Environmental Research 285 (2025) 122288



Contents lists available at ScienceDirect

Environmental Research

journal homepage: www.elsevier.com/locate/envres





Quantifying pathways of tyre wear into the environment

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ARTICLE INFO

Keywords:
Tyre wear
Microplastics
Particulate matter
Tyre and road wear particle
Mass flux

ABSTRACT

This study provides the first national-scale spatial analysis of tyre wear particle (TWP) pathways in the UK, employing a mass flux particle pathway framework integrated with the UK Integrated Assessment Model at 1 km^2 resolution. Results show 79.5 kt of TWPs are released annually, with between 1.3 kt to 6.7 kt enter the atmosphere, 23.0 kt to 34.0 kt reaching surface waters,18.5 kt to 30.2 kt depositing in soils, and 16.7 kt to 29.2 kt removed via management systems. Sensitivity analysis reveals notable uncertainties in these estimates. A significant rural-urban transfer mechanism redistributes 6.3 kt to 13.1 kt of urban-derived TWPs to agricultural soils through sewage sludge application. Atmospheric emissions are concentrated around major roads and urban centres, while soil and water pathways exhibit complex distributions driven by infrastructure systems. This study highlights the potential for improved spatial modelling of the pathways of tyre wear into the environment.

1. Introduction

Tyre wear particles represent one of the most significant yet underappreciated sources of microplastic pollution in the environment (Obanya et al., 2024). As vehicles move across road surfaces, the abrasion between tyres and pavement generates millions of tonnes of particulate matter annually. Global estimates suggest that approximately 3.4 million tonnes of tyre wear are released each year (Kole et al., 2017), with 1.3 million tonnes emitted in Europe alone (Wagner et al., 2018). These particles, typically ranging from 1 to 1000 μm in diameter, are beginning to be categorized as microplastics due to their polymer composition and physical properties (Knight et al., 2020). Recent studies have identified tyre wear as a dominant contributor to microplastic pollution, with production volumes that far exceed many other anthropogenic sources (Kole et al., 2017; Parker-Jurd et al., 2021). The scale of this issue is expected to increase with growing traffic volumes and the adoption of heavier electric vehicles, which despite their environmental benefits in reducing exhaust emissions, may generate increased tyre wear due to their greater mass (Timmers and Achten, 2016, 2018; OECD, 2020; Beddows and Harrison, 2021; Harrison et al., 2021).

Beyond their sheer volume, tyre wear particles pose significant environmental and health concerns due to their toxic properties. These particles contain a complex mixture of synthetic rubber polymers, carbon black, silica, oils, and various chemical additives including vulcanization agents, antioxidants, and heavy metals (Zhang et al., 2023). Once released, tyre wear particles contribute to degraded air quality as a significant component of non-exhaust traffic emissions (Mehlig et al., 2023; Tan et al., 2023). The smaller fraction of these particles can be inhaled contributing to the health impacts of airborne particulates (Xing et al., 2016). In aquatic environments, tyre wear particles can release toxic leachates that harm aquatic organisms, with studies demonstrating adverse effects on growth, reproduction, and survival of various species (Redondo-Hasselerharm et al., 2018; Hua and Wang, 2023).

The particles consist of a mixture of tyre material, road surface material, and material on the road surface, such as brake pad wear. These particles are termed 'tyre and road wear particles' (TRWP) due to the nature of particles containing a mixture of these materials (Kreider et al., 2010; Panko et al., 2013; Panko et al., 2018; Sommer et al., 2018). The tyre wear component of these TRWPs are termed 'tyre wear particles' (TWP) that are the focus of this study. TWPs are now recognised as a microplastic with distinct material properties (Sommer et al., 2018). These TRWPs leave the road and enter the environment through many pathways (Wik and Dave, 2009). These pathways reach terrestrial, aquatic, or atmospheric environments or can end through removal via infrastructure. These pathways of TRWPs into the environment are the topic of this study.

There is growing empirical evidence documenting the presence of TRWPs in the environment. The fraction of TRWPs that are airborne

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https://doi.org/10.1016/j.envres.2025.122288
Received 22 April 2025; Received in revised form 2 July 2025; Accepted 2 July 2025
Available online 3 July 2025
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have been identified as suspended particulate matter at air pollution monitoring sites (Panko et al., 2013; Hicks et al., 2021). For the fraction that remain local to the road, TRWPs have been identified in roadside soils (Knight et al., 2020; Rødland et al., 2023; Polukarova et al., 2025) and in urban runoff (Österlund et al., 2023; Lindfors et al., 2025). Once TRWPs have reached urban runoff systems their pathways become more complex, reaching downstream drainage infrastructure (Knight et al., 2020; Werbowski et al., 2021), rivers (Rauert et al., 2022), estuaries (Parker-Jurd et al., 2021), and sediments (Knight et al., 2020) with Munari et al. (2017) finding TRWP as the most abundant microplastic in Antarctic sea sediment.

With the growing evidence base reporting TRWP in the environment, modelling TRWP pathways through the environment has become a key next step for addressing TRWP pollution. Recent studies have adopted methodologies assessing the mass flux of TRWP through infrastructure and the environment (Unice et al., 2019a, 2019b; Baensch-Baltruschat et al., 2021) providing key estimates of the volume of TRWP reaching the environment. We build upon these recent studies by developing a tyre wear particle pathway framework to quantify the flux of tyre wear materials along potential environmental pathways in the UK, a new case study for TRWP mass flux analysis. We cover the entry of TRWP into terrestrial, aquatic, and atmospheric environments but do not further investigate their fate such as bioaccumulation and degradation.

Our approach is formed of two stages. First, we utilize the existing road transport sub-model with the UK Integrated Assessment Model (UKIAM) (Oxley et al., 2004, 2009; ApSimon et al., 2021), to generate 1 km^2 spatial estimates of TWP across the UK road network. Second, we develop a particle pathway framework to simulate the environmental pathways of tyre wear particles, accounting for different road types, roadside environments, and drainage systems in the UK. The framework allocates varying proportions of TWP to different environmental matrices (soil, water, and atmosphere) based on road infrastructure and the environmental context. This method provides a spatial map of TWP entering the environment across all of the UK, highlighting critical emission hotspots and the transfer of particles from urban to rural areas. Building upon the experience gained from mapping tyre wear particles for air quality modelling, we propose this first national mapping demonstrates the utility of spatially mapping all environmental pathways of tyre wear particles spatially.

2. Methods

We combine a spatial map of TWP for the UK with a particle pathway framework that quantifies the proportion of tyre particles that pass through environmental matrices. We use these to produce an inventory TWP along each pathway and to produce spatial maps of the influx and outflux of tyre wear material into the environment. In this section we first summarise how we calculate the map of TWP, followed by a description for how the particle pathway framework was created and applied with the TWP map.

2.1. Tyre wear particle map

The road-transport sub-model of UKIAM was employed to calculate the total mass of TWP across the UK along urban, rural, and highway roads (Oxley et al., 2004, 2009; ApSimon et al., 2021). This model maps the road network onto a 1 km^2 grid, where the TWP mass is calculated using a bottom-up approach. In each grid cell, road lengths are categorized as rural, urban or motorway and are combined with annual average daily flows to derive the vehicle kilometres driven (vkm). This is repeated separately for cars, LGVs, rigid and articulated HGVs, buses, and motorcycles within each grid cell to provide VKM by road type and vehicle type as shown in Equation (1). Finally, average vehicle speeds that are road type specific, are combined with EMEP/EEA guidebook emission factors to calculate TWP mass for Total Suspended Particles (TSP) (Ntziachristos and Boulter, 2019) as given in Equation (2) to provide emissions of TWP for each grid cell and road type.

$$VKM_{x,y,RT,VT} = AADF_{x,y,RT,VT} \times l_{x,y,RT} \quad \text{Equation 1}$$

$$E_{x,y,RT} = \sum_{VT} VKM_{x,y,RT,VT} \times EF_{VT}(S_{x,y,RT}) \quad \text{Equation 2}$$

Where *VKM* is vehicle kilometres driven within grid cell coordinates, *x* and *y*, for road type *RT*, and vehicle type *VT*; *AADF* is total annual average daily flow within the grid cell for the vehicle type and road type; *l* is the length of road within the grid cell for road type; *E* is the emitted mass of TWP within the grid cell for the road type; *EF* is emission factor for each vehicle type that is a function of the average speed, *S*, for the road type within the grid cell.

These speed dependant TSP emission factors, which have higher emission rates at lower average vehicle speeds reflecting more stopping and starting with congested conditions, are based upon total tyre mass wear rates found by Luhana et al. (2004). These emission factors provide the highest emission rates per kilometre driven for urban roads, followed by rural and motorway roads, aligning with other estimates of tyre wear rates across different road types Baensch-Baltruschat et al. (2020). We convert these TSP into total wear mass, assuming 10 % of tyre wear material are TSP providing similar wear rates reported in a literature review by Baensch-Baltruschat et al. (2020). We model TWP release for 2018, using the base year of the UKIAM model. For a full description of the transport sub-model and recent case studies, please refer to (Oxley et al., 2009; Mehlig et al., 2021; ApSimon et al., 2022, 2023). Our mass calculations of TWP do not include the road wear component of TRWP.

2.2. Particle pathway framework

A UK-specific particle pathway framework, illustrated in Fig. 1, was developed to estimate the movement of TWP across environmental matrices. The directional arrows show TWP pathways with percentages indicating mass flux proportions between stages, determined using literature values (Table 1). This framework assumes roads classified as rural, urban, or motorway share similar roadside environments and infrastructure within their respective categories. Our approach builds upon work by Baensch-Baltruschat et al. (2021) while incorporating removal pathways similar to Unice et al., 2019a,b offering insights into potential mitigation strategies. We finally apply this framework spatially using the TWP maps outlined earlier.

The mass flux parameters were selected from UK-specific empirical studies where available and supplemented by European research where necessary. Each of these mass flux parameters were modelled stochastically using either triangular or uniform distributions, as summarised in Table 1. Parameters that were found to have a central most likely estimate alongside a possible range were modelled as triangular distributions whereas parameters with no central estimate were modelled as uniform distributions spanning the range of values found in the literature. Each distribution is described below, stating the evidence from the literature used and the type of distribution. We adopted Monte Carlo methods to provide a global sensitivity analysis which required running the model 800 times to reach convergence of the pathway end points.

For atmospheric emissions of TWP, we adopt 5 % (0.1 %–10 %, triangular) estimate from Wagner et al. (2018) leading to most particles remaining on the local road. We differentiated between rural and urban environments due to their distinct drainage infrastructure and proximity to roadside soil in the UK.

For rural environments, we applied Blok's (2005) findings that 30 % (21 %–53 %, triangular) of TWP settles in roadside soil, with the remaining proportion transported by water runoff. For rural highways, we assume that 100 % of the TWP in runoff reaches stormwater management systems where 50 % (uniform range 30 %–100 %) will be removed through facilities (Koeleman and Smeitink, 2004) such as sumps (Knight et al., 2020), with the remainder reaching surface water.

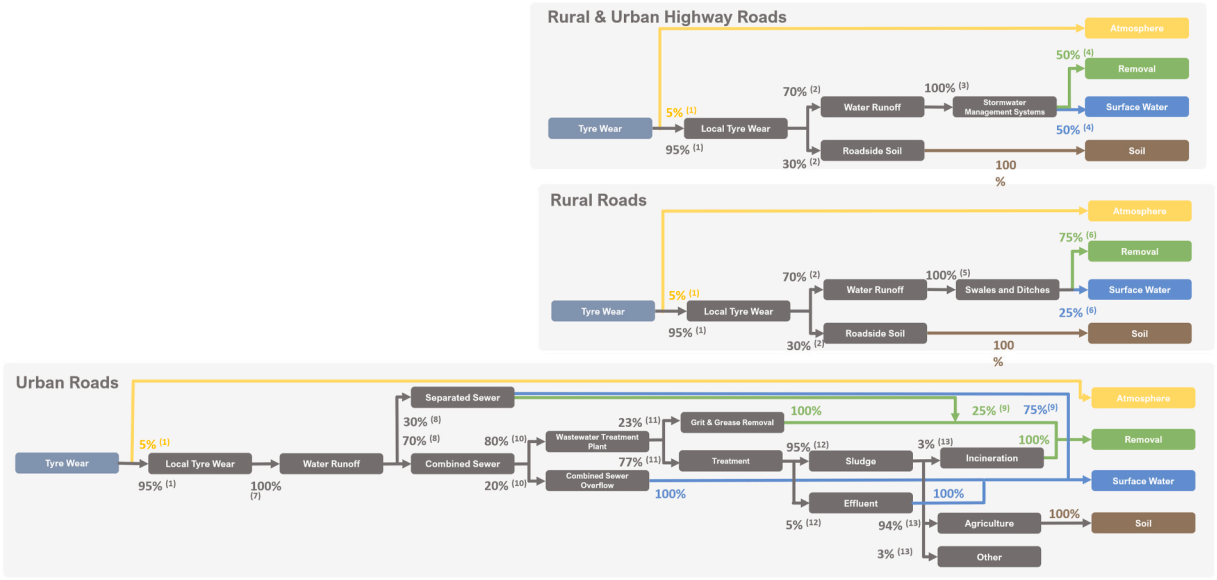


Fig. 1. Particle pathway framework where percentages show the mass flux between each stage; numbers refer to the stages outlined in Table 1 with associated references from the literature.

For non-highway rural roads, we assume 100 % of the TWP in runoff reaches swales and ditches removing 75 % (60 %–90 %, uniform) of the particles (Koeleman and Smeitink, 2004) and the remainder reaching surface waters.

For urban areas, following (Wagner et al., 2018), we assumed 100 % of non-atmospheric particles enter drainage systems, reflecting the paved nature of UK cities. Of this urban runoff, we assumed 70 % of TWPs reached combined sewers based on Ellis (1989), with a triangular range of 60 %–85 % from similar western European countries, reflecting the UK's historical reliance on Victorian-era combined sewage systems. The remainder of TWP in urban runoff was assumed to reach separated sewers. A portion of TWP transported through combined sewers are discharged into surface waters through Combined Sewer Overflows (CSO) where we have assumed that 40 % (30 %–50 %, uniform) of these TWPs reach surface waters based upon the portion of stormwater exiting the system through CSOs from Brombach et al. (2005).

TWP in combined sewers then reached Wastewater Treatment Plants (WWTP), where we assume that between 0 % and 45 % (uniform) of TWP are removed are removed from WWTP influent in the initial Grit and Grease phase based upon microplastic removal rates found by Murphy et al. (2016). Other studies do not report removal of microplastics at this stage of WWTP and so we have included a lower bound of 0 % for this stage since Murphy et al. (2016) also report that microplastics from the Grit and Grease phase were re-added to sludge for incineration. For TWPs that remain in the WWTP influent beyond the Grit and Grease phase, 95 % (72 %–100 % triangular) are retained in sludge with the remainder reaching the effluent (Magnusson, 2014; Magnusson and Wahlberg, 2014; Murphy et al., 2016; Kole et al., 2017; Leslie et al., 2017; Horton et al., 2021). For TWPs contained in sludge, we used reported distribution of sludge to agricultural land at 94.5 % (94 %–95 % uniform), incineration at 3.5 % (3 %–4 % Uniform), and the remainder to unquantifiable sources (Department for Environment Food & Rural Affairs, 2022; 2024).

Finally, we use the TWP map with the particle pathway framework to estimate the spatial distribution of TWP pathways. We use the road network data to identify urban, rural, and motorway roads to spatially determine the destination of TWP within each UKIAM grid cell. For TWP entering the atmosphere, we use UKIAM to simulate air pollutant dispersion (Oxley et al., 2009; ApSimon et al., 2021), producing resulting concentrations of TWP TSP. Next, to find the distribution of TWP entering soils, we use the particle pathway framework to calculate the distribution of mass on roadside soils and then combine this with the mass of TWP that is spread on agricultural soils through wastewater treatment plant sludge. We assume that sludge spreading has an equal spatial distribution to fertiliser use on agricultural soils in the UK and use the distribution used by UKIAM (ApSimon et al., 2022). Finally, we estimate the spatial distribution of TWP entering surface waters by allocating the mass of tyre particles that reach surface waters in the framework to the nearest fresh water course.

3. Results and discussion

We find 79.5 kt of TWP are released into the environment in the UK each year, where 4.0 kt enter the atmosphere (median value, with 1.3 kt to 6.7 kt, 5th to 95th percentile range across Monte Carlo simulations), 28.1 kt enter surface waters (23.0 kt to 34.0 kt), 23.9 kt enter soils (18.5 kt to 30.2 kt), and 23.1 kt were removed from the environment (16.7 kt to 29.2 kt). The flow from particle release through the environment is illustrated in Fig. 2 that shows the median mass at each stage of the pathway where the size of the bar in the Sankey diagram is proportional to the TWP mass along with the 5th to 95th percentiles across the Monte Carlo simulations; these results are also summarised in Table 2.

As shown in Fig. 2, urban-originated TWP that enter combined sewer systems and undergo wastewater treatment create a significant rural-urban transfer mechanism of tyre wear material with 9.1 kt of TWP possibly reaching agricultural soils each year in the UK (median value, with 6.3 kt to 13.1 kt, 5th to 95th percentile range across Monte Carlo simulations). The high retention efficiency of WWTPs (estimated at 95 % in our pathway) paradoxically creates a concentrated reservoir of TWP that are subsequently transferred to agricultural soils. With 94 % of UK sewage sludge applied to agricultural soils, this pathway transfers pollutants from urban to rural areas, potentially affecting ecosystems and food production.

This finding aligns with previous UK WWTP studies that have quantified high concentrations of microplastics in sewage sludge (Horton et al., 2021; Harley-Nyang et al., 2022), where TWP will likely follow these known pathways of other microplastic pollutants. Based upon the results of Harley-Nyang et al. (2022) and Horton et al. (2021) we estimate that approximately between 0.1 kt and 32 kt of microplastics are contained in sludge each year (using Harley-Nyang et al. (2022)'s extrapolated credit card example at 5 g per credit card with 811 kt of national sludge (Department for Environment Food & Rural

Table 1
The mass fluxes for each stage of the particle pathway framework given in Fig. 1 with mass flux distributions and the corresponding references from the literature.

Number	Pathway Origin	Pathway Branches	Mass Flux (Distribution)	Reference
1	TWP	Atmospheric tyre wear	5 % (0.1–10 % Triangular)	Wagner et al. (2018)
		Local TWP	95 %	
2	Local TWP	Rural & highway roadside soil	30 % (21 %–53 % Triangular)	Blok (2005)
		Rural & highway water runoff	70 % (47 %–79 % Triangular)	
3	Highway water runoff	Stormwater management systems	100 %	
4	Stormwater management systems	Removal	50 % (30–100 % Uniform)	Koeleman and Smeitink (2004)
		Surface Water	50 % (0–70 % Uniform)	
5	Rural water runoff	Swales and ditches	100 %	Koeleman and Smeitink (2004)
6	Swales and ditches	Removal	75 % (60–90 % Uniform)	Koeleman and Smeitink (2004)
		Surface water	25 % (10–40 % Uniform)	
7	Local TWP	Urban water runoff	100 %	(Baensch-Baltruschat et al., 2020, 2021)
8	Urban water runoff	Combined sewer	70 % (60 %–85 %, Triangular)	(Ellis, 1989, 1991)
		Separated sewer	30 % (15 %–40 %, Triangular)	
9	Separated sewer	Removal	15 % (0 %–30 %, Uniform)	(Baensch-Baltruschat et al., 2020, 2021)
		Surface Water	85 % (70 %–100 %, Uniform)	
10	Combined sewer	Wastewater treatment plant	60 % (50 %–70 %, Uniform)	(Brombach et al., 2005)
		Combined sewer overflow	40 % (30 %–50 %, Uniform)	
11	Wastewater treatment plant	Treatment	77.5 % (55 %–100 % Uniform)	Murphy et al. (2016)
		Grit and Grease Removal	22.5 % (0 %–45 % Uniform)	
12	Treatment	Sludge	95 % (72 %–100 % Triangular)	(Magnusson, 2014; Magnusson and Wahlberg, 2014; Murphy et al., 2016; Kole et al., 2017; Leslie et al., 2017; Horton et al., 2021)
		Effluent	5 % (0–28 % Triangular)	
13	Sludge	Incineration	3.5 % (3 %–4 % Uniform)	(Department for Environment Food & Rural Affairs, 2022; 2024)
		Agriculture	94.5 % (94 %–95 % Uniform)	
		Other	2 % (1 %–3 %, Uniform*)	

Affairs, 2024)). Our finding of 9.1 kt lies within this broad range, however it is likely that TWPs were not detectable using their methods (Knight et al., 2020). Baensch-Baltruschat et al. (2021) applied similar mass flux modelling methods and found between 5.6 kt and 11.7 kt of TWP reaches sludge where 1.4 kt to 2.8 kt of this reaches German agricultural soils. Our findings of TWP in sludge are similar to Baensch-Baltruschat et al. (2021) but with a higher rate of 9.1 kt TWP reaching soil is due to the far higher share of sewage sludge application to agricultural land in the UK compared Germany.

Validation of our results with real world data is currently only possible along the sewage sludge pathway since previous studies have assessed microplastic flows through WWTPs. Validation of other pathways remains challenging due to a lack of empirical data of measured TWP in the environment (Knight et al., 2020).

We find that 23 kt (16.7 kt to 29.2 kt) of TWP are removed each year. However, a portion of these TWPs are likely further transported, such as through clearing of stormwater management systems, to landfills and other disposal avenues such as incineration. We assumed similar removal efficiencies to that of Unice et al. (2019b) for water runoff into drainage infrastructure, but found differing proportions of TWP entering surface water, 20 % compared to our 37 % (30 %–45 % for 5th to 95th percentiles). We attribute this difference to the larger portion of TWP exiting combined sewers into surface water through CSO. This assumption was based on non-UK infrastructure, but may be improved

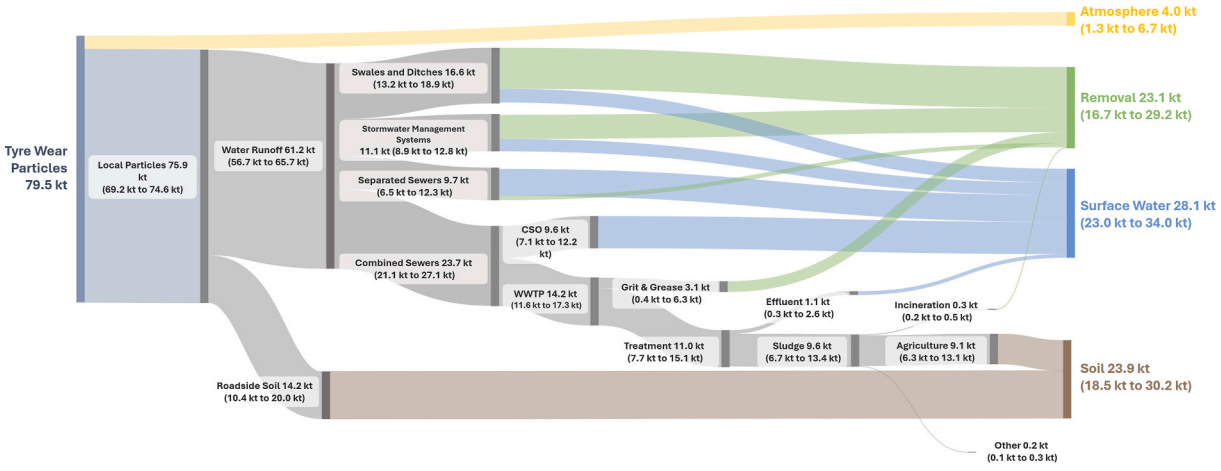


Fig. 2. The total mass flow of TWP through the environment in the UK showing the inventory of TWP mass along each pathway, where the bar size is proportional to the median mass, these median mass values are given in labels with the 5th to 95th percentile range; as median values are given for each stage of the framework, the input of each mass flux stage does not necessarily equal the total output of each mass flux stage. Diagram produced using Bogart (2025).

Table 2
Results from the global sensitivity analysis providing the TWP median, 5th percentile, 95th percentile, mean, and standard deviation across the Monte Carlo runs.

	Median (kt)	5th Percentile (kt)	95th Percentile (kt)	Mean (kt)	Standard Deviation (kt)
Atmosphere	4.0	1.3	6.7	4.0	1.6
Removal	23.1	16.7	29.2	23.1	3.8
Surface Water	28.1	23.0	34.0	28.3	3.3
Soil	23.9	18.5	30.2	23.9	3.5

in the future with the increasing amount of data published on UK CSOs (Giakoumis and Voulvoulis, 2023).

The spatial distribution of TWP in the UK reveals distinct patterns across environmental matrices. Fig. 3 illustrates the origin of these particles that enter different environmental compartments, while Fig. 4 shows their initial destinations. Our spatial analysis shows that TWP are most concentrated around major urban centres and along high traffic volume roads, where this pattern aligns with traffic volume. Our spatial analysis reveals atmospheric tyre wear emissions concentrate around urban areas and motorways. For surface waters, particles enter via rural road runoff and urban sewer discharges, with water bodies downstream of urban areas showing elevated inputs despite significant capture by treatment facilities. The soil pathway results demonstrate a significant rural-urban transfer mechanism, where urban-originated particles processed through wastewater treatment create a dispersed contamination pattern across agricultural soil following sludge application patterns rather than traffic density. Removal pathways follow urban areas with treatment facilities and highways with modern stormwater systems.

When comparing across environmental matrices, our analysis reveals that while atmospheric emissions follow a concentrated pattern near major transport roads and urban areas, the soil and water pathways demonstrate more complex spatial distributions due to the influence of infrastructure systems that redistribute particles. This redistribution creates secondary hotspots away from emission sources, particularly evident in agricultural areas receiving sewage sludge and in water bodies downstream of urban discharge points.

The cross-matrix analysis also indicates that different regions of the UK face varying challenges in managing tyre wear particles. Urban centres experience high local atmospheric concentrations but effectively transfer a significant proportion of particles to rural environments through wastewater treatment systems. Rural areas, while experiencing lower direct emissions, become recipients of urban-originated particles through agricultural applications of sewage sludge, creating a significant but often overlooked exposure pathway that requires targeted monitoring and potential regulation.

3.1. Limitations and future work

An important limitation of our study is the reliance on national averages for infrastructure systems, where local variations in sewer configurations and drainage systems could significantly affect particle distribution. Future work should incorporate GIS-based infrastructure mapping to match specific road segments with their actual drainage systems rather than applying uniform assumptions across road categories. Moreover, our 1 km^2 resolution is appropriate for national-scale assessment, higher resolution modelling is needed to capture roadside environments, particularly for urban areas. Although roadside soil deposition represents a relatively small proportion of total tyre wear fate, more detailed modelling of sewer systems and water runoff pathways is likely more beneficial for predicting the environmental destination of tyre wear particles. For example, the data captured and



Fig. 3. Maps show the origin of TWP that enter the atmosphere, surface water, and soil, or are removed from the environment.



Fig. 4. Initial destination of TWP for the atmosphere, surface water, and soil, or are removed from the environment. Note this destination removal map is equivalent to origin removal map given in Fig. 3.

methods employed by Thames21 (2025) for the Thames catchment area could be expanded across all of the UK.

Our framework does not consider the impact of TWP size on its pathway through the environment. Initial evidence suggests that measured size of TWP size affects pathways through the environment (Kovochich et al., 2021; Parker-Jurd et al., 2025). Future studies should disaggregate the pathway framework by particle size classes, as smaller particles have different transport pathways than larger particles, such as the filtering stages through waste water treatment plants (Koeleman and Smeitink, 2004) or the size of particle released into the atmosphere (Ntziachristos and Boulter, 2019; Saladin et al., 2024). Our analysis also highlights the critical need for empirical measurements at each stage of the environmental pathway, as current literature provides sparse and sometimes contradictory evidence on particle retention rates in various systems and does not differentiate by particle size or type. We encourage future studies measuring TRWP to consider how their results can inform future mass flux models, such as providing TRWP concentrations in CSO discharges and disaggregating TWRP from microplastics in sludge.

We have only covered the entry of TWP into the environment which only covers a limited set of the full TWP pathway. For example, future work could extend our framework by adding river transport and deposition of TWP in river sediments (Unice et al., 2019a, 2019b). Likewise, particles initially suspended in the atmosphere will be deposited and then further transported.

4. Conclusions

This study presents the first national-scale mapping of tyre wear particle pathways into the UK environment. By combining a road transport tyre wear particle emission model with a particle pathway framework, we have quantified the flux of tyre wear particle along environmental pathways and identified their spatial distribution across the country. Our findings indicate that 79.5 kt of tyre wear particles are released annually in the UK, with 4.0 kt entering the atmosphere (median value, with a range of 1.3 kt to 6.7 kt across 5th to 95th percentiles from Monte Carlo simulations), 28.1 kt (23.0 kt to 34.0 kt) entering surface waters, 23.9 kt (18.5 kt to 30.2 kt) entering soils, and 23.1 kt (16.7 kt to 29.2 kt) being removed from the environment through various management systems. Several conclusions emerge from this study:

1. The environmental fate of tyre wear particles is complex, with only a minority (approximately 30 % in rural areas) being deposited directly on roadside soils near their emission source. Most particles follow transport pathways through drainage systems, wastewater treatment plants, and will enter river systems, further transporting the particles, resulting in significant spatial redistribution from their original release points. This complexity highlights the need for distributed pathway mapping and measurements rather than focusing solely on roadside concentrations.
2. The wastewater treatment process creates a significant rural-urban transfer mechanism, with approximately 9.1 kt of urban-originated tyre wear particles being applied to agricultural soils annually through sewage sludge application. This represents a substantial redistribution of urban pollution to rural environments.
3. While existing infrastructure successfully removes approximately 30 % of tyre wear particles from environmental circulation, the remaining 70 % enter soil, water, or air matrices where they can potentially impact ecosystems and human health.

These findings have important implications for both environmental policy and future research. Our results highlight the need for integrated

approaches to tyre wear management that address multiple environmental pathways rather than focusing solely on airborne particles. Finally, our study provides a foundation for more future modelling and measurement of tyre wear particles entering the environment.

CRediT authorship contribution statement

Chunyi Zheng: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Daniel Mehlig:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Conceptualization. **Tim Oxley:** Writing – review & editing, Supervision, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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