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# Summary

In urban environments, road traffic is a primary driver of atmospheric pollution, significantly increasing particulate matter (PM) emissions, which pose substantial risks to human health and contribute to premature mortality worldwide. Within this context, as the automotive sector advances its transition toward electric vehicles, the environmental and health implications of non-exhaust emissions (NEEs) have become increasingly evident. Among these, brake wear dust (BWD) is particularly concerning due to its high metal content and its potential impact on both human health and environmental quality. On one hand, brake wear particles are an unavoidable byproduct of frictional braking in both conventional and electric vehicles, persisting as a mobile contaminant in urban settings. On the other hand, significant knowledge gaps remain regarding the mechanisms governing BWD infiltration into soil and groundwater systems, as well as the extent to which naturally occurring substances (e.g., humic acids) influence its mobility and fate. This issue is particularly pertinent in the context of upcoming Euro 7 emission regulation which will introduce specific limits for BWD and tire particulate emission, based on the Global Technical Regulation 24 (GTR 24). However, current frameworks still lack integrated approaches that account for subsurface pollution potential. The need of establishing standard methodologies to verify and limit such emissions has been evidenced by the literature in terms of air pollution, and this work aims at evidencing its relevance also in terms of groundwater quality protection. Addressing these gaps requires a deeper understanding of BWD transport mechanisms and their implications for air, soil, and water quality.

This study adopts a multi-phase approach to investigate the transport and fate of BWD in both unsaturated and saturated porous media, key environmental compartments that BWD may ultimately reach. Initially, the research examines atmospheric deposition mechanisms (wet and dry) to understand how model standardized particles (used as a proxy for BWD) deposit from air to terrestrial environments. The findings indicate that wet deposition is substantially more effective in removing coarse particles ( $>2\ \mu\text{m}$ ) than fine particles ( $<1\ \mu\text{m}$ ), which exhibit high atmospheric persistence. This first phase of the study provides a preliminary experimental framework for assessing at an early stage how BWD accumulates at the soil surface following atmospheric deposition.

Subsequently, real BWD samples were characterized through detailed chemical and morphological analysis using advanced analytical techniques (SEM-EDX, Raman spectroscopy, ICP-MS). The results confirm that BWD is a complex pollutant dominated by fine particles and irregular aggregates, with iron – primarily in

oxidized forms – as its major constituent, followed by trace amount of copper, aluminium, barium and zinc. The high iron oxide content not only raises concerns regarding potential toxicity but also suggests that BWD can act as a carrier for other environmental contaminants.

Laboratory-scale column tests further explore the transport of BWD – previously coated with humic acids to simulate interaction with naturally occurring organic matter – in porous media, representative of top soil and aquifer systems, by varying environmental conditions such as flow velocity, ionic strength, water saturation, and soil texture. In saturated sand columns, increased ionic strength (simulated with rainwater) inhibits particle transport, whereas increased flow velocity enhances their mobility. In unsaturated tests, for the same porous medium and velocity, BWD mobility is higher compared to saturated tests due to interactions at the air-water interface and capillary forces. Experiments conducted on real soils reveal that clay-rich soils effectively retain BWD particles, while sandy soils facilitate substantial migration, thereby increasing the risk of groundwater contamination. The modelling interpretation of experimental column tests results allows to extrapolate laboratory findings to real-world conditions: large-scale simulations using HYDRUS-2D model various urban scenarios, including continuous ponding, contaminated road ditch, and roadside contamination events. Numerical modelling confirms experimental results, demonstrating that while only a fraction of BWD reaches the water table, long-term accumulation in the transition zone between unsaturated and saturated layers poses a significant risk for delayed groundwater contamination. Additionally, high BWD concentrations persist in sediments within drainage infrastructures, highlighting the need for effective waste management and disposal strategies.

In conclusion, this integrated experimental and numerical analysis confirms that BWD is a persistent and mobile contaminant. Its environmental behaviour in subsurface environments is strongly influenced by factors such as particle size, soil composition, and water chemistry, which regulate both its retention in the unsaturated zone and its potential leaching into groundwater. The lack of standardized regulations for BWD emissions intensifies environmental risks, underlining the urgency of developing targeted assessment methodologies and policies. Given the interconnection of environmental matrices and the BWD fate observed in this study, establishing standardized testing and measurement protocols is crucial not only for air quality management but also for the protection of soil and groundwater resources. This research not only addresses critical knowledge gaps regarding BWD fate in porous media but also provides a foundation for future studies aimed at mitigating the long-term effects of non-exhaust emissions on environmental quality.