.4.3. Impact of drought and increased precipitation

Drought, increased precipitation volumes, and excessive salt concentrations due to road maintenance are suggested to influence the TWP in soil. Paper IV also showed that the retention efficiency of TWP in grass-vegetated columns C4 (10% clay) and C6 (10% clay + biochar) declined by 31% and 12%, respectively, following a three-week drought (2024-04-23 to 2024-05-22; Figure 10). This pronounced decline may be explained by structural changes in the fine-grained soil, such as cracking and the expansion of root-facilitated channels, which enhance preferential flow (Reinsch et al., 2024) and direct TWP transport. When watering resumed (e.g., on 2024-05-22), retention for C4 increased, while the biochar column still exhibited lower retention. These fluctuations suggest that soil moisture is an important factor for TWP retention, especially in fine-grained (clayey and silty) and biochar-amended soils, with dry conditions reducing retention due to physical changes in soil structure. Both total and dissolved metal concentrations in effluents may rise after drying, possibly due to formation of cracks providing preferential flow paths in the soil, pH changes and increases in dissolved organic matter (OM) contents (Blecken et al., 2009) and drought has also been shown facilitate transport of total and dissolved metals Cd, Pb, Cu and TSS in soils with vegetation, however some plant species may mitigate negative effects of extended drying on metal removal (Lange et al., 2020).

Paper V shows that simulated stormwater flows mimicking two approximate 50-year rainfall events occurring in close (1 month) succession led to a slight reduction (approximately 0.14–3.8%) in the total removal efficiency of control, ash, and biochar filters for tyre wear-related polymers, see Table 7. However, the differences in removal efficiency under increased irrigation volumes, especially when combined with cold conditions, were modest. This suggests that the transport of these polymer particles larger than 10 µm is not significantly affected by large irrigation volumes under cold climatic conditions.

Nevertheless, while the overall removal efficiency remained relatively stable, the vertical distribution of TWP, potential resuspension of previously captured particles, and the formation of preferential flow paths may have been influenced by the increased water volumes and cold temperatures. These aspects were not directly investigated in this study, but could play a role in microplastic mobility under extreme weather conditions. Additionally, snowmelt events and thawing of frozen water within soil pores, although not recorded in this study, may, similar to intense rainfall, result in delayed yet intensified stormwater infiltration and microplastic transport.

Table 7. Values represent the difference between the removal efficiencies ((RE when irrigated with 100L - RE when irrigated with lower water volumes)) of tyre wear-related polymers PI, PB and SBR when watering with simulated 50-year rainfall event and watering with water values representing normal conditions. Positive values show the filters are efficient in removing these polymers, even during a simulated 50-year rainfall event.

	Ash		Biochar		Peat		Control	
Polymer	2023-01-23 (100 L)	2023-02-28 (100L)	2023-02-13 (100 L)	2023-03-14 (100 L)	2023-02-08 (100 L)	2023-02-28 (100 L)	2023-02-21 (100 L)	2023-03-14 (100L)
Polyisoprene (PI)	0.47	2.02	0.52	2.68	0.14	2.02	1.14	0.42
Polybutadiene (PB)	1.37	2.74	1.17	3.81	0.24	2.74	2.09	0.56
Styrene-butadiene rubber (SBR)	0.53	1.65	0.31	1.65	-0.67	0.88	0.34	-0.12

4.5. Co-transport of TWP, tyre-derived chemicals and metals in soil

As discussed above (chapters 4.4.1 – 4.4.3), the transport of particles in soil and bioretention systems may be influenced by several factors, including vegetation, soil texture, and prevailing weather conditions. In addition, the chemical and physical properties of associated tyre-derived chemicals (TDC) and metals may also influence their mobility and retention and vice versa. In Paper III in clay-rich ditch soils (Ditch 2) and mixed-material soils (Ditch 1), no consistent correlation was observed between particle concentrations and total metal concentrations in the soil, except for copper (Cu, $p < 0.05$) and zinc (Zn, $p < 0.01$) in Ditch 1. Comparable findings were reported in Paper IV, where only barium (Ba) showed a significant correlation in the sand filter column C7 ($p = 0.007$). Similarly, Rødland et al. (2023a) found no significant correlations between particles and metals in rural roadside soils with lower traffic intensity. In contrast, analysis of stormwater spiked with sediment from the sedimentation basin showed a significant correlation ($p < 0.05$) between TWP and several total metals, see Table 8. These results are consistent with observations from stormwater collected during the studded tyre season (Järlskog et al., 2022a), roadside snowmelt (Gaggini et al., 2025b), and sediment from stormwater detention basins (Ianauzzi et al., 2025).

Effluent analyses from column experiments also showed strong correlations between particles and total metals, as well as between suspended solids and total metals (Table 8). The presence of correlations in influents and effluents, but not in the soil matrix, suggests that particles and metals may be co-transported in the water phase, while retention mechanisms in the soil differ. This discrepancy may be attributed to the complexity of interactions affecting transport, including sorption to dissolved organic carbon (DOC), leaching of metals from particle surfaces, and dynamic sorption or resorption within filter bed materials (Johansson et al., 2025).

Table 8. Correlation between TWP and total and dissolved metal concentrations in influent and effluent from the columns. Column composition: C1 and C2 = 25% clay; C3 and C4 = 10% clay; C5 and C6 = 10% clay + biochar; C7 and C8 = 75% sand; C9 and C10 = 100% sandy loam. Correlations with $p \leq 0.05$ are shown with R-values shaded in a green gradient (lowest to highest), and multiple R-values shaded in a blue gradient. Correlations below the significance level ($p \leq 0.05$) are displayed in light grey text."Tot." stands for "Total", and "Diss" stands for "dissolved".

		Fe Tot.	Fe Diss.	Ba Tot.	Ba Diss.	Cu Tot.	Cu Diss.	Cr Tot.	Cr Diss.	Ni Tot.	Ni Diss.	Zn Tot.	Zn Diss.
C1	R^2	0.48	0.084	0.094	0.17	0.30	0.27	0.49	0.048	0.026	0.11	0.63	0.017
	multiple R	0.69	-0.29	-0.31	-0.41	0.54	0.52	0.70	0.22	0.16	-0.33	0.79	0.13
	p-value	0.027	0.45	0.39	0.27	0.10	0.15	0.023	0.57	0.66	0.39	0.0060	0.74
C2	R^2	0.94	0.19	0.025	0.094	0.92	0.10	0.97	0.029	0.86	0.28	0.99	0.72
	multiple R	0.97	-0.44	0.16	-0.31	0.96	-0.32	0.99	0.17	0.93	-0.53	1.0	0.85
	p-value	3.5E-06	0.24	0.66	0.42	9.8E-06	0.40	1.3E-07	0.66	1.2E-04	0.14	1.3E-09	3.7E-03
C3	R^2	0.010	0.20	0.076	0.047	0.17	0.0045	0.023	0.077	2.42E-05	0.059	2.87E-05	0.031
	multiple R	0.10	0.45	-0.28	-0.22	0.41	0.067	0.15	0.28	0.0049	-0.24	-0.0054	-0.18
	p-value	0.81	0.27	0.51	0.60	0.31	0.88	0.72	0.51	0.99	0.56	0.99	0.67
C4	R^2	0.84	0.46	0.18	0.28	0.90	0.50	0.87	0.20	0.82	0.42	0.91	0.53
	multiple R	0.92	-0.68	0.42	-0.53	0.95	-0.71	0.93	0.45	0.91	-0.64	0.96	-0.73
	p-value	0.00018	0.043	0.22	0.15	2.5E-05	0.033	9.2E-05	0.22	2.9E-04	0.06	1.6E-05	0.026
C5	R^2	0.13	0.43	0.061	0.080	0.32	0.32	0.11	0.24	0.16	0.17	0.062	0.10
	multiple R	0.36	0.66	-0.25	-0.28	0.57	0.56	0.33	0.49	0.40	0.41	0.25	0.32
	p-value	0.31	0.055	0.49	0.46	0.086	0.11	0.35	0.19	0.26	0.27	0.49	0.40
C6	R^2	0.98	0.077	0.72	0.27	0.95	0.50	0.96	0.18	0.99	0.04	0.98	0.29
	multiple R	0.99	0.28	0.85	0.52	0.98	-0.71	0.98	0.43	1.00	0.19	0.99	-0.54
	p-value	1.4E-08	0.47	0.0018	0.15	1.6E-06	0.033	4.9E-07	0.25	1.7E-09	0.62	2.4E-08	0.14
C7	R^2	0.71	0.18	0.11	0.21	0.68	0.10	0.68	0.093	0.66	0.04	0.82	0.19
	multiple R	0.84	0.42	-0.33	-0.46	0.83	0.32	0.83	0.31	0.81	-0.21	0.91	0.43
	p-value	0.0022	0.26	0.36	0.21	0.0033	0.41	0.0032	0.42	0.0045	0.59	0.00030	0.24
C8	R^2	0.65	0.016	0.062	0.17	0.45	0.059	0.75	0.0034	0.76	0.15	0.88	0.19
	multiple R	0.80	-0.12	-0.25	-0.41	0.67	-0.24	0.87	-0.058	0.87	-0.39	0.94	0.44
	p-value	0.01	0.75	0.49	0.28	0.03	0.53	1.1E-03	0.88	9.8E-04	0.30	6.1E-05	0.24
C9	R^2	0.98	0.59	0.12	0.20	0.92	0.56	0.98	0.82	0.055	0.11	0.46	0.008
	multiple R	0.99	0.77	-0.34	-0.44	0.96	0.75	0.99	0.91	0.23	-0.33	0.68	-0.089
	p-value	3.0E-07	0.03	0.37	0.27	0.000052	0.03	2.5E-07	0.0018	0.55	0.42	0.043	0.83
C10	R^2	0.97	0.029	0.0016	0.18	0.001	0.11	0.97	0.52	0.90	0.11	0.96	0.21
	multiple R	0.98	0.17	-0.04	-0.43	0.032	-0.32	0.99	0.72	0.95	-0.33	0.98	-0.46
	p-value	1.5E-06	0.69	0.92	0.29	0.93	0.43	1.3E-06	0.045	8.2E-05	0.43	2.8E-06	0.25
Influent	R^2	0.48	0.29	0.48	0.12	0.55	0.20	0.55	0.15	0.60	0.18	0.57	0.024
	multiple R	0.69	-0.54	0.69	-0.34	0.74	-0.44	0.74	-0.39	0.78	0.42	0.75	0.16
	p-value	0.026	0.11	0.027	0.33	0.015	0.20	0.015	0.26	0.0084	0.23	0.012	0.67

Notably, Paper IV also showed that particles rarely correlated with dissolved metals, which supports the interpretation that they primarily behave as mobile solids. However, the absence of consistent correlations across all filter types suggests that factors such as particle size, vegetation, and the presence of sorption materials may influence transport behaviour differently.

In Paper IV, the retention efficiency (RE) of fourteen tyre-derived chemicals (6PPD, 6PPD-Q, DPPD, IPPD, CPPD, 7PPD, HMMM, DPG, TWQ, MTBT, PhBT, MBT, BTSA, and OHBI) in unvegetated columns was assessed (Table 9).

Table 9. Retention efficiency of the fourteen tyre-derived chemicals (TDC[a]), 6PPD, 6PPD-Q, DPPD, IPPD, CPPD, 7PPD, HMMM, DPG, TWQ, MTBT, PhBT, MBT, BTSA, and OHBI in unvegetated columns C1 (25% clay), C3 (10% clay), C (10% clay + biochar)5, C7 (75% sand) and C9 (sandy loam).

		6PPD	6PPD-Q	DPPD	IPPD	CPPD	7PPD	HMMM	DPG	TMQ	MTBT	PhBT	MBT	BTSA	OHBT
C1	Filtered water	100%	100%	100%	100%			94%	96%	100%	81%			82%	78%
	Particles	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%		100%
	Sum	100%	100%	100%	100%	100%	100%	96%	100%	100%	97%	100%	100%	96%	99%
C3	Filtered water	89%	76%	100%	100%			-17%	50%	87%	39%			76%	-119%
	Particles	97%	99%	99%	98%	100%	100%	98%	99%	99%	98%	99%	100%	99%	99%
	Sum	97%	98%	99%	98%	100%	100%	15%	99%	99%	90%	99%	100%	95%	93%
C5	Filtered water	100%	100%	100%	100%			83%	92%	100%	65%			77%	39%
	Particles	100%	100%	100%	100%	100%	100%	100%	100%	100%	99%	100%	100%	100%	100%
	Sum	100%	100%	100%	100%	100%	100%	88%	100%	100%	94%	100%	100%	95%	98%
C7	Filtered water	100%	100%	100%	100%			97%	96%	100%	87%			86%	57%
	Particles	100%	100%	100%	100%	100%	100%		100%	100%	99%	100%	100%		100%
	Sum	100%	100%	100%	100%	100%	100%	98%	100%	100%	98%	100%	100%	97%	99%
C9	Filtered water	91%	91%	100%	100%			-57%	74%	100%	34%			47%	-153%
	Particles	99%	100%	100%	99%	100%	100%	94%	99%	100%	99%	99%	100%	99%	99%
	Sum	99%	99%	100%	99%	100%	100%	-15%	99%	100%	90%	100%	100%	89%	92%

[a]**6PPD** (*N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine*), **6PPD-Q** (*6PPD-quinone*), **DPPD** (*N,N'-diphenyl-phenylenediamine*), **IPPD** (*N-isopropyl-N'-phenyl-p-phenylenediamine*), **CPPD** (*N-(cyclohexyl)-N'-phenyl-phenylene-diamine*), **7PPD** (*4-N-(5-methylhexan-2-yl)-1-N-phenylbenzene-1,4, diamine*), **HMMM** (*hexamethoxymethylmelamine*), **DPG** (*diphenylguanidine*), **TMQ** (*2,2,4-trimethyl-1,2-dihydroquinoline*), **MTBT** (*2-(methylthio) 1,3benzothiazole*),

For particulate-bound TDC, RE was generally high (>97%) across all columns, except for the more water-soluble compound HMMM in the sandy loam column C9 (RE = 94.2%). These results suggest that filtration or sorption mechanisms may be effective in retaining particle-associated TDC. However, lower retention and leaching were observed for OHBT and HMMM in some filtered water samples, indicating that additional treatment approaches may be needed to limit the transport of these compounds to sensitive recipients. The variation in retention efficiencies points to a combination of concurrent processes, including filtration, sorption, and leaching, either from particle-bound compounds or from pre-existing pollutants in the soil. In some cases, retention or increased concentrations in leachate may also result from transformation processes. For example, ten chemicals, including phenylguanidine (PG), aniline, 2-(methylthio)benzothiazole (2-MTBT), 2-amino-benzothiazole (NH_2-BT), 2-(4-Mo)BT, 2-hydroxybenzothiazole (2-OHBT), benzothiazole-2-sulphonic acid (BTSA), 4-hydroxydiphenylamine (4-HDPA), 6PPD-Q, and nitroso-diphenylamine (NO-DPA), showed increasing concentrations over a 28-day experimental period (Foscari et al., 2024). Given the

complexity of these interactions, further research is warranted to improve understanding of the transport behaviour of dissolved TDC, particularly OHBT and HMMM, as well as their degradation pathways, transformation kinetics, and potential environmental implications. Overall, while some co-transport of particles, tyre-derived chemicals, and metals appears to occur under certain conditions, the extent and mechanisms of this co-transport are influenced by multiple interacting factors and merit continued investigation.

4.6. Effectiveness of measures aiming to reduce and remove TWP in Non-Urban and Urban Areas

As highlighted in Chapter 2.4, the measures can be divided into those which focus on source reduction and those which mitigate the spread of TWP. Paper I showed that personal vehicles contribute approximately 55% of TWP emissions in Sweden, underscoring the importance of optimising their design and usage. Key strategies include reducing gross vehicle weight, improving tyre rubber formulations, and exploring technologies such as vehicle-mounted particle collection systems. Although no such devices are commercially available yet, laboratory tests, such as those conducted by The Tyre Collective, demonstrate promising results. Heavy-duty vehicles account for roughly one-fourth of total TWP emissions. However, emission factor measurements or estimates for these vehicles remain scarce and poorly documented, indicating a significant gap in current knowledge and a high potential for further research in this area.

This thesis has mostly explored the effectiveness of measures mitigating the spread of TWP. Three different types of measures retaining TWP have been studied in this thesis: a stormwater system, bioretention filters commonly practised in urban settings, and road ditches, primarily typical in rural settings but also frequently practised in urban settings. In general, the effectiveness of stormwater-related measures is evaluated by alignment with the environmental objectives, such as Swedish Environmental Quality Objectives, EU Water Framework Directive (WFD), EU Taxonomy for Sustainable Activities, Zero Pollution Action Plan (2021–2030), Sustainable Development Goals, and compliance with guideline values at specific monitored locations. Road ditches present a special case, as they may also fall under various guidelines related to soil protection and land use, such as the EU Soil Strategy for 2030, the Soil Monitoring Law (2025 Provisional Agreement), and the Land Use and Soil Sealing Guidelines.

At present, the EU has not established numeric threshold values for TWP concentrations in water, soil, or air, nor are such limits currently enforced at the municipal level in Sweden. Therefore, the effectiveness of these measures can only be evaluated by extrapolating findings from specific case studies, such as those presented in this thesis, and assessing their relevance and applicability to broader environmental contexts.

Stormwater systems

The stormwater system investigated in Paper II exhibited a decrease in TWP (1.6–500 µm) concentrations in sediments along the flow path, from the gully pots to well WA and finally to the outlet pipe sediment (see Chapter 4.2 and Paper II). Moreover, the fine fraction of TWP was highly abundant in standing water samples and remained prevalent in the sediments within the stormwater system. These findings indicate that conventional stormwater treatment components, such as gully pots and sand traps, are relatively ineffective at retaining finer TWP fractions. This highlights the high mobility of TWP in the water phase and their tendency to resuspend in standing water. While these limitations may not justify a complete redesign of stormwater systems, they highlight the need for improved management strategies in environmentally sensitive areas. Future monitoring and sampling efforts should also be adapted to better capture and analyse smaller TWP fractions, which are currently underrepresented but play a critical role in downstream transport and accumulation.

Road Ditches

In general, the results from paper IV showed that the soil columns have overall high retention of TWP, metals and several particulate-bound, and a few dissolved tyre-derived chemicals (PPD and PPDQ). Tyre wear particles smaller than 500 µm were retained with RE between 84–99% across the different soil types used in the experiment. Particle-bound tyre-derived chemicals exhibited higher retention (94–100%) and the dissolved ones (-153–100 % with a mean retention for all columns for all analysed TDC equal to 70 %). However, several of the dissolved tyre-derived chemicals, such as IPPD, MTBT, HMMM, OHBT, exhibited lower retention than, for example, 6PPD, 6PPD Q, DDP and TMQ.

As earlier highlighted, the vegetation and porous soils can facilitate the transport of both TWP and metals. To improve the design of road ditches filled with sand, structural modifications such as lined cells, compacted clay lenses, geotextiles, or drainage pipes leading to treatment systems (e.g., sedimentation dams) can be implemented, especially in areas where groundwater protection is critical. Filtration efficiency can also be enhanced by incorporating dense, salt- and cold-tolerant turf or a dedicated biochar layer targeting fine particle retention. These potential modifications should be carefully evaluated, balancing the pollutant-retention capacity of road ditches with their essential drainage function, especially in light of projected increases in runoff due to climate change. In locations where the risk of high flows is significant, but pollutant retention remains a priority, stormwater should be diverted to temporary storage and treatment facilities to prevent overload and ensure effective contaminant removal.

Papers III and IV also showed that TWP can be found at greater depths (down to 0.5 m) in clayey soils, likely due to vertical transport through cracks formed during dry periods. To minimise this, cracking should be reduced by maintaining surface organic matter (e.g., mulch or topsoil) to buffer shrink-swell cycles. Not least, in climates with distinct dry and wet seasons, it may be beneficial to disrupt cracks before the onset of heavy rainfall.

Since vegetation can significantly influence the transport of TWP, and given that these particles tend to accumulate in the topsoil, the role of vegetation warrants further investigation. Although this study did not include direct sampling from vegetation, future research should assess the extent to which TWP are retained by vegetation, either through physical interception or sorption to organic matter, and how much is instead transported via preferential flow paths created by

root systems. Moreover, variations in vegetation type, as well as differences in establishment stage and life cycle, may influence the capacity of vegetation and road ditch soil to retain TWP and should be carefully considered in future studies.

Amendment with biochar was shown to increase the retention of TWP in the fine-grained, non-vegetated soils. The results suggest that biochar may offer a strategy to reduce the spread of TWP in and from roadside ditches, while simultaneously contributing to climate mitigation by offsetting CO_2 emissions from the production of road construction materials such as concrete and reinforcement steel. For analytical consistency, biochar may be applied as a distinct layer rather than mixed with sand, as mixed biochar-sand matrices are difficult to sieve and analyse for TWP. However, biochar-amended soils with vegetation cover demonstrated lower retention efficiency, particularly following drought conditions. These findings highlight the need for further research to determine the long-term relevance of biochar in near-road environments, especially under varying weather conditions and over extended time periods

Bioretention system

Bioretention filters (Paper V) with the addition of sorption materials have demonstrated removal efficiencies of 97–100% for tyre wear-related polymers, including styrene-butadiene rubber (SBR), polybutadiene (PB), and polyisoprene (PI) in particle fractions larger than 10 µm. These results are consistent with previous findings on rubber particle removal in biofilters, including those by Lange et al. (2021), who reported 80–88% removal for rubber particles sized 100–300 µm in both vegetated and non-vegetated sand-based filters, and Smyth et al. (2021), who observed 89% removal in filters composed of 62% sand and 38% silt.

To date, no other studies have specifically addressed the behaviour of microplastics and TWP in bioretention systems under extreme weather conditions. However, the findings presented here in Paper V provide valuable insights and highlight the need for further research on the resilience and performance of stormwater treatment systems under changing climatic conditions, particularly in response to longer periods with drought, increased rainfall intensity and frequency.

5. CONCLUSIONS

The findings presented in this thesis offer evidence-based insights into the occurrence, transport, and retention of TWP, traffic-related metals, and TDC in Swedish road environments and stormwater systems. These results are relevant for decision-makers involved in environmental regulation, infrastructure planning, and sustainable transport policy.

A comprehensive methodology was developed to estimate national TWP emissions, incorporating emission factors by tyre type, vehicle category, and road type, alongside annual mileage data. Heavy-duty vehicles were further categorised by weight class and number of tyres. Passenger cars contributed the largest share of emissions (55%), followed by heavy-duty vehicles (31%), light-duty vehicles (10%), buses (3%), and motorcycles (0.09%), with rural roads accounting for the highest emissions. The mileage-based approach proved reliable for estimating emissions from passenger cars and light-duty vehicles. However, uncertainties in emission factors and mileage data for heavy-duty vehicles and buses reduced the accuracy of national estimates for these categories. TWP were quantified throughout stormwater systems, including gully pots, wells, and ditches, with limited retention of the fine particles. Fine particles (1.6–20 μm) constituted a substantial portion of the total TWP load in both standing water samples (78±17%) and in sediment samples from the stormwater system (32±23%). In road ditch soils, TWP (<500 μm) were widespread, with concentrations decreasing with distance from the road but showing no consistent trend with depth. A strong correlation between TWP and zinc was observed in Ditch I, while in another, Ditch II, zinc appeared to leach independently of TWP, possibly due to prolonged contact with water.
Vegetation influenced TWP transport by creating preferential flow paths through root systems, particularly during dry periods when soil cracking enhanced vertical movement. Biochar amendment improved TWP retention and vegetation growth in fine-grained soils, though its effectiveness declined under drought conditions, which warrants further long-term evaluation. The addition of biochar also improved the retention of TDC and metals, and may contribute to climate mitigation by offsetting carbon emissions from construction materials such as concrete and steel. While increased irrigation under cold conditions had a limited impact on overall TWP removal efficiency in bioretention filters with the addition of sorption materials, potential resuspension and altered flow dynamics may still affect particle mobility. Soil moisture was identified as an important factor for effective retention in fine-grained soils.

Metal concentrations (e.g., Zn, Cu, Cr) increased alongside TWP in topsoil, although correlations between TWP and metals were generally absent in soil matrices. In contrast, strong correlations between TWP and total metals were observed in effluent waters, but not with dissolved metals, supporting the particulate nature of TWP transport. Co-transport of TWP and metals was evident in the water phase, as indicated by correlations in influent and effluent samples. However, retention in soil was more variable and likely governed by complex interactions involving sorption, leaching, and soil composition.

Fourteen tyre-derived chemicals (TDC), particularly 6PPD and 6PPD-Q, were quantififed and with the highest concentrations in topsoil. Particulate-bound TDC were retained with high efficiency (>97%) across most soil columns, while more soluble compounds (e.g., HMMM, OHBT, MTBT, BTA) exhibited variable leaching, indicating the need for further investigation into their environmental behaviour.

6. FUTURE WORK

The following is of high interest for future research:

- Quantifying accurate TWP emission factors from heavy-duty vehicles through field measurements.
- Investigate degradation pathways of TWP and leaching studies on tyre-related chemicals, both in controlled environments and in real-life environments.
- Investigate microbial degradation behaviour and the biological influence of TWP degradation.
- Study the function of vegetation as a natural retention barrier in retaining TWP in road ditches.
- Study effects of winter road maintenance such as salting and snow melting on TWP transport through fine-grained soils.
- Research the impact of climate variability, specifically alternating drought and heavy rainfall, on the hydraulic and pollutant-filtering performance of roadside ditches.
- Further study the dual functionality of biochar as a pollutant sorbent and long-term carbon sink in ditch systems.
- Investigate the synergistic effects of combining various sorbent materials, ditch designs, flow conditions, and vegetation types on the capture efficiency of metals, organic pollutants, and microplastics in suburban highway ditches.

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