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Polukarova, M., Johansson, G., Rødland, E. et al (2026). Transport processes of tyre wear particles, tyre-derived chemicals, and metals in road ditch
soil with and without the addition of biochar. Microplastics and Nanoplastics, 6(1).
http://dx.doi.org/10.1186/s43591-026-00237-x

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Microplastics and Nanoplastics

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Transport processes of tyre wear particles, tyre-derived chemicals, and metals in road ditch soil with and without the addition of biochar

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Abstract

This study investigates the transport of tyre wear particles (TWP), a significant source of microplastics, together with metals and tyre-derived chemicals (TDC) in soil mixtures that could be used in road ditches. The aim was to identify soil mixtures with high pollutant retention. In a ten-month column experiment, soil mixtures were tested to evaluate their retention efficiency (RE) for TWP, metals, and TDC from polluted stormwater used for irrigation at different frequencies. The soil mixtures consisted of duplicates both with and without grass, made from clay, sand, and biochar added as a carbon sink and sorbent. The samples were analysed by Pyr-GC/MS for TWP in soils 0.3–500 µm and water 1.6–500 µm. The stormwater used for column irrigation was collected from a sedimentation facility next to a highway with an AADT of 105,000 vehicles, including 11% heavy-duty trucks. It contained concentrations of TWP ranging from 1.8 to 3.2 µg/L. In addition, stormwater spiked with sediments from the same facility was used for irrigation, resulting in concentrations of TWP of 230–1500 µg/L. After the experiment, the top layer contained 91–96% of retained TWP mass (0.3–500 µm) in soil mixtures, with decreasing amounts at greater depths. The removal efficiencies for TWP (1.6–500 µm) from stormwater were high and ranged from 93% in clay with grass and up to 99% in sandy loam–clay without grass. Biochar-amended soils generally exhibited similarly high retention of TWP as the corresponding soils without biochar. The concentrations of tyre-derived chemicals were highest in the upper soil layers and followed the order: 6PPD > BTSA > DPG > DPPD > 6PPD-Q > OHBT > TMQ > MBT > MTBT > PhBT > IPPD > HMMM > 7PPD > CPPD. Grass enhanced TWP transport following drought conditions, suggesting that vegetation may increase particle mobility within road ditch soils under certain climatic conditions. Nevertheless, TWP mainly accumulated in the upper soil layers, and all investigated soil mixtures showed high retention efficiencies. Overall, the results indicate that sandy loam-clay, sandy, and biochar-amended road ditch soils all have a high capacity to retain TWP. While biochar did not provide a clear additional retention benefit under the conditions tested, vegetation may influence TWP mobility and should be considered in the design and management of road ditch systems.

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Highlights

- All the studied soil mixtures showed high TWP retention efficiencies of 93–99%.
- TDC, particularly 6PPD and 6PPD-Q, were efficiently retained in several of the soil mixtures.
- TDC were retained in the total fraction but more mobile in the <0.45 µm fraction.
- Biochar-amended soils showed similar TWP retention to the corresponding soils.
- Vegetation may enhance TWP mobility in roadside soil, particularly under drought conditions.

Keywords Toxic trace metals, Microplastics, Sand, Clay, Column study, Filtration, Carbon capture

Introduction

In areas with high traffic intensity, a complex cocktail of contaminants, including microplastics (MP), metals, and organic pollutants (OP), has been reported [1–5]. Among these, tyre wear particles have emerged as a significant environmental concern. Their environmental risks have attracted regulatory attention, including within the European Union's Euro 7 emissions standard, the first to include non-exhaust emissions within its scope [6, 7]. In Sweden alone, the annual release of tyre wear particles (TWP) into the environment is estimated to be between 11,000 and 12,000 metric tonnes [5]. Tyre wear particles have been found in multiple environmental matrices [8, 9] and yet their transport in complex matrices, such as soil, remains under-researched, despite its importance for the design and maintenance of roadside ditches [10, 11].

Beyond their high volume of emissions, TWP raise significant concern due to their chemical and morphological characteristics. The main components of tyres are natural rubber and synthetic rubber polymers. In addition, tyres contain tyre-derived chemicals (TDC), which constitute 5–10% of the tyre mass [12]. These chemicals are used during tyre production and are important for properties such as road-grip, fuel and energy efficiency, as well as for external noise reduction [8, 13, 14]. They include preservatives, antiozonants, antioxidants, desiccants, plasticisers, and processing aids. Common chemical groups reported in tyres include amines, phenols, guanidines, benzothiazoles, melamine-based compounds, and p-phenylenediamine (PPD) [14]. The environmental occurrence of TDC and their transformation products was confirmed in various matrices [15, 16], and several exhibit a complex mixture of acute and chronic ecotoxicological effects in aquatic ecosystems [17, 18]. Besides organic additives, tyre rubber also contains metals such as zinc, commonly present as zinc oxide. In addition, metals associated with brake wear, including iron, copper, zinc, barium, chromium and lead [19, 20], as well as metals reported at elevated concentrations in road environments, such as nickel, vanadium and cadmium, can accumulate by sorption on TWP surfaces [21–23]. Several of these metals, including Pb, Hg, Cd, Cr and As, are known to cause a range of adverse effects in humans, including neurological, reproductive, cardiovascular, respiratory, and genetic impacts [24, 25]. Metals are frequently observed in road ditch soil [26], but few studies have investigated their co-occurrence with TWP and their combined transport and retention in roadside environments.

Although soil is likely the primary environmental sink for TWP and associated TDC, most existing studies have focused on their occurrence and behaviour in aquatic systems and airborne dust, as well as their toxicity to aquatic organisms, highlighting a critical gap in understanding their fate in soil environments [15]. Only a few studies have examined TWP transport in soils [10] or engineered soils in bioretention filters [27–31], and to our knowledge, no studies have yet investigated factors affecting transport of TWP and TDC in soil mixtures, representative of road ditch soil. Research on MP suggests that factors such as particle size of the MP [32, 33], the presence of dissolved organic matter [34], irrigation intensity [35], drought [36], and vegetation/plants [37] influence their transport through soil. However, whether these or other factors similarly affect the transport and fate of TWP in ditch soils remains unknown.

Although biochar has been studied in agricultural and stormwater contexts, its application in roadside soil systems for the retention of MP and TWP remains largely unexplored. Previous studies have demonstrated biochar's potential to improve soil structure, water retention, and pollutant adsorption, particularly in bioretention systems and sandy or degraded soils [38]. Biochar has been shown to enhance soil moisture and boost plant resilience amid variable moisture and salinity levels. Additionally, biochar can help mitigate climate change by serving as a stable carbon sink, sequestering carbon over long periods and lowering greenhouse gas emissions [39, 40]. These combined properties suggest that biochar may be a valuable amendment for roadside ditches, particularly under increasingly variable climatic conditions. Such variability may include more frequent droughts, drying-rewetting cycles, freeze-thaw events, and more intense and heavier rainfall. These conditions can alter soil structure, promote cracking and the development of preferential flow pathways, and thereby affect the transport of TWP and associated contaminants. By improving

water-holding capacity and soil structure, biochar may help maintain pollutant retention under such conditions.

This study addresses these knowledge gaps by investigating the transport patterns of TWP, TDC, and traffic-related metals in controlled soil column experiments designed to represent a range of roadside ditch soil types, thereby providing essential data to support environmental risk assessment and the development of pollution-mitigation strategies in near-traffic environments. Through column experiments, we evaluate, for the first time, the retention efficiency and vertical distribution of these pollutants in various engineered soil mixtures and commercially available sand substrates with and without vegetation cover and biochar amendment, selected for their potential to enhance sorption capacity and carbon sequestration. The following hypotheses are addressed: (1) Roadside ditches effectively retain TWP and associated TDC; (2) Vegetation enhances the retention of TWP and TDC; (3) Biochar amendments influence pollutant retention within the soil matrix.

Materials and methods

To evaluate the transport of TWP, TDC and metals in different soil matrices, column experiments were conducted. Each column had a different soil mixture and was irrigated with road runoff.

Column design and soil mixture selection

Ten PMMA columns (0.65 m height and 0.25 m diameter) were constructed and packed with five different homogenised soil mixtures. The main soil layer consisted of soil mixtures containing different proportions of clay, sandy loam, sand and biochar, selected to examine TWP and TDC transport under different road ditch soil conditions. The sandy loam consisted of a commercially available landscaping soil used in Swedish road construction projects. Each mixture was tested with and without grass vegetation. Each column consisted of a topsoil layer, a main soil layer and underlying drainage layers of sand and gravel.

For the column experiments five soil mixtures were evaluated in the main layer (Fig. 1, Fig. S1 and Table S1 in Supplementary Material). Columns C1–C2 contained 25% clay, Columns C3–C4 contained 10% clay, Columns C5–C6 contained 10% clay and biochar and Columns C7–C8 were dominated by sand and Columns C9–C10 consisted of sandy loam. In Columns C1–C6 the clay was mixed with sandy loam to better represent heterogeneous roadside ditch soils, which typically contain varying grain sizes and layers due to natural variability and road construction. The clay-rich soil mixtures were selected because of their natural occurrence in parts of Sweden. It was also selected to build on Polukarova et al. [41], who studied TWP occurrence and distribution in clay-filled roadside ditches at Testsite E18 in Västerås, from where the clay was collected (Fig. S2). This enabled further investigation of TWP transport in clay-rich ditch environments relevant to Swedish road infrastructure located in areas with naturally clay-rich soil. Sand was included because it is widely used as a filter material for particle

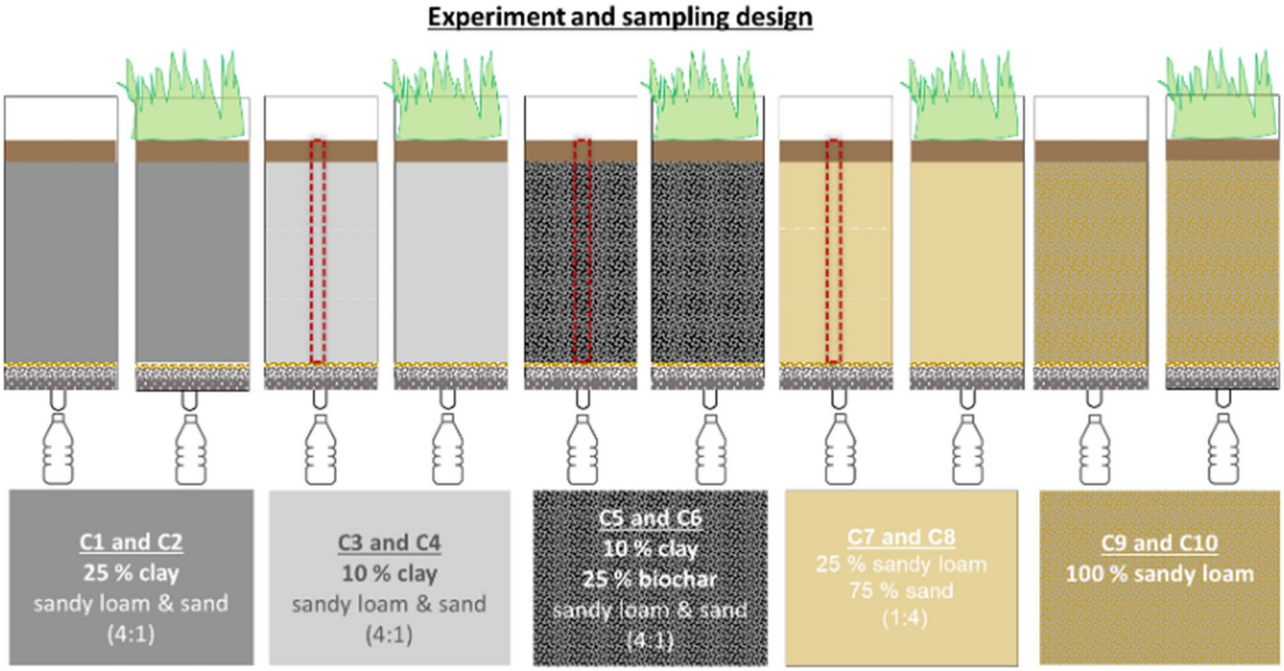

Fig. 1 Design of the columns used for the experiment. The red lines indicate in which columns (and which layers) the soil was sampled after the experiment

removal in water treatment systems and is therefore relevant for assessing TWP transport. Its uniform texture and high permeability made it a suitable reference material for evaluating TWP mobility under roadside drainage conditions. Morainic soils are the most common natural soil type in Sweden and are widely used in road construction, the landscaping soil used in C9–C10 was considered representative of typical Swedish road ditch conditions. Although more processed and homogenised than natural moraine, its particle-size distribution and composition reflect materials commonly used in roadside environments, providing realistic conditions for assessing TWP transport (Fig. S2). The amendment of biochar was selected for its reported capacity to sorb stormwater pollutants [42] and contribute to carbon sequestration [39]. The biochar was supplied by Hjelmsäters Egendom and produced from FSC-certified local conifer wood chips and harvest residues, mainly from spruce forest affected by spruce bark beetle. Its physical and chemical characteristics are described by Johansson et al. [28]. Topsoil was used to support seed germination, vegetation establishment and early growth, while representing the top layer typically present in roadside ditch environments.

Detailed descriptions of the materials used to construct the main and topsoil layers, including material sources, clay sampling and storage procedures, soil mixture compositions, particle-size distributions, organic matter contents, physical and chemical characteristics, and initial material characterisation, are provided in the Supplementary Material (Sections 1.2 and 1.8, Fig. S3, S4 and Table S8). Before packing, the soil mixtures were homogenised, and the columns were saturated with tap water for two weeks to promote soil settlement and establish flow conditions similar to roadside ditches. Initial concentrations of metals and TWP in the column materials were determined before the experiment (Tables S2, S10, S11 and Fig. S4). Concentrations varied among the materials but were below Swedish guideline values for sensitive land use [43].

Selection of vegetation

The high variability in roadside ditch vegetation across Sweden makes selecting a representative vegetation type challenging. The chosen mixture consisted of various grass species commonly found in Nordic countries and widely used in roadside ditches, including *Festuca rubra, Festuca pratensis, Festuca ovina,* and *Agrostis capillaris* (86%), along with a mix of herbs (14%) as listed by Vegtech [44]. Notably, Festuca rubra is frequently used and studied in phytoremediation projects involving contaminated soils. It has demonstrated promising effects on the mobility and accumulation of soil contaminants, including metals [45, 46]. Vegetation was established in all evenly numbered columns prior to the start of the experiment. Detailed information on the vegetation establishment procedures, growth conditions, harvested biomass and vegetation observations is provided in the Supplementary Material (Section 1.3 and Fig. S5).

Irrigation

Before irrigation with stormwater, the columns were flushed with 6 L tap water on 2024–02-13 to assess contaminant leaching from the column materials. Tap water was used instead of deionised water to better represent environmentally relevant conditions, including pH, alkalinity, conductivity, and ionic strength; its chemical composition is publicly reported by the supplier [47]. The effluent was collected for chemical analysis. The columns were then irrigated weekly with real stormwater for four weeks, from 2024–02–13 to 2024–03-12, to promote soil settling; this period is referred to as the establishment phase. Stormwater was collected from a sedimentation facility in Gårda, Gothenburg, which drains a 5.1 ha catchment area, including 2.1 ha of impervious surfaces composed mainly of roads (82%), rooftops (6%), and other sealed surfaces (12%) [48]. The nearby E6 highway lies within the catchment and carries approximately 105,000 vehicles per day, including 11% heavy-duty vehicles, according to the Swedish Transport Administration. The stormwater was stored outdoors in 20–25 L plastic (PE) containers at variable temperatures of 0–25 °C. From 2024-02-12, the columns were irrigated on 11 occasions over 8.5 months with 6 L stormwater per event, with decreasing frequency over time (Fig. 2). This volume ensured consistent irrigation and sufficient sample volume for chemical analysis.

From the sixth irrigation event, the stormwater was spiked with sediment from the Gårda facility to keep the concentrations TWP in the effluent above analytical limits of quantification and to simulate high pollutant loads, including concentrations reported in stormwater and tunnel studies [49]. The sediment had previously been analysed for TWP-related polymers and other microplastics [28], showing 4.6% PB (11,500 µg/kg dry sediment) and 56% PI (142,000 µg/kg dry sediment), indicating abundant rubber wear particles with substantial natural rubber content. The sediment was collected with a grab sampler, homogenised, and 0.1 L was added to the influent of each column during each irrigation, corresponding to approximately 0.016% of the irrigation water volume. It was stored either outdoors in sealed plastic PE/PP boxes or refrigerated. Concentrations of TWP and other studied contaminants in inflowing and spiked stormwater are provided in Supplementary Material 2.5 and 2.7.

During periods without weekly stormwater irrigation, the columns received small amounts of tap water (0.5 L) to maintain vegetation on 2024–06-17 and 2024–08-13; this period is referred to as "summer irrigation". From

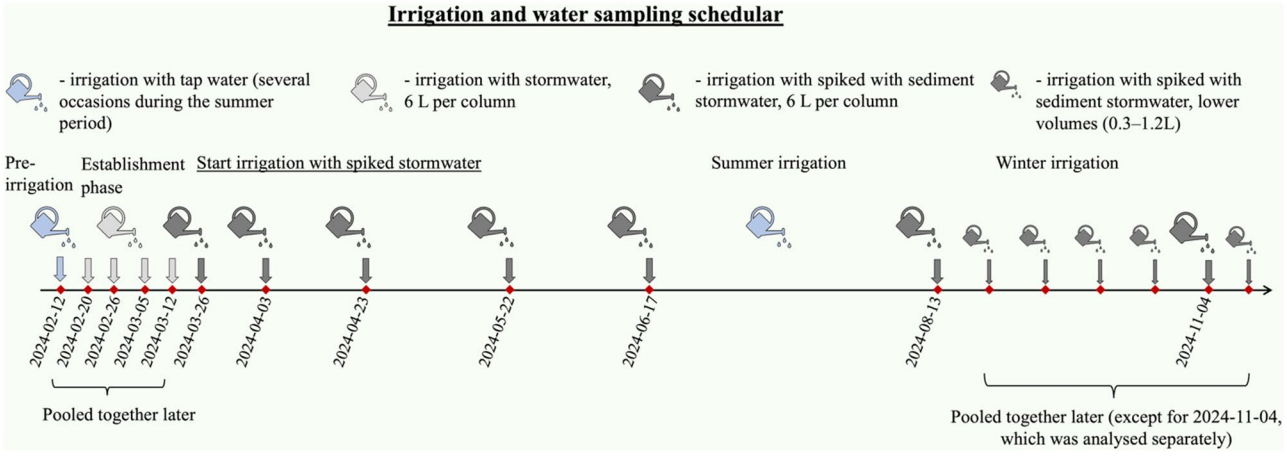

Fig. 2 Schedule for the irrigation of the columns

early September to 6 December, the columns were irrigated with 0.3–1.2 L stormwater per event, spiked with sediment from the Gårda facility. The added sediment volume corresponded to 10% of the stormwater volume. Samples from these five events were pooled for analysis and referred to as "winter irrigation".

Water sampling

Effluents from the columns were collected after each irrigation event. For Columns 5–10, sampling was performed within 24 h after irrigation, while effluent from Columns 1–4 was collected within three days because of their lower hydraulic conductivity. The collected effluent was weighed to determine volume and subsampled for TWP, TDC, metal, TOC/DOC, TSS and VSS analyses. For dissolved organic carbon and dissolved metals, samples were filtered through 0.45 µm filters prior to analysis. Detailed information on sample collection, preservation, storage and handling is provided in the Supplementary Material (Section 1.5)

The mass-based retention efficiency, RE, for each analysed parameter was estimated as:

$RE(i) = ((M_{i,in} - M_{i,out})/M_{i,in})$ x 100%

where

RE is the retention efficiency in percent,

$Mi_{,\,in}$ is the mass (concentration in water multiplied by volume of water) of the analysed TWP and TDC in the influent water

$Mi_{,\,out}$ is the mass (concentration in water multiplied by volume of water) of the analysed TWP and TDC in the effluent.

Soil sampling after the experiment

Following the completion of the irrigation, soil samples were collected from three non-vegetated columns (C3, C5, and C7) for analysis of loss on ignition (LOI), concentrations of metal, and TWP and TDC. These specific columns were selected to investigate TWP transport in three distinct soil types: clay-rich soil (C3), sand (C7), and biochar-amended clay soil (C5). Sampling was performed by excavating the soil layer by layer. First, the topsoil (0–0.05 m) was removed and sampled. Then, the main (0.05–0.50 m) soil layer was divided into three equal sublayers (0.05–0.2 m, 0.2–0.35 m and 0.35–0.50 m), which were sampled individually. This stratified sampling approach was used to assess the vertical distribution of TWP within the soil profile and to better understand their mobility through different soil compositions.

Chemical analyses

Tyre wear particles

As some of the analysed water samples had particles agglomerated or stuck to the walls of the glass water bottles, all samples were treated in an ultrasonic bath (Bandelin RK 510 H) for 30 minutes. The samples were subsequently shaken and wet-sieved using an ISO 3310/Fisherbrand test sieve with a mesh size of 500 µm. The fraction passing the sieve (<500 µm) was collected for TWP analysis, while coarser particulate matter was excluded. The selected cut-off is considered environmentally relevant because previous laboratory and field studies have shown that most TWP occur at sizes well below 500 µm. Reported mass distributions are typically dominated by particles in the micrometre range, whereas TWP larger than 200 µm are less frequently reported [14, 50–52]. Furthermore, the use of a 500 µm cut-off allowed direct application of the analytical method developed by Rødland et al. [53], thereby facilitating comparison with previous studies. Thereafter, the samples were transferred to 50 mL Falcon tubes and centrifuged (Labex Sigma 4–16, 3,000 rpm) before vacuum filtration on binder-free glass fibre filters (GF/Whatman, pore size 1.6 µm, diameter 25 mm), which had been pre-treated for 2 h at 550 °C in a muffle furnace. The supernatant was filtered

first, after which the particle pellet was resuspended and transferred onto the same filter. This procedure effectively served as a pre-concentration step, allowing the relatively particle-free water fraction to be filtered before the concentrated particulate matter was added, thereby reducing filter clogging and improving filtration efficiency. Furthermore, concentrating the particulate fraction onto a single filter helped ensure that enough particulate material was collected for reliable Pyr-GC/MS analysis of TWP. This was particularly important for samples with high organic matter content, where filters occasionally became clogged before sufficient material had been accumulated for analysis. To minimise particle losses due to adhesion to the filtration equipment, ultra-pure water was used to rinse particles from the walls of the filtration cup and sample containers. Ethanol was additionally applied to reduce particle adhesion and aid in the removal of residual organic matter. The air-dried filters were weighed before and after filtration and then rolled into pyrolysis cups for analysis. Influent samples were analysed in duplicate due to the limited filtered volume, whereas effluent samples were analysed as a single replicate for each sample and irrigation event. Detailed information on the Pyr-GC/MS analytical settings, method development, accuracy, and precision is provided in Supplementary Material Section 1.6 and in Rødland et al. [53].

Post-experiment soil samples were collected from the top layer (0–0.05 m) of columns C3, C5, and C7, as well as from three depths within the main layer (0.05–0.20 m, 0.20–0.35 m, and 0.35–0.50 m). Post-experimental soil samples from the top layer were analysed in triplicate. The post-experimental soil main layer was also analysed for TWP in triplicate, with one replicate per sublayer. Pre-experimental soil samples (C3, C5, and C7) from the top layer were analysed in duplicate, and those from the main layer in triplicate. The soil samples were initially air-dried and subsequently dry-sieved using a Fisherbrand 500 µm test sieve (ISO 3310) mounted on a mechanical sieving machine. The fraction passing through the sieve (<500 µm) was collected and used for subsequent analyses. To ensure complete dryness, a subset of the samples was also freeze-dried. Following drying, approximately 10–11 mg of each sample was weighed into a 100 mL Erlenmeyer flask, to which 100 mL of 30% hydrogen peroxide (H_2O_2) was added for oxidative treatment. The samples were incubated overnight at 50 °C with continuous stirring at 100 rpm. After incubation, the samples were filtered using 13 mm GF-75 glass fibre filters (pore size of 0.3 µm) and subsequently dried at room temperature. The dried filters were then spiked with an internal standard (deuterated Polybutadiene, d_6-PB, Polymer Source, Quebec, Canada) and analysed using pyrolysis–gas chromatography/mass spectrometry (Pyr-GC/MS). The samples were analysed with a multi-shot pyroliser (EGA/PY-3030D) equipped with an auto-shot sampler (AS-1020E) (Frontier lab Ltd., Fukushima, Japan) coupled with a gas chromatograph-mass spectrometer (GC/MS) (5977B MSD with 8860 GC, Agilent Technologies Inc., CA, USA) following the methods established by Rødland et al. [53] using the markers benzene (m/z 78), α-methylstyrene (m/z 117), ethylstyrene (m/z 118), and butadiene trimer (m/z 91) with some modifications. The combined concentration of SBR and BR was used to calculate the concentration of TWP in each sample. This calculation is based on the method described in Rødland et al. [53], using the measured concentrations of SBR + BR in reference tyres ($n = 31$) relevant to the Nordic road environment, along with a Monte Carlo prediction model. This provides the average concentration of TWP in each sample, based on 100,000 model simulations, as well as the median values, standard deviations and percentiles. For further analytical details, see Supplementary Material Section 1.6.

Tyre-derived chemicals

The sampling for the TDC analysis was carried out to obtain an initial indication of the presence of these chemicals in stormwater and to assess their potential retention efficiency in the different soil mixtures. The sediment-spiked influent stormwater sample and five effluent samples without grass (C1, C3, C5, C7, and C9) from the winter irrigation period, along with six soil samples collected after the experiment from the top and main layers of columns containing 10% clay (C3), biochar (C5), and sand (C7), were analysed for the presence of 14 tyre-derived chemicals: 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-sulphonic acid (BTSA), and 2–1,3-benzothiazol-2-ol (OHBT) (Table S7). All these samples were analysed as single replicates. The soil samples were taken and analysed as a representative sample from a volume of 2.5 L (top layer) and 22.1 L (main layer). For influent and effluents, a single representative sample was taken and analysed from the collected volumes of 0.19–1.3 L. Sample preparation and analysis followed the method described by Meland et al. [12], 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 additional 1 mL Milli-Q 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-triple quadrupole mass spectrometry (UPLC-MS/MS) was used for target quantitation of the TDC. The Xevo TQ-S MS/MS instrument (Waters) was employed as described by Meland et al. [12]. 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.

Trace metals

Influent and effluent water samples, along with non-sieved soil samples collected before and after the experiment from non-vegetated columns containing 10% clay (C3), biochar (C5), and sand (C7), were analysed for concentrations of the following metals: As, Ba, Pb, Cd, Co, Cu, Cr, Hg, Ni, V, and Zn. Post-experiment soil samples were collected from the top layer (0–0.05 m) of each column, as well as from three depths (0. 05–0.20 m, 0.20–0.35 m, and 0.35–0.50 m) in the main layer of the same columns, following the same methodology used for sampling soil for TWP analysis. Soil samples from the top layer were analysed 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 using a single replicate. These samples were not sieved prior to analysis. Prior to the metal analyses at an external certified laboratory, the water samples were shaken thoroughly before being digested with 7 M HNO_3 (Merck, Germany) prepared using DuoPur acid purification system (Milestone, Italy). After digestion, the concentrations of trace metals were determined using inductively coupled plasma mass spectrometry (ICP-MS), in accordance with the Swedish-adopted European and international standards SS-EN ISO 15587–2:2002 and SS-EN ISO 17294–2:2016. Soil metal analysis was conducted in accordance with the Swedish standard SS 28,311:2017mod and SS-EN ISO 11885:2009. The metal analyses were performed by an ISO/IEC 17,025-accredited external laboratory.

Other parameters

Additional soil and water properties were determined following standardised methods to characterise the column materials and effluents. These included grain-size distribution, organic matter content, hydraulic conductivity, conductivity, TOC/DOC and TSS/VSS. Detailed analytical procedures and results are provided in the Supplementary Material (Section 1.8).

Results and discussion

Tyre wear particles

Concentrations in soil

In Fig. 3 (and in Table S11 in Supplementary Material), the concentrations of TWP (0.3–500 µm) in the original soil are compared with the soil after the 41-week period of irrigation with highly polluted stormwater.

The concentration of TWP (0.3–500 µm) in the topsoil before it was placed in the columns was 8.0 ± 3.3 g/kg ($n = 2$), and the concentrations in the main layer of columns without grass, C3 (10% clay), C5 (10% clay + biochar), and C7 (75 sand) were 1.2 ± 0.50 ($n = 3$), 1.8 ± 0.80 ($n = 3$), and 1.1 ± 0.50 g/kg ($n = 3$) respectively, see Fig. 3. The concentrations of TWP in the original topsoil can be compared with concentrations (in fractions < 500 µm) in road ditch soils reported by Polukarova et al. [41] of 0.74 ± 0.2 to 12 ± 1.89 g/kg and 0.83 ± 0.14 g/kg, Rødland et al. [11] of 2.0–26 g/kg and Beaurepaire et al. [54] up to 16 g/kg, highlighting that the the concentrations TWP in the topsoil used in these experiments are high and at concentrations close to soils along heavily trafficked roads. These high concentrations can be explained by rubber contamination either due to contamination already present in the original plant soil or introduced during production. Commercial planting soil may become contaminated with rubber particles through several potential pathways, including contact with rubber-based conveyor belts and machinery during processing and bagging, contamination of raw materials such as compost, bark, peat, or sand, and deposition of tyre wear particles during storage, transport, or handling near traffic environments. Considering the small number of samples in this study, these results motivate further investigation of the concentrations of TWP in commercially available plant soils. If these soils show high concentrations of TWP, the uptake of TWP by plants and accumulation in small organisms should be investigated further. Nevertheless, the TWP concentrations in the topsoil after the irrigation

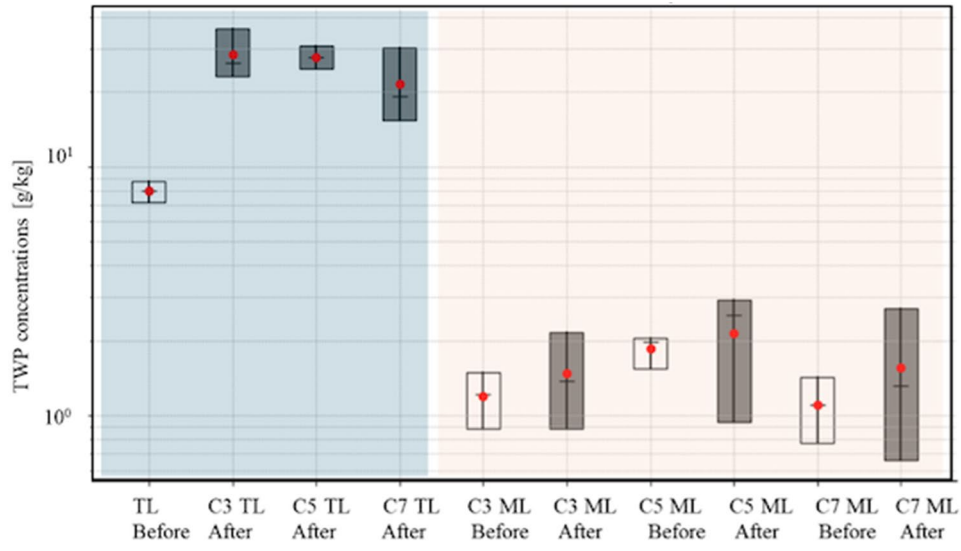

Fig. 3 The concentrations of TWP in soil from clay (10%) column (C3), biochar-amended clay (10%) column (C5) and sand (75%) column (C7) before and after the 41 weeks period of irrigation with polluted stormwater. All columns without grass. TL = top layer (0–0.05 m) and ML = main layer (0.05–0.50 m). Note that the y-scale is logarithmic

period were much higher, reaching up to 28 g/kg, and in the middle layers of C3 2.2 g/kg, C5 2.9 g/kg, and C7 2.7 g/kg.

In Fig. 4, concentrations of TWP in the top and main layers of the columns C3, C5, and C7 before and after the irrigation period are presented. In all the soil mixtures in the studied columns, the concentrations of TWP increased during the experiment, with the highest TWP increase in the top layer (TL), with increases corresponding to 256% in C3, 247% in C5 and 171% in C7. In the main layer (ML), the highest increases were found nearest the top, i.e. 0–15 cm below the top layer. As shown in Fig. 4, the increases thereafter are reduced with depth to become a leaching of TWP from the bottom layers. In summary, there is a net TWP accumulation of 22, 21, and 15 g/kg in C3, C5 and C7, respectively, indicating a net retention through the columns, with similar accumulation in C3 and C5 and the smallest accumulation in C7.

Concentrations in the influent

The concentrations of the TWP in the highly polluted stormwater used for irrigation during the experimental period are presented in Table S12 in the Supplementary Material. The concentration of TWP in the incoming stormwater during the soil settling phase was approximately 2.5 mg/L, which is lower than concentrations reported for highway runoff of 51–59 mg/L by Dröge and Tromp [55], and 89–170 mg/L sampled by an automatic sampler [56], but higher than those observed in retention ponds of 0.074–0.23 mg/L by Rauert et al. [57]. Similarly, the concentrations TWP was higher than values reported for stormwater ponds, with up to 0.022 mg/L by Rasmussen et al. [58]. It should be noted that water in stormwater ponds is generally expected to have lower concentrations of pollutants compared to untreated stormwater. A summary of studies addressing TWP mass quantification in runoff is available in Gaggini [59]. When spiked with runoff sediment, the stormwater used for the irrigation of the columns had TWP concentrations ranging between 250 and 910 mg/L (mean: 660 ± 89 mg/L), which is higher than in untreated tunnel wash water containing 6.2–130 mg TWP/L (mean = 72 mg/L) [12]. However, direct comparison across studies remains uncertain because differences in sample preparation and filtration procedures, as well as analytical methodology, can substantially influence reported concentrations of TWP.

Retention efficiencies

In Table 1 and Supplementary Table S14, the total retention efficiency (RE) of TWP (1.6–500 µm) accumulated in all columns is presented. Generally, TWP were retained with RE ranging from 93% to 99% among the different soil types used in the experiment. The columns with the lowest total RE of 93% were columns C4 (10% clay) and C6 (10% clay + biochar) with grass.

Despite the high overall mean retention observed throughout the experiment (Table 1), leaching of TWP and metals occurred during the column settling and establishment phase (2024–02-13 to 2024–03-12), as shown in Fig. 5 and Tables S12, S14–15 in the Supplementary Material. The RE presented in Fig. 5 is based on the mass of TWP in the water at the inlet and outlets, and the RE in Table 1 is based on the total accumulated mass of TWP in soil before and after the experiments. Leaching of TWP and metals in the establishment phase has also been observed previously in bioretention filters in a

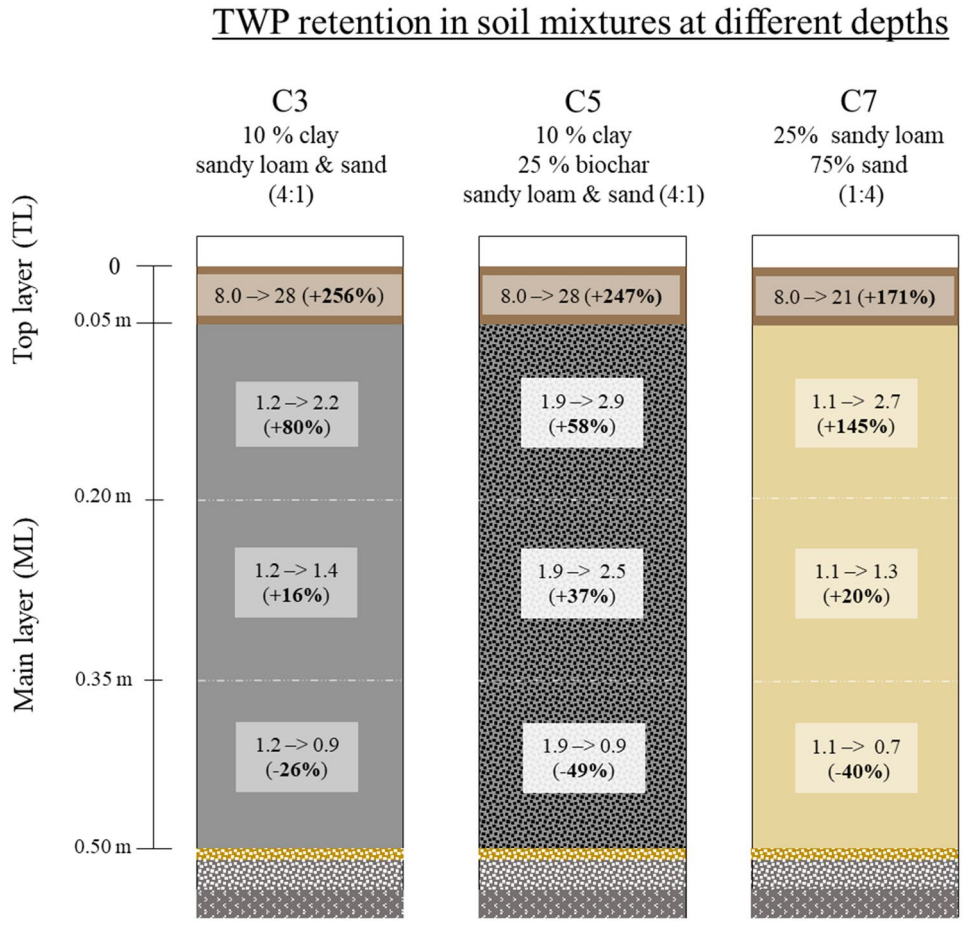

Fig. 4 The concentrations of TWP [g/kg] in the top and main layers of the columns C3, C5 and C7 before and after the irrigation period. In parentheses is the retention efficiency of the TWP at the different soil depths

Table 1 Total mass-based retention efficiency (RE) of TWP accumulated in the soil in different columns. Columns with grass are highlighted in green colour

Column	Texture of the main soil layer	Total accumulated TWP RE (%)[a]
C1	25% clay	99
C2	25% clay	98
C3	10% clay	99
C4	10% clay	93
C5	10% clay + biochar	98
C6	10% clay + biochar	93
C7	75% sand	97
C8	75% sand	98
C9	100% sandy loam	99
C10	100% sandy loam	97

[a]The retention efficiencies are calculated as a mean value for all the sampling occasions with stormwater

field pilot [28]. During the summer period (SP), irrigation was conducted using small amounts of tap water, while all other irrigation events during the winter period (WP) used polluted stormwater. The RE showing the total mass of the retained TWP during the SP was not estimated, as it was considered low or negligible given the low irrigation volumes.

Column C1 (25% clay) showed similarly high overall retention of TWP as C3 (10% clay) and C9 (100% sandy loam), despite differences in particle-size distribution. C3 and C9 had similar fine-particle contents (<0.063 mm) and generally coarser grain sizes than C1. The similar retention in C3 and the sand column C7 may reflect filtration in sand and possible preferential transport through cracks in the clay matrix of C3, potentially formed during dry periods, although cracking was not directly assessed. This interpretation is consistent with previous studies highlighting the role of particle size and physical straining in porous soils [60, 61].

In unvegetated columns, soil particle size did not significantly affect TWP retention. No correlation was found between the proportion of fine particles (<63 µm) and TWP in effluents ($n = 5$, multiple $R = 0.058$, $p = 0.926$), although the limited dataset reduces statistical power. This suggests that factors other than soil particle size, such as the relatively low density of TWP compared

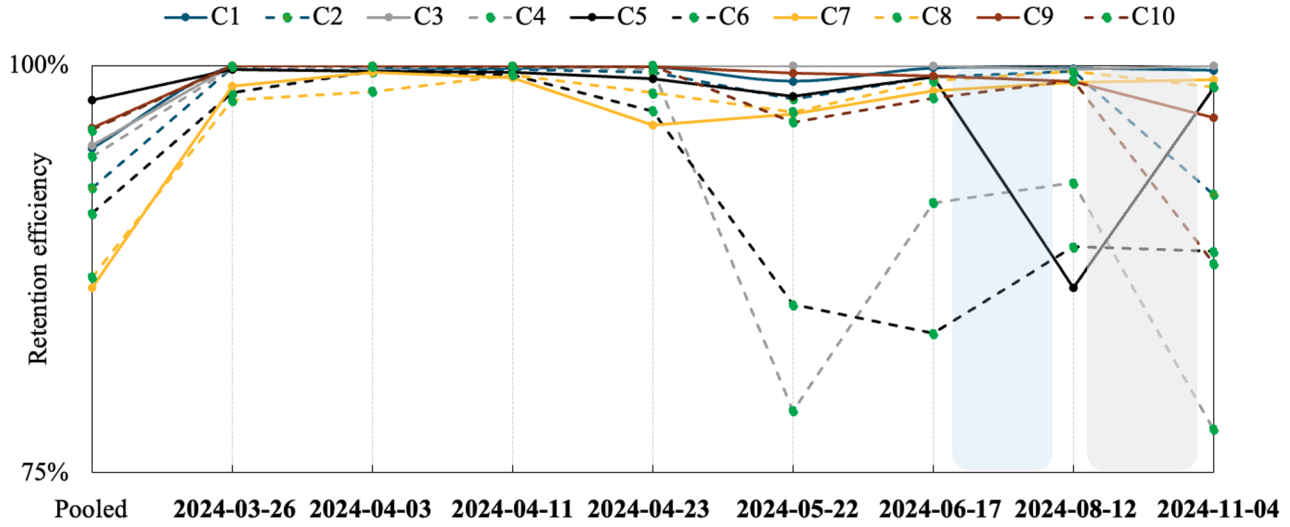

Fig. 5 Retention efficiency (RE) of TWP in columns during the experiment. Calculated from the mass of TWP in water in influent and effluent water. C1–C2 (25% clay), C3–C4 (10% clay), C5–C6 (10% clay + biochar), C7–C8 (75% sand), C9–C10 (100% sandy loam). C2, C4, C6, C8, and C10 had surfaces covered with grass. Occasions marked in bold represent irrigation with sediment-spiked stormwater. The blue-shaded area indicates a period of low-volume tap water irrigation, and the grey-shaded area shows the period of low-volume irrigation with sediment-spiked stormwater

with mineral particles, may influence mobility. Except for C7, no correlations were found between TWP and TOC/DOC in leachates, indicating limited sorption of TWP > 1.6 µm to natural organic matter. The correlation in C7 may reflect co-mobilisation of organic matter and TWP during sand percolation.

Biochar-amended non-vegetated soil also showed high retention: C5 (10% clay + biochar) reached 98%, comparable to C3 (99%), indicating no clear additional benefit of the amount of biochar added for TWP retention under the tested conditions. However, biochar may still provide other benefits, such as improved soil quality, plant growth, drought and salinity tolerance, carbon sequestration, enhanced temporary water storage and flow attenuation within the soil profile and interactions with organic pollutants and metals. The vegetated biochar column C6 also showed high overall retention, but TWP leaching increased after drought, possibly due to changes in biochar structure, shrinkage of the clay matrix, or both. Similar effects of drying on preferential flow and microplastic transport have been reported previously [61]. Further research is needed to assess the long-term suitability of biochar in near-road environments under varying weather conditions and over longer periods.

Despite high overall retention efficiencies, the time-resolved results showed event-specific variation. C1 and C2 (25% clay) retained 99% and 98% of accumulated TWP, respectively, but the vegetated C2 showed slightly higher water and TWP transport during some irrigation events, likely due to root-induced macropores and preferential flow. Overall, vegetated columns tended to enhance water and TWP transport. However, vegetation may also promote surface retention through dense fibrous roots, organic matter accumulation, increased water retention, sorption, and microbial activity. These dual effects highlight the complex role of vegetation in regulating TWP mobility and indicate that the influence of soil organic matter requires further study.

After a three-week drought, the vegetated C4 (10% clay) and C6 (10% clay + biochar) showed markedly reduced retention efficiencies of 31% and 12%, respectively. This decline likely reflects drought-induced cracking and expansion of root-facilitated preferential flow pathways in fine-grained soils. Retention increased again in C4 after watering resumed, suggesting that soil moisture strongly controls TWP retention, particularly in fine-grained soils. These findings indicate that dry periods, vegetation, and clay-rich soils may facilitate the transport of both TWP and metals through preferential flow. To improve road-ditch design, measures such as lined cells, compacted clay lenses, geotextiles, or drainage pipes connected to treatment systems may be considered where groundwater protection is important. Filtration could also be enhanced by dense, salt- and cold-tolerant turf or a dedicated biochar layer. Such modifications should balance pollutant retention with the primary drainage function of road ditches, particularly under future climate conditions with higher runoff volumes. Where high-flow risks are substantial, and pollutant retention remains a priority, runoff should be diverted for temporary storage and treatment.

A limitation of this study is the lack of replicated columns for each treatment. Because of the high analytical costs of TWP analyses, only one column was used for each soil mixture and vegetation combination. Thus, the nine sampling occasions represent repeated observations

from the same columns rather than independent treatment replicates. The consistently high TWP retention across all soil mixtures (93–99%) indicates that substantial TWP retention is a robust feature of these systems. However, the effects of vegetation and biochar should be interpreted cautiously, as treatment differences could not be statistically evaluated using replicated units. Future studies should therefore include replicated columns and larger biochar volumes to strengthen the assessment of treatment effects. Studies designed for mass-balance assessments would also improve understanding of the long-term fate, storage, transformation, and degradation of TWP and associated tyre-derived chemicals in roadside soil systems.

Another factor to consider is the particle-size range of the investigated TWP. This study analysed TWP of 1.6–500 µm in water samples, and 0.3–500 µm in soil samples, representing a substantial fraction of TWP reported in road runoff and roadside environments (Section "Tyre wear particles"). However, TWP size distributions vary with tyre composition, vehicle type, pavement characteristics, traffic conditions, and environmental weathering. For example, Gaggini et al. [62] found that 41% of the TWP mass in snow samples was associated with particles in the 1.6–20 µm size fraction within an analysed size range of 1.6–500 µm. While not necessarily representative of all environmental settings, this result highlights that a considerable proportion of TWP mass may occur in the smaller size fraction. Fragmentation may also generate smaller particles over time, including nanoscale tyre particles. Because particle size strongly affects filtration, retention, and mobility in porous media, the retention efficiencies observed here are likely specific to the investigated size range. Larger particles are generally retained in upper soil layers by physical straining, whereas smaller particles may migrate deeper. The environmental significance of nanoscale TWP remains uncertain: if retained near the surface, they may interact with soil biota, vegetation, and runoff processes; if transported deeper, their high mobility and large specific surface area may facilitate the transport of tyre-derived chemicals and metals, increasing the risk of long-term subsurface and groundwater contamination. Thus, the high retention efficiencies observed in this study are robust for the investigated particle-size fraction but may not apply to all TWP size distributions or environmental settings. Future studies should, when analytical methods allow, examine the transport and fate of submicron and nanoscale tyre particles under varying road, soil, and climatic conditions.

Tyre-derived chemicals

Concentrations in soil

Table S16 shows concentrations of TDC in the top and main soil layers of selected columns after irrigation. All fourteen TDC, except CPPD, were quantified. The highest concentrations were found for 6PPD (4.0–860 ng/g), exceeding concentrations reported in soils from Shantou, China (0.0080–65 ng/g [63]), but comparable to concentrations reported in road dust (1.3–490 ng/g). The 6PPD oxidation product 6PPD-Q ranged from 1.0 to 80 ng/g, which is higher than reported in dust but within the range found in Hong Kong and Chinese soils [63, 64]. The second-highest concentrations were found for BTSA, a transformation product of benzothiazole derivatives used as vulcanisation accelerators in tyre production. BTSA has previously been found in sewage, sewage sludge, river water, and urban aerosols [65, 66] and was introduced to the columns via the influent stormwater. The concentrations of DPG were also found at relatively high concentrations (3.0–150 ng/g), within but below the range reported for roadside soils in the northeastern United States (15–7600 ng/g; [67]).

The concentrations of TDC were highest in the top layer, while concentrations in the main layer were substantially lower, although the degree of reduction varied among compounds and soil treatments. The strongest retention was found for BTSA, with main-layer concentrations corresponding to less than 0.1–6% of those in the top layer. Similarly, 6PPD and 6PPD-Q were largely retained in the upper layer, with main-layer concentrations representing approximately 0.5–3.7% and 2.1–4.4% of the corresponding top-layer concentrations, respectively. In contrast, MBT showed greater downward transport, reaching 31–48% of the top-layer concentrations in C5 and C7. Although the limited number of samples and the comparison of only two soil layers preclude a detailed assessment of vertical distribution, the results indicate predominant accumulation of TDC in the upper soil layer. This pattern agrees with Zhang et al. [63], who found 6PPD-Q only in soils up to 20 cm depth, whereas 6PPD was also found at 20–40 cm depth. The lower concentrations in the main layer suggest retention in the upper soil layer through filtration and sorption, together with degradation and leaching during percolation.

Concentrations in the influent

Fourteen tyre-derived chemicals (TDC) were analysed in sediment-spiked influent and effluent samples collected during winter irrigation (Table S17). All TDC were quantified in the total influent, whereas CPPD, 7PPD, PhBT, and MBT were below the LoQ in the filtered water fraction. In the spiked influent, concentrations ranged from <LoQ to 2.1 µg/L in the filtered water fraction and from 0.095 to 35 µg/L in total water (including particle-bound TDC).

The highest influent concentrations were found for 6PPD (35 µg/L) and DPG (34 µg/L), both compounds commonly associated with tyre tread, followed by BTSA

(10 µg/L) and TMQ (8.9 µg/L) (Table S17). The high concentrations of DPG are consistent with its widespread use as a vulcanisation accelerator, and both 6PPD and DPG have frequently been found in roadside soils [68]. TMQ and BTSA have also been reported in urban aerosols, sewage sludge, and water [65, 66]. The concentration of 6PPD was higher than concentrations reported in urban runoff from Hong Kong, German wastewater treatment plants, and road runoff in Pierce County, but within the range reported for untreated tunnel wash water [36, 64, 69, 70]. The elevated concentrations are likely explained by spiking with stormwater sediment and by reduced 6PPD degradation in dark sediment conditions compared with runoff exposed to ozone and solar radiation. This is supported by the predominance of 6PPD in the larger particulate fraction. The influent concentration of 6PPD-Q (3.6 µg/L) was also higher than the median reported for urban runoff but similar to peak concentrations in tunnel wash water [12, 64]. The 6PPD/6PPD-Q ratio likely reflects limited photochemical transformation in the sediment and may also vary seasonally with ozone-driven oxidation in roadside soils.

Other TDC were generally within the ranges reported for tunnel wash water by Meland et al. [12], with similar concentrations of IPPD, MTBT, and TMQ, higher DPG and DPPD, and lower HMMM. Overall, the influent had concentrations of TDC comparable to or higher than those reported previously, supporting its relevance for studying sorption and transport in stormwater from heavily trafficked roads and urban streets.

Retention efficiencies

Retention efficiencies (RE) of the fourteen tyre-derived chemicals (TDC) in the unvegetated columns are shown in Table 2. Particle-bound TDC were strongly retained, with RE > 97% in all columns, except for the more water-soluble HMMM in C9 (100% sandy loam), where RE was 94%. This indicates effective filtration or sorption of particle-bound TDC in all soil mixtures.

For filtered water, RE varied more. CPPD, 7PPD, PhBT, and MBT were below the LoQ in both influent and effluent, while DPPD and IPPD were below the LoQ in all effluents despite being found in the influent. This suggests sorption and/or transformation during soil passage. For IPPD, rapid disappearance in aqueous systems has been reported, with a half-life of 0.6 ± 0.1 days under activated-sludge conditions [82]. In the filtered water, 6PPD, 6PPD-Q, and TMQ were efficiently retained in all columns (RE > 76%). The highest RE occurred in the biochar-amended column C5 (≥99%), likely due to sorption related to their relatively moderate-to-high log Kow values. High RE in the sandy C7 column may also reflect enhanced degradation/oxidation and longer standing time of sampled effluent after rapid flow-through. In C9, RE was similar to or between that observed in C1 and C3. For the filtered water, DPG, MTBT, and BTSA, RE ranged from 34% to 96%. Retention was higher in the clay-rich C1 than in C3, likely due to slower flow and greater filtration. Biochar increased RE for DPG and MTBT compared with C3, suggesting additional sorption. In column C7, the RE was slightly higher than in C1, potentially due to faster flow, degradation/oxidation, and longer effluent standing time. Changes in the filtered-to-particle-bound ratios also indicate ongoing leaching from particles and/or chemical transformation, highlighting the need for time-resolved sampling to assess formation, degradation, and kinetics.

HMMM and OHBT showed the greatest variation among columns. Their low log Kow values indicate hydrophilic behaviour and weak particle retention. Positive RE was observed in C1, C5, and C7, whereas negative RE, indicating leaching, occurred in C3 and C9. This may reflect release of residues stored in pore water or weakly sorbed to particle surfaces, especially after drying–rewetting. Similar leaching behaviour has previously been reported for HMMM and OHBT, suggesting slow release from TWP or formation from precursors [83]. The concentrations of MBT, another water-soluble compound, was not found > LoQ in the filtered influent, although it has been associated with toxic effects together with DPG, emphasising the need for improved analytical methods and further studies of its soil transport.

Because these results are based on limited sampling occasions, they should be interpreted as indicative rather than definitive. Future studies should include more detailed temporal sampling and monitor soil moisture conditions, as drying-rewetting dynamics may strongly influence TDC leaching.

Metals

Table 3 shows the percentage change in the concentrations of metals at different depths within the unvegetated soil columns (C3, C5, and C7) after irrigation. Similar to TWP and TDC, metals accumulated primarily in the topsoil layer (0–0.05 m) in all soil mixtures, consistent with observations from roadside soils [26], long-term field monitoring of bioretention systems [84], and laboratory biofiltration studies [85, 86].

In C3 (10% clay), the concentrations of metals s increased in the topsoil but generally decreased in the 0.05–0.20 m layer and remained unchanged or decreased in the deepest layer. In C5 (10% clay + biochar), topsoil accumulation was also pronounced, while several metals showed increased concentrations in deeper layers, particularly at 0.20–0.35 m. In C7 (75% sand), topsoil accumulation was lower, and increases were more evident in the 0.05–0.20 m layer, with generally decreasing concentrations at greater depths.

Table 2 Retention efficiency (RE) of the fourteen tyre-derived chemicals (TDC), 6PPD, 6PPD-Q, DPPD, IPPD, CPPD, 7PPD, HMMM, DPG, TMQ, MTBT, PhBT, MBT, BTSA, and OHBT in unvegetated columns C1 (25% clay), C3 (10% clay), C5 (10% clay + biochar), C7 (75% sand) and C9 (100% sandy loam)

		Retention efficiency (RE) of the fourteen tyre-derived chemicals														
		6PPD	**6PPD Q**	**DPPD**	**IPPD**	**CPPD**	**7PPD**	**HMMM**	**DPG**	**TMQ**	**MTBT**	**PhBT**	**MBT**	**BTSA**	**OHBT**	**Mean all**
Solubility in water [g/L]		<1 at 17°C[a]	0.0384 ±0.01[b]	insoluble[c]	0.6 at 20 °C[d]	no info[e]	soluble in organic solvents, not water[f]	soluble[g]	0.325 at 20 °C[h]	<0.1 g/L at 19 °C[i]	insoluble[j]	no info[e]	no info[e]	highly soluble in water[k]	no info[e]	
log Kow		4.68[l]	3.98[m]	no info	no info	no info	no info	2.04[m]	2.90[m]	no info	3.22[m]	no info	1.83[m]	no info	2.354[m]	
C1	**Filtered water**	100%	100%	100%	100%			94%	96%	100%	81%			82%	78%	93%
	Larger particles	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%		100%	100%
	Total water	100%	100%	100%	100%	100%	100%	96%	100%	100%	97%	100%	100%	96%	99%	99%
C3	**Filtered water**	89%	76%	100%	100%			−17%	50%	87%	39%			76%	−119%	48%
	Larger particles	97%	99%	99%	98%	100%	100%	98%	99%	99%	98%	99%	100%	99%	99%	99%
	Total water	97%	98%	99%	98%	100%	100%	15%	99%	99%	90%	99%	100%	95%	93%	92%
C5	**Filtered water**	100%	100%	100%	100%			83%	92%	100%	65%			77%	39%	86%
	Larger particles	100%	100%	100%	100%	100%	100%	100%	100%	100%	99%	100%	100%	100%	100%	100%
	Total water	100%	100%	100%	100%	100%	100%	88%	100%	100%	94%	100%	100%	95%	98%	98%
C7	**Filtered water**	100%	100%	100%	100%			97%	96%	100%	87%			86%	57%	92%
	Larger particles	100%	100%	100%	100%	100%	100%		100%	100%	99%	100%	100%		100%	100%
	Total water	100%	100%	100%	100%	100%	100%	98%	100%	100%	98%	100%	100%	97%	99%	99%
C9	**Filtered water**	91%	91%	100%	100%			−57%	74%	100%	34%			47%	−153%	43%
	Larger particles	99%	100%	100%	99%	100%	100%	94%	99%	100%	99%	99%	100%	99%	99%	99%
	Total water	99%	99%	100%	99%	100%	100%	−15%	99%	100%	90%	100%	100%	89%	92%	89%

[a] - [71]; [b] - [72]; [c] - [73] ; [d] - [74]; [e] - since no reliable vendor or database reports a measurable water-solubility value, the substance can reasonably be considered practically insoluble in water; [f] - [75]; [g] - [76]; [h] - [77]; [i] - [78]; [j] - [79]; [k] - [80]; [l] - [81]; [m] - log K_{ow} were extracted from https://pubchem.ncbi.nlm.nih.gov/

Table 3 Percentage increases and decreases of metals in soil in unvegetated columns C3(10% clay), C5 (10% clay + biochar), C7 (75% sand) at different depths during the experiment

		Depth [m]	Percentage increases and decreases of metals in soil							
			Ba	Pb	Co	Cu	Cr	Ni	V	Zn
C3	Top layer	0–0.05	72%	26%	200%	500%	300%	150%	98%	740%
	Main layer	0.05–0.20	−12%	−30%	−26%	−34%	−33%	−19%	−17%	−14%
		0.20–0.35	14%	2.0%	−4.0%	−13%	8.0%	31%	17%	7.0%
		0.35–0.50	−5.0%	−3.0%	−21%	−28%	−33%	−15%	0.0%	−11%
C5	Top layer	0–0.05	62%	32%	98%	480%	240%	130%	60%	730%
	Main layer	0.05–0.20	−14%	−7.0%	−8.0%	3.0%	5.0%	9.0%	5.0%	34%
		0.20–0.35	4.0%	27%	31%	18%	140%	102%	53%	86%
		0.35–0.50	−13%	−13%	2.0%	−13%	47%	37%	11%	38%
C7	Top layer	0–0.05	38%	14%	80%	440%	210%	110%	50%	523%
	Main layer	0.05–0.20	21%	18%	11%	48%	21%	14%	6.0%	79%
		0.20–0.35	11%	7%	−4.0%	−14%	6.0%	−3.0%	−1.0%	14%
		0.35–0.50	5.0%	11.0%	−7.0%	−14%	2.0%	−8.0%	−1.0%	7.0%

The only significant correlation between TWP and metals in soil was for Ba in C7 ($p = 0.007$). Similar to findings reported by Polukarova et al. [41] and Rødland et al. [11], correlations between TWP and metals in roadside ditches were generally weak.

Overall, the results indicate that both metals and TWP were predominantly retained in the upper soil layer. However, metal distributions are additionally influenced by geochemical processes such as sorption, precipitation, cation exchange and complexation processes, which may explain the generally weak correlations between concentrations of TWP and metal. Exploratory correlations between TWP and concentrations of total and dissolved metal in column influent and effluents are presented in Table S18.

Conclusions

The results showed that the soil columns had overall high retention of TWP, metals and most of particulate-bound TDC, while some tyre-derived chemicals measured in filtered samples leached(−153% to 97%) or variability between columns. Grass vegetation did not enhance the retention of TWP and TDC in this study. However, because vegetation was not directly sampled and TWP accumulate in topsoil, the role of vegetation on TWP transport through road ditches should be further investigated. Future research should determine how much TWP and TDC vegetation retains through interception or sorption versus how much is transported via root-related preferential flow. Differences in vegetation type, establishment stage, and life cycle may also affect retention and should be considered. Preferential flow paths likely caused by drought and/or vegetation roots facilitate the transport of TWP in most of the soil mixtures. Amendment with the selected biochar maintained the already high retention of TWP, TDC and metals in the fine-grained, low-permeability soils used in this study. However, biochar showed no clear additional retention benefit compared with the corresponding clay-amended soils. Given its reported benefits, including carbon sequestration and soil improvement, its potential role in near-road environments warrants further study. For analytical consistency and future reuse of road materials, biochar may be better applied as a distinct layer rather than mixed with sand, since mixed biochar–sand matrices are difficult to sieve and analyse for TWP. Biochar-amended soils with vegetation showed lower retention efficiency, particularly after drought, indicating that long-term performance should be evaluated under varying weather conditions and for different amounts and types of biochar. Because this study used single columns for each treatment, replicated experiments are needed to strengthen statistical assessment of soil composition, vegetation, and biochar effects on pollutant retention.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s43591-026-00237-x.

Supplementary Material 1

Acknowledgements

We would like to express our gratitude to the Swedish Road Administration for providing the clay soil material, and to Amir Saeid Mohammadi (Chalmers University of Technology), for his valuable assistance with laboratory work and the construction of the experimental columns. We also thank Anders Karlsson and Bruno Oliveira Gonçalves, as well as staff from Renova, for their contributions to the project. Finally, we are grateful to Mats Gustafsson (Swedish National Road and Transport Research Institute, VTI) for his thorough review and insightful comments on the manuscript.

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Stromvall: Writing – review & editing, Supervision, Conceptualisation. Yvonne Andersson-Skold: Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Conceptualisation.

Funding
This study was funded by Swedish Transport Administration (Trafikverket) under Grant Agreement TRV 2020/50260.

Data availability
The datasets supporting the conclusions of this study are available in the Results and Discussion section and in the Supplementary Material. The full underlying datasets are available from the corresponding author upon reasonable request.

Declarations

Ethical approval
Not applicable.

Generative AI and AI-assisted technologies in the manuscript preparation process
During the preparation of this manuscript, the authors used Microsoft Copilot to assist with text condensation, spelling, and grammar checking. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Competing interests
The authors declare no competing interests.

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Received: 7 April 2026 / Accepted: 6 October 2026

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