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Quantifying abrasion of microplastics from mountain bike tires

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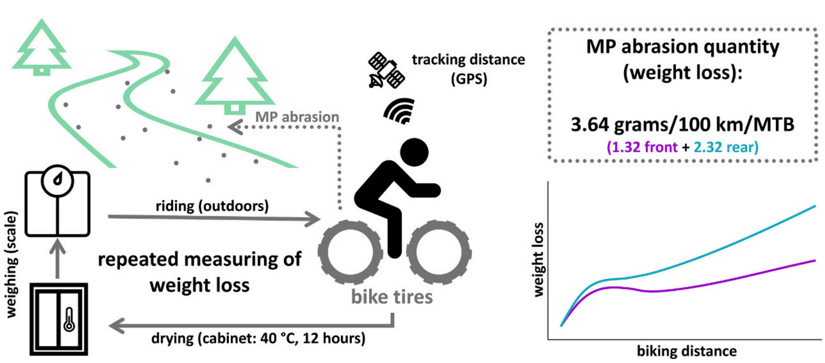
HIGHLIGHTS

- Gravimetrical method is suitable to quantify microplastic abrasion of bicycle tires
- Average abrasion rate of 3.62 g / 100 km and mountain bike
- Rear tires have higher abrasion rates than front tires
- Abrasion rates are highest at the beginning of the use cycle
- Mountain bikes have generally lower abrasion rates than motorized vehicles

GRAPHICAL ABSTRACT



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ABSTRACT

Current research on microplastics (MPs) primarily focuses on investigating environmental samples, often lacking in identifying the actual sources and emission quantities. Little is known about the quantity of bicycle tire abrasion in real-use scenarios. Mountain biking, a popular outdoor sport produces tire wear particles (TWP) directly in natural environments. This study quantifies microplastic abrasion from mountain bike tires in real-life usage.

We measured the weight loss of mountain bike tires gravimetrically over their period of use to quantify abrasion throughout their lifecycle. We found an abrasion rate of 3.62 g (median) per 100 km per mountain bike. The rate was higher for the rear tire (median 2.32 g; IQR = 1.58 to 3.59 g) compared to the front tire (median 1.32 g; IQR = 1.06 to 2.64 g). After higher abrasion rates of the new tire, rates decrease, and average abrasion stabilizes at around 1.43 g (median front and rear; IQR = 1.07 to 1.60 g) per 100 km per tire. This dynamic is due to the abrasion of excess material and sharp edges produced during manufacturing. Gravimetrically measuring material loss proved effective in assessing MP abrasion from mountain bike tires. Combining these findings with average bicycle kilometrage statistics for Germany results in an emission of 59 to 88 g of tire material per mountain biker per year. Calculated emissions from cycling (rider-number * average kilometrage * abrasion rate) would contribute <1 % to the total annual MPs emissions, significantly lower than motorized vehicle tires, which contribute about 30 %.

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1. Introduction

Microplastics (MPs), plastic particles <5 mm in size, have emerged as a pervasive environmental pollutant. These particles originate from various sources, including the breakdown of larger plastic debris, cosmetic products, and notably, the abrasion of vehicle tires (Thompson et al., 2004). So far, researchers have tried to quantify the rate of microplastic release from motorized traffic (mostly of cars and trucks), examined their distribution in different environments, detected fraction sizes and explored the potential ecological risks associated with their accumulation (Prenner et al., 2021; Unice et al., 2013). Tires release synthetic particles into the environment as a conglomerate of tire and road wear particles (TRWPs) mostly by acceleration, deceleration and shear forces (Gehrke et al., 2020; Klüppel, 2014; Knight et al., 2020; Kole et al., 2017; Prenner et al., 2021; Reiber, 2019; Silvestro and Technik Zentrum, 2022; Sommer et al., 2018). Cars release approximately 11 g of microplastic per 100 km (all four tires combined) (Silvestro and Technik Zentrum, 2022). This results in 57 % of total microplastic emissions from road traffic and 30 to 35 % of total microplastic emission in Germany (Baensch-Baltruschat et al., 2021; Sommer et al., 2018). Tire material can be found in street runoff and potentially impacts aquatic and terrestrial ecosystems, wildlife and human health (Knight et al., 2020; Sundt et al., 2016).The European parliament declared tire wear officially as one of the major sources of MPs illustrating their significance for society and environment (The European Parliament and the Council of the European Union, 2020).

Bicycling as an environmental-friendly form of transportation and popular leisure activity also emits MPs, but its quantity and significance is unknown yet. Mountain biking, by its nature, involves direct interaction with natural terrains, leading to direct release of MPs in ecological systems. A key element in this interaction is the tire, which directly influences rider safety, performance and environmental health. The choice of tire is influenced by rider level, riding style, terrain and personal preferences. Unlike most vehicle tires, mountain bike tires are used on unpaved, often rugged trails, which may lead to specific patterns of wear and subsequent MP generation (Mountainbike Tourismusforum Deutschland e.V., 2022). The direct interaction of tire and terrain can cause multiple potentially negative consequences for riders and the environment, i.e. soil, flora and fauna (Kuwaczka et al., 2023). The disposal of tire wear particles directly into ecosystems is largely unstudied. Despite the significant growth in the popularity of mountain biking, the associated increase in use of equipment and the short pathways of MPs from mountain bike tires into the environment, there has been limited research into the specific contributions of mountain bike tire abrasion to MP pollution.

Mountain biking has become one of the most popular outdoor recreational activities of this time with 16.6 million (20 % of the total population) active riders in Germany (Mitterwallner et al., 2021; Schlemmer et al., 2020). This trend has increased the need for knowledge regarding the technical aspects of equipment and underscores the need for comprehensive research into the environmental impacts of mountain biking, particularly regarding MP emissions from tire abrasion. In addressing this gap, it is crucial to consider the broader context of tire abrasion research. Studies on motorized vehicle tires have shown that microplastic emissions are influenced by various factors, including tire composition, road surface, driving behaviour, and environmental conditions (Gehrke et al., 2020, 2021, 2023; Silvestro and Technik Zentrum, 2022).

Current methodologies for detecting and identifying polymer types and concentrations of MPs in environmental samples include spectroscopic techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and Raman spectroscopy (Rocha-Santos and Duarte, 2015). Additionally, techniques like pyrolysis-GC/MS allow for the analysis of complex mixtures of MPs by breaking them down into identifiable chemical components (Dierkes et al., 2019). Specifically focusing on tire abrasion, gravimetric analyses have been employed to measure weight loss in motorized vehicle tires over time, correlating this data with the distance travelled to estimate microplastic emissions (Kole et al., 2017). Laboratory simulations using road simulators and field studies tracking real-world tires use via air samplers have both been utilized to understand the rate of tire wear (Kreider et al., 2010; Panko et al., 2013). Results revealed that tire wear particles (TWPs), a mix of synthetic rubber and road debris, are a significant source of microplastics in urban runoff and atmospheric deposition (Kreider et al., 2010).

Despite increasing attention and studies on the abrasion of car and truck tires, leading to a better documented environmental impact of these transportation forms, the contribution of bicycle tires to microplastic pollution remains mostly unexplored. Due to similar chemical compositions of all tire types, currently used methods can't distinguish between source of tire particles and lack the possibility of quantification for bicycles.

The current research highlights a significant knowledge gap in the emissions and effects of MPs from bike tires, particularly mountain bikes. This gap in research is critical, given the growing popularity of cycling and mountain biking, which suggests a potential increase in MP emissions from these sources (Kuwaczka et al., 2023; Mitterwallner et al., 2021). Addressing this gap will require targeted studies to develop standardized measurement techniques and quantify the environmental distribution and impacts of MPs from bicycle tires. This study aims to establish a method for investigating the quantity of MP emissions from mountain bike tires and providing a scientific basis for further studies. Such research is essential for developing comprehensive strategies to mitigate microplastic pollution and to protect environmental health (Browne et al., 2011).

2. Methods

2.1. Study design

To investigate the microplastic emissions from mountain bike tires due to abrasion we chose a gravimetric approach in a field study. Participants were provided with a new set of mountain bike tires. Tires were weighed at the beginning and after different use periods. Activities were tracked via GPS-devices. The primary objective was to measure the general weight loss of the tires and correlating this data with the distance travelled to measure and quantify the abrasion rate and potential MP emissions.

All participants ($n = 9$) were experienced in the sports and used conventional mountain bikes without electrical assistance. All tires (Model Schwalbe "Wicked Will", size 29 × 2,4 in.) were equipped with thermoplastic polyurethane (TPU) inner tubes (Model Schwalbe Aerothan), to minimize inner friction. All participants were instructed to maintain their usual mountain biking habits (e.g., riding style and route choices) to reflect a realistic usage scenario. Participants were riding in average 17 tours (± 5 SD) with a mean distance of 29.2 km (± 6.7 SD) and a mean speed of 14.6 km per hour (± 1.9 SD).

2.2. Drying and weighing protocol

Prior to the main study, a pilot study was conducted to develop a standardized drying and weighing protocol. This protocol ensured consistency and accuracy in tire weight measurements. The following steps were established:

1. Drying: Tires were thoroughly cleaned with a brush and water to remove any dirt and debris. They were then placed in a drying cabinet (Type Heratherm OMH740, Thermo Scientific) set at a constant temperature of 40 °C with 0 % humidity for 12 h to ensure complete drying. This setting worked to exclude any additional water which might be soaked into the tire via use or air humidity.
2. Weighing: A high-precision lab scale (Model FZ-3000i, A&D Company, Limited; weighing range: 3200 g; accuracy: 0.01 g) was used to

weigh the tires. Each tire was weighed immediately after been taken out of the cabinet in triplicate to account for any variability in the measurements. The mean of the three measurements was recorded as the tire's weight.

At the beginning of the study, each set of new tires was dried and weighed following the established protocol. This initial weight served as the baseline of each individual tire for subsequent measurements.

2.3. Tracking and interval measurements

Participants rode their mountain bike tours following their individual habits. They were instructed to track all the rides conducted with the survey tires using GPS-enabled devices (e.g. cycling computer or smartphone). This allowed for precise recording of the distance travelled with the survey's tires. Recorded GPS-tracks were provided remotely by the participants via an online outdoor-platform (*Komoot*: Outdoor Route Planning and Navigation Platform, Komoot, n.d.). In addition, the subjects were asked to keep a travel diary and document the travelled distance, weather and special equipment or incidents for each ride. At predetermined intervals (latest after 500 km between two measuring points), participants returned the tires for the next weighing. The interval measurements followed the same protocol as the initial weighing. To correct for potential weight loss due to aging processes, three pairs of unused tires of the same batch were weighed at regular intervals. These reference tires had not shown any weight loss over the study period in any measurement.

2.4. Data collection and analysis

The weight loss of each tire set was calculated by comparing the baseline weight with the weights recorded at each interval. This data was then correlated with the distance travelled to determine the rate of tire abrasion. The abrasion rate of each measurement interval was calculated as the weight loss per 100 km travelled. After each weighing the tires were handed back to the same subject for the next measurement interval, keeping the assignment to front and rear wheel.

2.5. Statistical analysis

Data analysis was performed using the software R (version 4.3.3, R Core Team, 2024). The median abrasion rates were calculated for all samples, and Spearman regression analysis was used to explore the relationship between tire weight loss and distance travelled. The difference between abrasion rates of front and rear tires was tested (Wilcoxon signed-rank test). The proportions of three location-based surface attributes from OpenStreetMap (OSM) - *smoothness*, *tracktype*, and *surface* classes - were calculated for all rides of all subjects using tracked GPS files (Open Street Map, 2024a, 2024b, 2025). Due to insufficient coverage of OSM data in the areas where participants cycled, attributes could not be included for further analysis.

3. Results

Our results display a continuous weight loss over travelled distance over every measuring point and all subjects' tires. The correlation between the absolute weight loss and the travelled distance was significant for both tire positions (Spearman's rho: front = 0.65 and rear = 0.76; $p < 0.05$), with the rear losing more weight compared to the front tire over travelled distance (see Fig. 1). The Wilcoxon signed-rank test showed a statistically significant difference in weight loss over distance between the front and rear tire (see Fig. 2) over the study period.

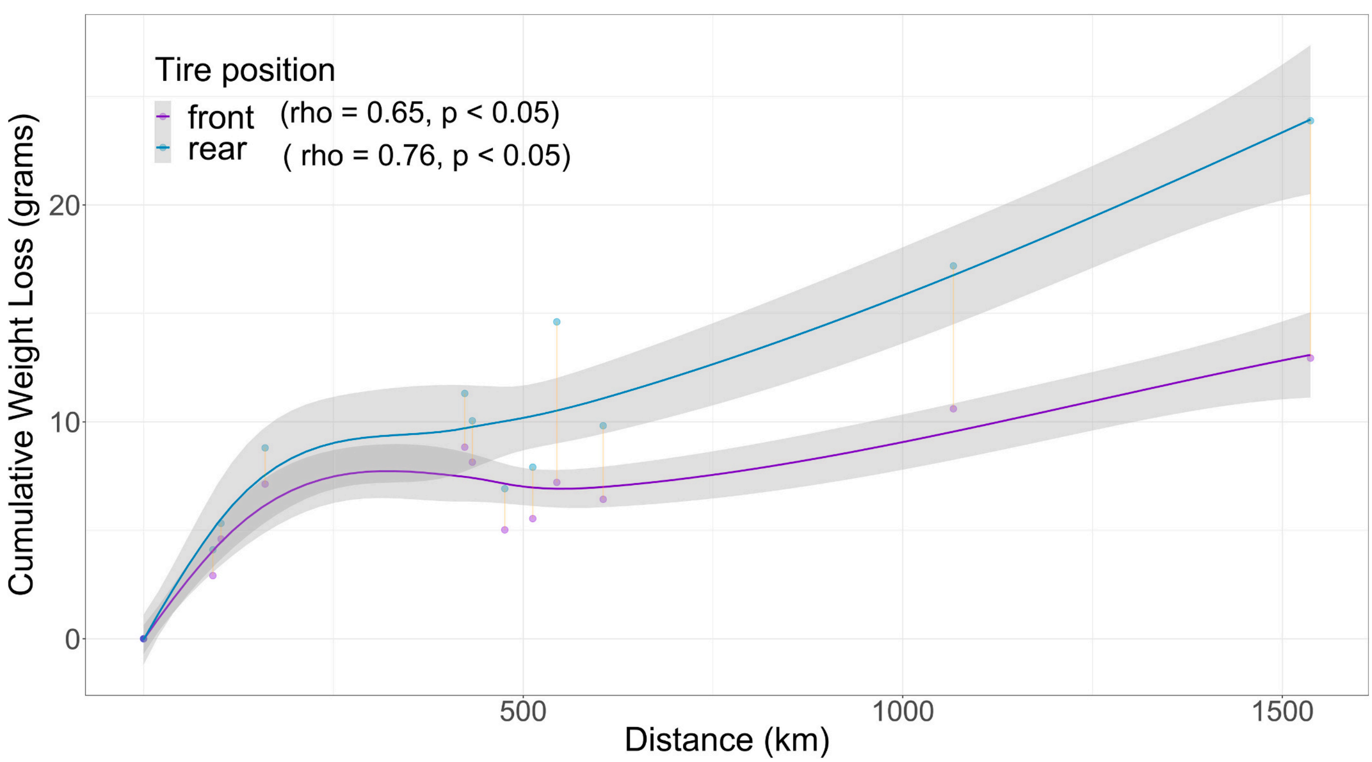

Fig. 1. Total weight loss of tires (in grams) over distance ridden (in kilometers) compared to baseline weight of each tire pair and measurement. Measurements from the front tire (purple) and rear tire (blue) from the same subject at same measuring point are connected by orange lines. The blue and purple lines show the loess regression of associated tires (front and rear). Spearman's rho shows a significant ($p < 0.05$) correlation (front: rho = 0.65; rear: rho = 0.76) between the weight loss of tires and the distance travelled. Rear tires consistently showed higher weight loss values than associated front tires at every measuring point. The slight negative incline at one section of the loess smoothing line is an artifact of the smoothing method and variation in individual data points, and no actual decrease in cumulative tire weight loss.

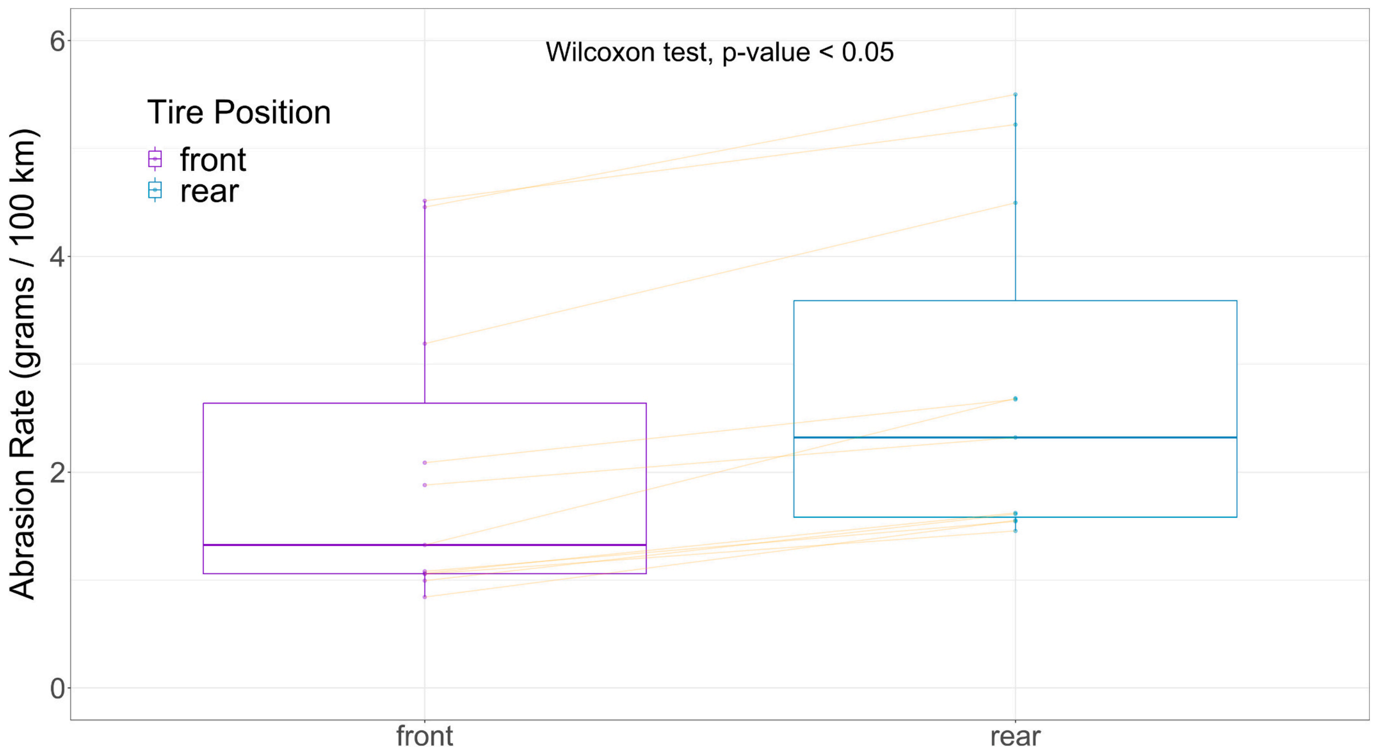

Fig. 2. Comparison of the abrasion rate (grams/100 km) at every measuring point of all subject's tires. Measurements from the front tire (purple) and rear tire (blue) from the same subject and same measuring point are connected by orange lines. The weight loss per 100 km for the front tire has a median value of 1.32 g and for the rear tire of 2.32 g. Rear tires consistently showed higher weight loss per 100 km values than associated front tires at every measuring point. The Wilcoxon signed-rank sum test showed a significant difference ($p < 0.05$) in weight loss per 100 km between the two groups.

The median abrasion rate over all tires and measuring points was 1.75 g (IQR = 1.36 to 3.07 g) per 100 km and tire. The average rate was higher for the rear (median 2.32; IQR = 1.58 to 3.59 g) compared to the front tire (median 1.32 g; IQR = 1.06 to 2.64 g). After high abrasion rates of the new, unused tires (median 2.93; IQR = 2.04 to 4.50 g), average abrasion rates drop after 500 km down to 1.43 g (IQR = 1.07 to 1.60 g) per 100 km and tire. Additionally, the abrasion pattern on the tire surface clearly shows the most material loss at the central part of the contact area which is used mostly when riding the bikes and more wear on the tread pattern of the rear compared to the front tire (see Fig. 3).

4. Discussion

4.1. *Microplastic from mountain bike tires*

Abrasion quantities from mountain bike tires are low, in average 3.64 g per 100 km (sum of front and rear tire median), compared to cars with 11 to 12 g or trucks with up to 94.9 g per 100 km and vehicle (Giechaskiel et al., 2024; Lee et al., 2020; Silvestro and Technik Zentrum, 2022). Our results showed higher abrasion rates at the first 500 km of a new set of tires, with a constant mean abrasion afterwards. This

Fig. 3. Comparison between a new, unused tire (left) and a front (middle) and rear (right) tire after a travelled distance of 1500 km.

decrease in abrasion per kilometer after a certain use period aligns with studies on car tires, which measured higher abrasion rates on new tires compared to those that had already travelled a longer distance (IDIADA, 2022; Silvestro and Technik Zentrum, 2022). This pattern might be caused by the rounding of the sharp edges and the relatively quick wear of the protruding material from the production process (tiny hair-like structures) on the new tire.

The higher abrasion of the rear tire compared to the front tire at every measurement is also supported by the findings on tire abrasion of cars, where studies consistently demonstrate that tire abrasion rate is always higher on the wheels located on the drivetrain end of motorized vehicles (front or rear drivetrain) (IDIADA, 2022; Liu et al., 2022). This might be explained by two factors. The drive-train end of the vehicle not just usually carries a higher load of the system weight but also transfers the acceleration force (driving torque) from the vehicle to the surface. Both factors refer to the rear tire of conventional mountain bikes without electrical assistance, which were used in our study. With electrical assisted bikes not just the general abrasion, but also the discrepancy between front and rear tire can be expected to be larger with higher weight and driving torque (Kuwaczka et al., 2023; Mitterwallner et al., 2021). The loads applying on the front and rear tires of the mountain bikes (including the weights of bike and driver) are distributed in a 40:60 ratio, when driving in sitting position on flat terrain. When driving uphill or downhill and for overcoming obstacles on the trails (e.g. rocks or roots), riding techniques require a permanent variation of the center of gravity of the rider-bike-system. Our study design didn't include sensors on subject's bicycles permanently measuring load distribution so real-time load-distribution data are not available for any analysis. However, the ratio between the abrasion rate of the front (1.32 g / 100 km) to the rear tire (2.32 g/100 km) are 36:64, closely resembling the usual weight distribution while cycling.

The tire material (rubber composition), its hardness degree and the tire tread pattern might also have an influence on abrasion of MPs. In real-life mountain biking, often tire models with different hardness and tread pattern are used for front and rear tires on the same mountain bike. In this pilot study we aimed at establishing a method for quantifying MP abrasion. Following the need for standardization in this concern, we investigated only one commercially available, broadly used tire model (Schwalbe "Wicked Will"), suitable for different mountain biking categories (cross-country, trail, all mountain) for the front and rear tire.

4.2. Scaling up

The lower and upper limit of mean bike kilometers ridden by German cyclists per year according to a survey from de, 2015 are 1632 and 2422 km respectively (fahrrad.de de, 2015). By multiplying these values with our median measured abrasion quantity of 3.64 g per 100 km per bicycle, we calculated an emission between 59 and 88 g of tire material per capita and year. The average annual kilometrage from this survey seems very high and we would suggest lower values and therefore lower abrasion quantities per person and year. This would also indicate values much closer to the estimated 15.6 g per cyclist and year in Germany by the Fraunhofer UMSICHT institute (Bertling et al., 2022). Nonetheless, our calculation is still much lower than the estimated value for cars of 1228.5 g per capita and year of the same study. If we multiply the values for the 16 million mountain bikers in Germany (IfD Allensbach, 2023), the total annual MP emission for the sport would be approximated between 944 and 1408 metric tons of tire material. With an estimated value of 330,000 tons of total annual MPs emission in Germany, mountain biking would contribute <1 %, while cars contribute about 30 to 35 % with 98,400 tons per year (Baensch-Baltruschat et al., 2021; Bertling et al., 2022).

Using the same method for scaling up for England and the USA, biking would make up the same percentages, while cars contribute a major share of the total annual MPs emission. (Cycling, 2023; Kole et al., 2017; Statista Research Department, 2024; UK Centre for Ecology& Hydrology, 2020) On the level of the European Union and globally, the share of bicycle particles on the total emission of MPs is estimated to be in the same range while the emission of cars can have a share of up to 60 % (European Commission Combating Microplastic Pollution in the European Union, 2023; Ipsos, 2022; Kole et al., 2017; Schwarz et al., 2023).

This simplified methodology for scaling total emission of bicycle tires have the potential for over- or underestimations. The various styles of bike tires (e.g. road cycling, gravel biking) and user groups (e.g. beginners and experts, competitive and leisure riders, bikers with and without electrical support) might have higher or lower abrasion quantities especially taking different environmental conditions into account. The tire model used in this study also has a more aggressive tread pattern which might lead to higher abrasion rates then tires with a less pronounced tread pattern. Another study including those variables is highly recommended to shed more light into the sources and emitted quantities of MPs.

4.3. Influential factors on abrasion

Rubber compositions might lead to significant differences in abrasion rates as was already shown in further studies on different car tires (Silvestro and Technik Zentrum, 2022). The tire tread of cars typically consists of styrene-butadiene rubber, which is based on styrene, a precursor of polystyrene, combined with natural rubber and other unspecified additives (Sommer et al., 2018). For bicycle tires, the composition may vary in included components and ratios, between tire brands and models. With different requirements for different styles of cycling (e.g. road, gravel, mountain biking), compositions of rubber material might vary significantly between brands and between models within a brand. Data on the chemical composition of rubbers generally is not available because manufacturers do not disclose rubber compounds, as this information is considered proprietary and protected as a trade secret. Additionally different cycling styles also require various tread patterns and tire sizes (diameter and width), potentially having an impact on abrasion quantities. Abrasion rates can be influenced by environmental factors (temperature, moisture, surface characteristics, grip etc.), applied forces (acceleration and deceleration, speed, cornering forces, system weight, riding style etc.) and bike and tire conditions (tire pressure, tube system, wheel characteristics, suspension) (Boulter, 2006; Schläfle et al., 2023, 2024; Stojanovic et al., 2022; Wang et al., 2017). Higher speed and acceleration forces have proved to generate higher abrasion quantities of particles in past studies on cars (Denby et al., 2013; Kupiainen and Pirjola, 2011; Pohrt, 2019). For cycling riding speed is expected to have similar effects on the abrasion rate and slower speed could reduce these. Additionally, to the system weight (bike and rider weight combined) and tire type, riding style and surface type might have the highest impact on the abrasion rates. To make a robust estimate, a larger dataset of wear values and environmental factors of the routes taken is needed. These data could be generated through a larger-scale participant study in the same style of this pilot study including different tire models.

4.4. Fate of particles and environmental impact

In a comprehensive review on the contribution of tire wear to pollution, it was concluded that only 2.5 % of the abrasion of car tires gets emitted into the air (as PM10, particles below 10 μm), which suggests that a bigger share of the abraded material sticks to surface materials or gets emitted as bigger particles which are not airborne (Giechaskiel et al., 2024). If the abrasion process on bikes functions similar as for car tires, in the sport of mountain biking, done in various environments, tire material most likely sticks to gravel, rocks, roots and soil particles. Another study estimated that 12 to 20 % of the vehicle tire particles find their way into surface waters, 66 to 77 % stay on road banks and soil near roads, and 5 % get emitted as fine-air fraction

(Baensch-Baltruschat et al., 2021). Mountain biking is usually exercised directly within the natural environment, which lead to short path of the emission source of MPs to natural environments and organisms, which suggest a bigger share of the emitted particles reaches soil, water, vegetation and organisms. Due to the overall lower distances and lower emission rates per distance from bicycles compared to motorized vehicles the absolute MP emission into the environment will most likely still be much lower. Nonetheless the emission could be a problem referring to possible and necessary intervention points discussed in the next paragraph.

4.5. Recommendations

While governmental bodies started to take efforts in recent years on the regulation of various parts of the lifecycle of tires, the dispersion of microplastic particles into the environment just recently got attention from politics (The European Parliament and the Council of the European Union, 2020; Trudsø et al., 2022). There are different conceivable solutions to reduce or even eliminate the emission of MPs by bicycle tires into the environment which can be applied at different stages of the life cycle.

4.5.1. Reduction by production

First, production processes could be optimized to reduce or already remove the excess material in the factory facilities. This could be done be shredding off the excess material (tiny hair-like structures) which have no function on the performance of the tire.

There have been tests on material with even better properties but less wear, featuring rubber with 50.9 % less wear and 43.2 % better wet grip due to the changed composition of the tire material. (Li et al., 2021). Even tests on rubber material with a higher longevity by self-healing properties could be a solution (Araujo-Morera et al., 2019). More sustainable source materials could be a solution even though bio-based doesn't mean partly or completely biodegradable (Ayar et al., 2021). But reduction of MP emissions by biological degradation doesn't seem to be a sufficient solution at the current state of technology. Tires consist of various components and production steps which make them almost not biodegradable at all (Nielsen et al., 2024). Some components such as carbon black, used as a filler and for sturdiness of the tire, show no biodegradability and even reduce the biodegradability of other components when combined to tire rubber (Cadle and Williams, 1980; Tsuchii et al., 1990, 1997; Tsuchii and Tokiwa, 2006). Biodegradability could even shorten the lifetime if tires in the use phase don't get stored in conditions that don't allow the degradation.

4.5.2. Reduction by collection

Even though airborne particles seem to make up a small fraction of emitted material, the collection of particular matter already while riding might be a solution. Specially designed device mounted on cars already showed promising results and capture over 50 % of airborne particles (Dong et al., 2021; Ttc, 2020).

Some bike tire brands established measures to reduce source and general waste material by introducing a recycling system, where old bike tires and even inner tubes can be collected by bike shops and be send back to the producer for recycling into new tires (Schwalbe Ralf Bohle GmbH, 2015).

4.5.3. Reduction by user behaviour

Choosing the right tire and pressure for your needs is an essential part not just for a better cycling experience, but it could also be beneficial to reduce abrasion quantities. A study on car tires showed varying abrasion depending on the choice of tire and their dedicated use-scenario (e.g. summer and winter tires). The using of recommended tire pressure and user driving behaviour indicated potential to reduce abrasion of material (Andersson-Sköld et al., 2020; Silvestro and Technik Zentrum, 2022). In the context of cycling especially the choice of the dedicated tire model for the right riding style might be a promising measure to reduce the already low abrasion quantities.

A good review on measures, research and potential on the reduction of tire wear, focusing on motorized vehicles, can be found in Stojanovic et al. (Stojanovic et al., 2022).

4.6. Gravimetrical approach: Proof of concept

Our study quantifies the emission of MPs via bicycle tires, utilizing repeated measures of tire weight and tracking of all rides to calculate the weight loss of tires over travelled distances. This weight loss served as a proxy for the quantity of lost bike tire material in the form of MPs. With multiple measuring intervals over the use period, we gained insights into the change and dynamics of material loss within the lifespan of a mountain bike tire. Our method yielded comprehensive and consistent results, and its validity is supported by the constant results of an indirect, gravimetrical approach on the abrasion of MPs from car tires (Silvestro and Technik Zentrum, 2022).

To get a clearer insight in the microplastic quantities and distribution in the environment, future research should aim to investigate tire abrasion across a wider variety of bicycle types, including road, gravel, and mountain bikes. Specifically, there is a need for studies that compare tire wear across different cycling disciplines and consider the impact of environmental factors such as surface type, gradient, and weather conditions. Additionally, future investigations could benefit from incorporating bike-specific parameters like tire width, pressure, and tread pattern, alongside rider-related factors such as weight, riding style, and speed. By integrating GPS-tracked real-world data and developing predictive models, researchers could gain deeper insights into optimizing tire durability and performance across diverse cycling conditions.

CRediT authorship contribution statement

Fabian Sommer: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Luca Brockmann:** Writing – review & editing, Investigation, Data curation. **Manuel J. Steinbauer:** Writing – review & editing, Supervision, Resources. **Volker Audorff:** Writing – review & editing, Supervision, Resources, Conceptualization.

Ethics statement for subject study

The study and all included procedures were approved by the Ethics Committee of the University of Bayreuth.

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.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2025.178971.

Data availability

Data will be made available on request.

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