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Tyre wear particles: an abundant, yet widely unreported microplastic?

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Abstract

Owing to their physical and chemical properties, particles generated by the abrasion of tyre tread against road surfaces, or tyre wear particles, are recognised as microplastics. Recent desk-based studies suggest tyre wear to be a major contributor of microplastic emissions to the environment. This study aimed to quantify tyre wear in roadside drains and the natural environment near to a major road intersection. Tyre particles were identified by visual identification and a subsample confirmed as tyre wear by GC-MS using N-cyclohexyl-2-benzothiazolamine (NCBA) as a marker. The abundance of tyre wear within roadside drains was greater in areas associated with increased braking and accelerating than high traffic densities ($p = <0.05$). Tyre particle abundance in the natural environment ranged from 0.6±0.33 to 65±7.36 in 5 mL of material, with some evidence of decline with distance from the road. This study offers preliminary data regarding the generation and abundance of this under-researched microplastic.

Keywords

Microplastics; tire wear particle; vehicle emissions; run-off; traffic density; drainage

1 Introduction.

Microplastic accumulation within the environment has been well documented in scientific literature and is an area of significant concern in pollution research, with an ever-increasing number of publications on the subject (Barboza and Gimenez, 2015; Völker *et al*., 2019). However, a lack of standardised and practical procedures for the extraction and identification of microplastics remains (Van Cauwenberghe *et al*., 2015; Ivleva *et al*., 2016; Horton *et al*., 2017). Microplastics are typically described as solid, water insoluble, polymer-based materials less than 5 mm in size with a low degradation rate (Verschoor *et al*., 2016; Boucher *et al*., 2017). Tyre wear particles fit this description and were first recognised as a potential pollutant in the 1970's (Cadle and Williams, 1978). Yet, 40 years later it was reported that there is still uncertainty surrounding the distribution and quantity of these particles in the environment (Magnusson *et al*., 2016). Microplastics can originate from the abrasion of plastic products while in use (Boucher *et al*., 2017). Primary microplastics are released directly into the environment, while secondary microplastics originate from degradation and fragmentation of larger plastic wastes once exposed to the marine environment (Boucher *et al*., 2017). Plastic materials offer a wide range of applications as they are lightweight, durable, versatile, and inexpensive (Cole *et al*., 2011). However, substantial quantities of end of life plastics, as well as particles generated during the use of products, are accumulating as waste and litter (Barnes *et al*., 2009; Lusher *et al*., 2017).

Tyre wear particles are defined as particles generated during a complex physio-chemical process driven by frictional energy between the rolling shear of the tyre tread against the surface of the road (Kreider *et al*., 2009). This typically produces particles which are elongated in shape (Dannis 1974; Williams and Cadle.,

1978; Padovan *et al*., 1999; Adachi and Tainosho., 2004) with an aspect ratio of 0.64 (Kreider *et al*. 2010), yet smaller particles exists with potentially different dimensions (Dahl *et al.,* 2006; Gustaffson *et al.,* 2008; Wang *et al.,* 2017; Wagner *et al.,* 2018). Tyre wear composition varies depending on the brand and purpose of the original tyre however, a typical all-season passenger tyre can contain 30 styrene-butadiene rubbers, 8 natural rubbers, 8 kinds of carbon black, 40 different chemicals as well as polyester and nylon fibres (Lassen *et al*., 2015). Consequently, giving rise to copious tyre formulations (Kreider *et al*., 2010). The principle components consist of 40 - 60 % rubber content (synthetic and natural), 20 - 35 % filler (carbon black and silica) and 12 -15 % oils (Wagner *et al.,* 2018). The physical and chemical characteristics are poorly understood as tyre wear particles can also incorporate material from the road and surrounding environment. The relative encrustment of road wear to tyre particles reportedly varies between 10 and 50 % (Sommer *et al*., 2018). This may include asphalt, road dust, gravel, oils, and plasticisers. The abundance, and rate, at which tyre wear particles are generated varies dependant on a number of factors but is reported to increase as a consequence of vehicle load, under or over inflation of tyres, deviations in wheel alignment, wheel position (front wheels wear preferentially), over exposure to the elements, aggressive braking, acceleration, or driving at high speeds (Kole *et al*., 2017; Verschoor *et al*., 2016). Kole *et al.* (2017) compiled estimates of tyre wear generation data, extrapolated to global vehicles and population, reaching emissions of nearly 6,000,000 tonnes yr^{-1}, equating to 0.81 kg yr^{-1} per capita.

A study conducted in Norway indicated that aggregate particles generated from the wear of vehicle tyres and the road surface, typically referred to as tyre road wear particles (TRWP's), were the most important single source of primary microplastics to the natural environment (Sundt *et al*., 2014). It further stated that "a significant portion have the potential to reach water bodies and the ocean, while some is released directly into the sea". Similarly, a report produced in Denmark reached an almost identical conclusion (Lassen *et al*., 2015). However, both acknowledge that in several cases claims were based upon desk-based estimations. These reports appear to serve the basis for many subsequent articles and reports (Essel *et al*., 2015; Magnusson *et al*., 2016; Boucher and Froit, 2017; Eunomia, 2018). Several of the publications regarding tyre wear contributing to microplastic emissions reach a general consensus that there is a lack of reliable quantitative data on tyre wear in the natural environment, and notably the pathways of tyre wear to the oceans (Sundt *et al*., 2014; Essel *et al*., 2015; Magnusson *et al*., 2016). There is a considerable lack of empirical data regarding the abundance and distribution of tyre wear particles on roads, in drains, or in the environment.

Whilst tyre wear particles have been acknowledged as a pollutant for decades (Cadle and Williams, 1978), they have only recently been recognised as a microplastic (Sundt *et al*., 2014). To our knowledge no study has isolated or detected tyre wear particles using methods typically employed for more conventional microplastics (e.g. Fourier-transform infrared spectroscopy and Raman spectroscopy). Consequently, tyre wear particles have not always been included under the term. This is reflected in the frequency in which tyre wear is reported in environmental samples. For example, 91 results were retrieved for articles published between 2000 and 2019 containing the term 'microplastic' in the title and 'occurrence' or 'prevalence' in the topic in the Web of Science database. Of these, 35 gave a list of microplastic identified from environmental samples (Figure 1). Only two (Munari *et al*., 2017; Song *et al*., 2015), equating to 1 % of the studies, reported synthetic rubber that had the potential to be tyre wear particles. Song *et al*. (2015) collected water samples from Jinhae Bay, Korea and found synthetic rubber to comprise 0.7 % of the polymers identified. However, it is worth noting that Song *et al*. (2015) did not report the specific type of rubber identified. Munari *et al*. (2017) reported styrene-butadiene rubber, a hard rubber used in tyre tread, to be the most common material at 94.13 % by weight of the plastic debris extracted from marine sediment in Terra Nova Bay, Antarctica.

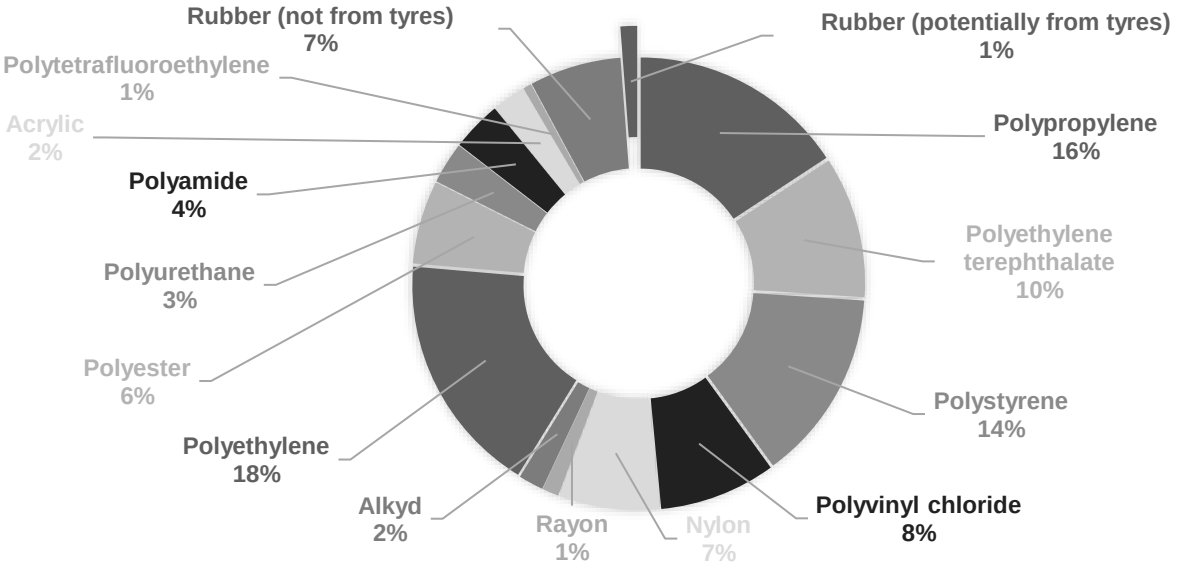

Figure 1. The % of different types of microplastic reported across all articles identifying microplastics from the environment (papers published 2000-2019 with 'microplastics' in the title and 'occurrence' or 'prevalence' in the topic (Web of Science). See Table S1 for references.

A portion of tyre particles generated at the tyre-road interface will be deposited on the road surface. Precipitation may wash tyre wear particles away from these impervious surfaces (Gnecco *et al*., 2005), whilst dispersal via the wind could provide another important pathway (Sorme *et al*., 2002). According to Verschoor *et al*. (2016) in the Netherlands approximately 10 % of tyre wear produced each year is estimated to enter surfaces waters, a further 40 % is deposited on the soil, while 45 % are retained on the road surface. An additional 5 % is reported to be present in the air. Some of these particles are thought to ultimately enter the marine environment (Gnecco *et al*., 2005). However, it should be noted that these proportions reflect the use of open asphalt concrete road surfaces which are present infrequently outside of the Netherlands (Kole *et al.,* 2017). Recently, tyre wear particles have been found to contribute to total particulate matter less than 2.5 μm in diameter, known as $PM_{2.5}$, in the range of 0.27 – 7 % (Panko *et al*., 2019; Grigoratos and Martini, 2014), and in the range of 0.84 - 10 % within PM_{10} (particulate matter less than 10 μm in diameter) (Israël *et al*., 1994; Panko *et al*., 2013; Grigoratos and Martini, 2014). Some of the highest concentrations of tyre wear, in both $PM_{2.5}$ and PM_{10}, were recorded at sites where significant braking activity occurred, which is likely to promote tyre wear abrasion (Panko *et al.,* 2019).

In terms of potential toxicity, Kose *et al.* (2008) reported that major contaminants within road-dust, are polycyclic aromatic hydrocarbons (PAHs) and heavy metals, which are known carcinogens, endocrine disruptors and mutagens. Tyre wear is also an anthropogenic source of zinc which is known to cause reproductive, developmental and behaviour responses in aquatic organisms (Adachi *et al.,* 2004; Wik and Dave, 2009). Some microscopic fragments may also be bioavailable and could be taken up from the environment and gut of biota into other body tissues (Barnes *et al.*, 2009). Wik and Dave (2009) report acute and chronic toxicity of tyre particle leachate of 10 to > 10,000 mg/L. A Predicted No Effect Concentration (PNEC), based upon long term tests using *Ceriodaphnia dubia* and *Pseudokirchneriella subcapitata*, were determined as 3.9 mg/L and 0.3 g/kg dw for water and sediment respectively. Wik and Dave (2009) determined that this PNEC exceeded predicted environmental concentrations therefore concluding that tyre wear particles pose a potential risk to aquatic organisms. However, Marwood *et al.* (2011) and Redondo-Hasselerharm *et al.* (2018) argue that the toxicity of tyre wear under conditions representative of the natural environment, demonstrated that tyre wear poses a low potential risk to aquatic ecosystems. Evidentially, the toxicity of tyre wear is an area of study which requires further investigation.

The main aims of this study were to quantify the abundance and examine the distribution of tyre wear particles in the natural environment, as well as identify the road conditions that influence their generation and subsequent release. This required preliminary development of techniques for the isolation and identification of tyre wear particles from environmental samples.

2. Methods

2.1 Sampling of Tyre Wear Particles from the Environment

A minimum of 1 L of wet sediment was collated from several sediment cores (adapted for wet sediment using a bung at either end) from the bottom of storm drain sumps, the repository at the bottom of roadside drains designed to capture solids thereby reducing the likelihood of blockages in the pipework. As a result, this also lessens the volume of particulates being released into surface waters. Drain sumps were selected based upon their location on roads with variable traffic densities, and levels of braking and accelerating in the city of Plymouth (Devon, UK). As a result, the chosen drains (n=12) were used to give an indication of the presence or generation of tyre wear between roads subject to different levels of traffic density and driving behaviour (HT HBA, HT LBA, LT HBA, LT LBA) (Table 1). Further additional samples were collected from the natural environment including; the River Plym and Plym Estuary (n=6), soil (n=4) and road surface material (n=1) (Table 2). The location was chosen as it lies close to Plymouth's major highway, the Devon Expressway (A38) (Figure 2). The River Plym flows North to South into the Plym Estuary. The tidal reach extends 5.5 km to where the Tory Brook joins the River Plym (Langston *et al*., 2003). The A38 is less than 0.2 km south of the tidal reach (Figure 2), hence there is some potential for movement of water in both directions.

Table 1. Descriptions of roadside drain sediment sample types.

Traffic type		Description
HT HBA	High traffic density, high braking and acceleration	Collected from drains in close proximity to high levels of braking and accelerating due to at least one of the following; bends, steep gradients, junctions/traffic lights, and from roads with high traffic density.
HT LBA	High traffic density, low braking and acceleration	Collected from drains on flat, straight roads away from areas stopping or starting e.g. in continuous 40 mph zone, from roads with low density traffic loads.
LT HBA	Low traffic density, high braking and acceleration	Collected from drains in close proximity to high levels of braking and accelerating due to at least one of the following; bends, steep gradients, junctions/traffic lights, and from roads with low traffic density.
LT LBA	Low traffic density, low braking and acceleration	Collected from drains on flat, straight roads away from areas stopping or starting e.g. in continuous 40 mph zone, from roads with low density traffic.

Table 2. Descriptions of natural environment (1-10) and roadside sampling site (11).

Site	Description
1	River sediment, north of the bridge
2	Soil, north of the bridge
3	Soil, beneath the bridge
4	River sediment, south of the bridge
5	Soil, south of the bridge
6	Wastewater Treatment (WWT) effluent pipe, south of the bridge
7	River sediment, south of the WWT
8	Soil, south of the WWT
9	Lugworm casts, Plym Estuary
10	Sediment, Plym Estuary
11	Road surface material

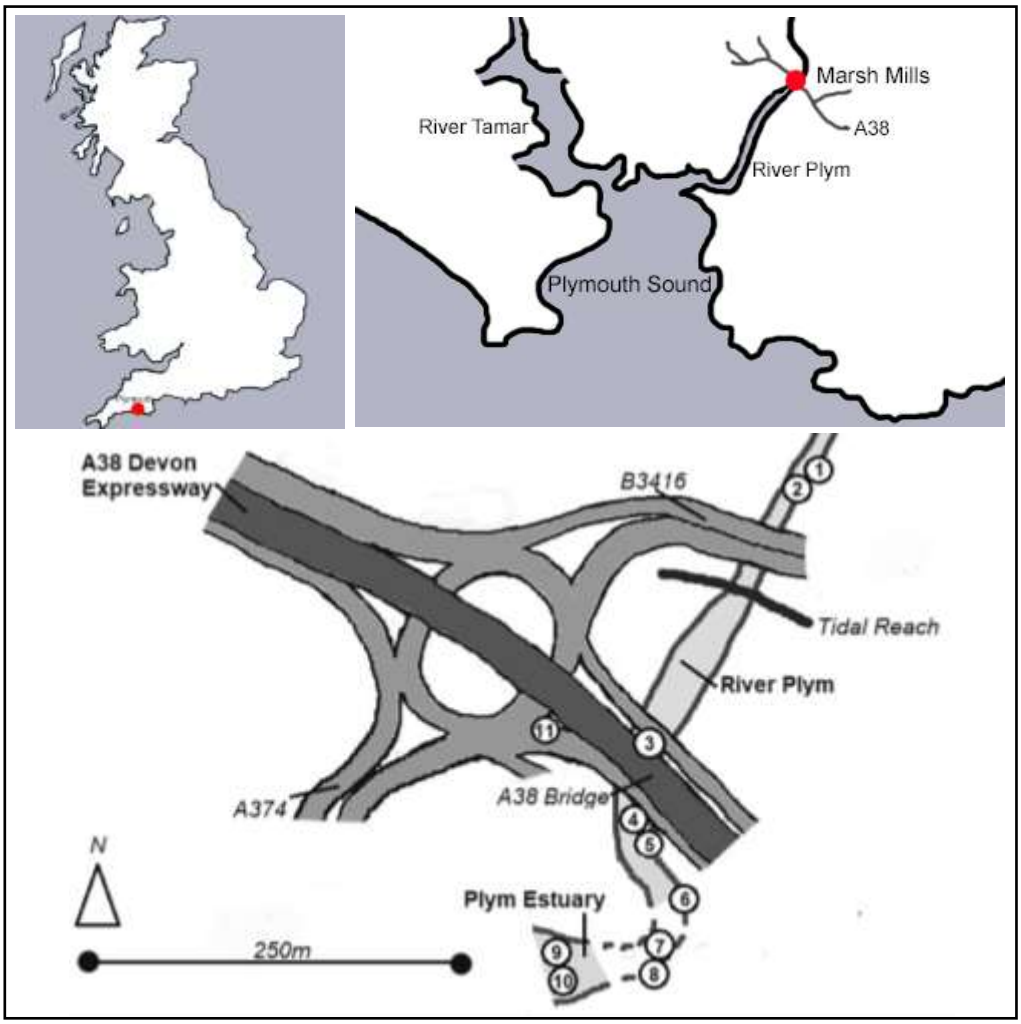

Figure 2. Map showing the natural environment (1-10) and roadside sampling sites (11) (Table 2) in and nearby the River Plym and A38.

2.2. Tyre Wear Particle Identification and Extraction

A filtration method was used to isolate tyre wear particles from soil and sediment. This method was based on preliminary investigations which found that after 50 seconds approximately 50 % of artificially generated tyre wear particles had settled from the top of a settling column into a collecting plate. The artificial particles used were produced from a Prestivo passenger car tyre using a rasp. It should be noted that this method has its limitations as directly abraded particles, intended to act as a proxy for TRWP's, may differ from those found in the environment (Kreider *et al.*, 2010). Directly abraded tyre tread is thought to have a density in the range of 1.13 to 1.16 g cm^{-3} (Rhodes *et al.*, 2012) while the density of tyre wear generated in the environment is estimated to range between 0.94 and 2.5 g cm^{-3} (Verschoor *et al.*, 2016; Sommer *et al.*, 2018; Vogeslang *et al*., 2018; Unice *et al.*, 2019). Consequently, the two may vary in their settling behaviour. Each wet 5 mL sample of soil, drain sludge, and sediment was mixed with 150 mL of pure water and gently introduced to the top of a settling cylinder filled with 1000 mL of pure water. The water solution was given 50 seconds to settle, then the top 1000 mL of suspended material was passed through vacuum filtration and collected onto filter paper of ≤1.6 µm. This process was repeated in triplicate. Filter papers were then observed under a dissection microscope (using magnifications from x10 - x40). Visual identification of tyre particles was based on the following criteria; a) the particle was black in colour, b) the particle returned to its original shape after compression using a mounted needle and c) the particle did not crumble, break or separate when compressed. The number of tyre wear particles on the filter paper was then doubled to account for the approximate 50 % of particles remaining in the settling cylinder after 50 seconds and so provide an estimate of the total tyre particle content for each sample. Particle size was measured using an eye piece graticule, where a lower limit of 50 µm was used due to the limitations of visual identification below this size. This method allowed a relatively fast estimation of the average number of tyre wear particles in a 5 mL sample of wet material.

A 5 mL sub-sample from each drain type (Table 1) was subject to gas chromatography mass spectrometry (GC-MS). N-cyclohexyl-2-benzothiazolamine (NCBA) was used as a chemical marker for the presence of tyre wear in the environment. NCBA was chosen as benzothiazole (and its derivatives, including NCBA) are utilised in a small number of applications such as antifreeze, some pesticides, and corrosion inhibitors, yet its widest application is as a vulcanisation accelerator in vehicle tyre tread (Brownlee *et al.*, 1992; Wik and Dave, 2009). It is incorporated to improve durability, contributing 0.5 - 2 % of the total weight (Wik and Dave, 2009; Grigoratos and Martini, 2014; Wagner *et al.,* 2018). The protocol for GC-MS is described by Kumata *et al*. (2000). In brief, samples were soxhlet extracted with toluene/methanol (1:1 v/v) for >100 cycles. The extract was concentrated, and liquid-liquid extracted (LLE). The extract sample was rinsed twice, first with a base solution (H_2O pH adjusted to pH 9 with sodium hydroxide NaOH), and second with 10mL (1:1) H_2O pH 9 methanol, the aqueous phase was carefully removed after each rinse. The retained fraction was subject to an acid wash with 10 mL of 0.18 M sulphuric acid (H_2SO_4) aqueous solution (pH<2), repeated three additional times for optimum extraction. The denser acidic aqueous phase from each rinse was combined, made basic (pH9), and back extracted with 4 x 5 mL of dichloromethane. The dichloromethane phase containing benzothiazolamines was roto-evaporated until dry, taken up in 1.5 mL dichloromethane, and subject to column chromatography on a 5 % H_2O deactivated silica gel column. A procedural blank was analysed in the same manner. It should be noted that the use of chemical markers to calculate the concentration of tyre wear particles can result in an underestimation (Spies et al., 1987; Kumata et al., 1997; Reddy and Quinn, 1997; Zeng et al., 2004, Wik and Dave, 2009). This is due to the marker being subjected to degradation if it leaches from the rubber (Wik and Dave, 2009). Equally, the use of markers can lead to an overestimation if there are other sources of the chemical present in the environment (Wik and Dave, 2009).

Scanning Electron Microscopy (SEM) was used to produce detailed images of the physical and morphological characteristics of tyre wear particles.

Tyre wear particle abundance was compared across the 12 environmental sites (Figure 2) using a 1-way analysis of variance (ANOVA) following confirmation of the assumptions of parametric analysis using Levenes and Shapiro Wilks tests. An unpaired Welch Two-Sample t-test was also used. The drain samples (Table 3) generated from each sample type were examined using multivariate and one-way ANOVA's, and principle component analysis. All data was processed, analysed, and presented using Microsoft Excel, Matlab R2016a, R (version 3.2.3) or Minitab 18.

3. Results

Scanning Electron Microscope (SEM) images of a tyre wear particle isolated from a roadside drain are shown in Figure 3. Tyre wear particles generally exhibited an elongated shape (a) and, at closer magnification (b), the incorporation of material from the road surface, similar to that of Kreider *et al*. (2010) was visible.

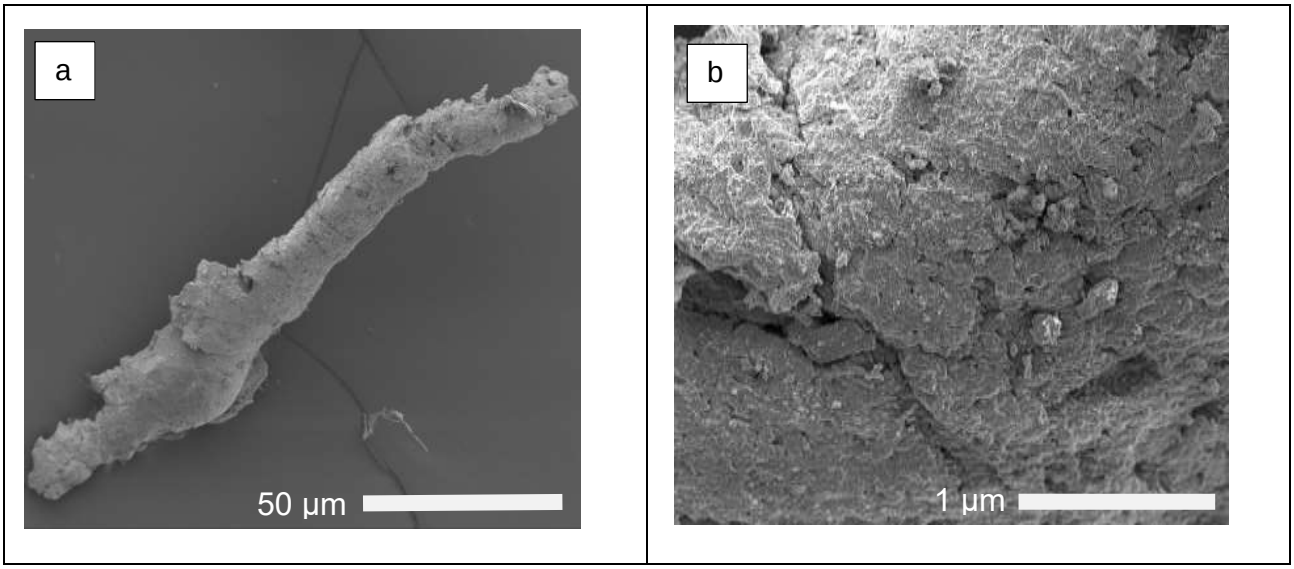

Figure 3. Tyre road wear particles (TRWP) photographed on a Scanning Electron Microscope (SEM) showing tyre wear isolated from (a) environmental drain samples and (b) at closer magnification to indicate the incorporation of other materials. Size indicated by the scale bar.

The GC-MS analysis detected NCBA in half of the roadside drain sump samples analysed, confirming the identity of the material as tyre wear (Figure S1). Concentrations varied between 0.019 and 0.236 mg kg^{-1}. The procedural blank yielded no detectable concentrations of NCBA.

The maximum tyre particle size within drain sump material varied between HT LBA at 220 µm, and the largest within the LT HBA category at 600 µm (Table 3). The greatest abundance of tyre wear particles above 50 µm were within HT HBA (655 ±120.1 per 5 mL ($\bar{x}$ ± SE)), and the fewest in the LT LBA (56 ±35.7 5 per mL ($\bar{x}$ ± SE)). Despite notable differences with regards to total abundance and particle size, little difference was noted between the mean values, samples recording consistently similar means (Table 3).

Table 3. Abundance range and maximum and mean particle length averaged over three replicates from the three sites of each traffic type (HT HBA, HT LBA, LT HBA and LT LBA) (±SE).

Traffic Type *(taken from three sites)*	Total Abundance (5 mL) *Range*	Maximum Length Recorded (µm)	Mean Length (µm) *Average (±SE)*
HT HBA	286 - 655	569	94± 3.5
HT LBA	68 - 84	220	95± 6.6
LT HBA	202 - 328	600	98± 3.2
LT LBA	56 - 174	350	101± 7.5

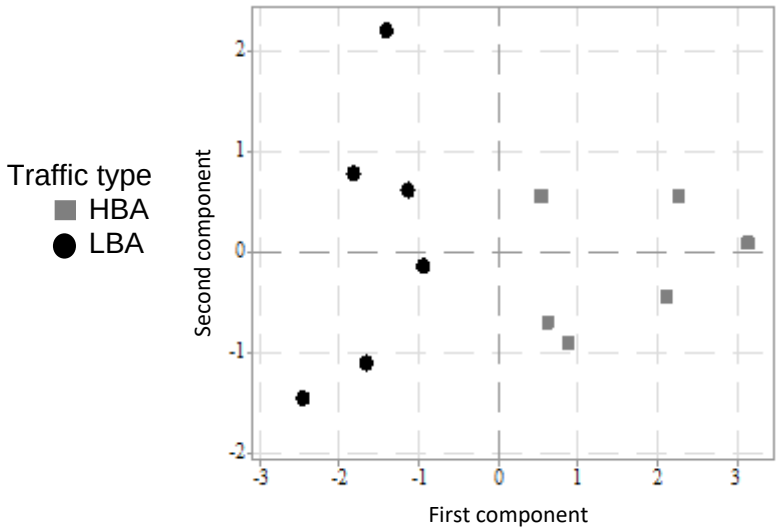

Figure 4. Score plots generated by principle component analysis of variables for high level of braking and accelerating, and low levels of braking and accelerating.

Principle component analysis is a statistical tool used to explain the variance-covariance of a set of variables through linear combinations by clustering samples based upon their similarity This was used to illustrate disparities between sampling locations. Samples collected from drains in close proximity to high levels of braking and accelerating were effectively separated from those collected near low levels of braking and accelerating, explained by 53.4 % within the first component, and 26.1 % within the second (Figure 4).

Multivariate ANOVA analysis was used to test for statistical differences between the total abundance of tyre wear particles generated in high and low traffic densities (HT and LT), and high and low levels of braking and acceleration (HBA and LBA). The abundance of tyre wear > 50 µm within HBA and LBA were found to be significantly different (Wikl's Λ, p= <0.05) whereas HT and LT were not (Wikl's Λ, p= >0.05). The same pattern was observed for particle size (whereby there was a significant difference in size between HBA and LBA sites (Wikl's Λ, p= <0.05), but not HT and LT (Wikl's Λ, p= >0.05).

Suspect tyre wear particles were found at 10 of the 11 environmental sampling sites (90.9 % of sites). The results are given as the average number of tyre wear particles at the site in a 5 mL sample. Road surface material (site 11, Figure 2) had the second highest abundance of tyre wear particles collected from the natural environment, of 44.6 ± 2.91 ($\bar{x}$ ± SE) per 5 mL. The sediment samples north of the bridge (site 1, Figure 2) contained 9.33 ± 0.44 ($\bar{x}$ ± SE) tyre particles per 5 mL, whereas no tyre particles were found in the soil (site 2, Figure 2). A major input becomes clear when investigating the soil sample directly beneath the bridge (site 3, Figure 2). This site produced an average of 65 ± 7.36 ($\bar{x}$ ± SE) per 5 mL, the highest of all the sites. In the sediment south of the bridge (site 4, 6 and 7, Figure 2) the average abundance of tyre wear particles generally declined with distance from the road to 13.3 ± 1.52, 14± 2.52 and 6.6 ± 0.88 ($\bar{x}$ ± SE) per 5 mL respectively. However, it is noteworthy that the site under investigation was tidal therefore, there is the possibility of particles moving in both north and south with water flow. Site 6, which shows a small increase in average abundance was located next to a wastewater treatment (WWT) effluent pipe. In the soil south of the bridge (site 5 and 8, Figure 2) the average abundance of tyre wear particles declined more dramatically, from 15.3 ± 2.73 to 0.6 ± 0.33 ($\bar{x}$ ± SE) per 5 mL respectively. 1.3 ± 0.33 ($\bar{x}$ ± SE) per 5 mL were found within casts of a marine invertebrate species *Arenicola marina* (site 9, Figure 2) in the Plym Estuary. No tyre wear particles were found in the surrounding sediment (site 10, Figure 2). There was a significant difference between the tyre wear particle count at the different sites ($F(11, 14) = 14.92$, $p = <0.05$) (Figure 5).

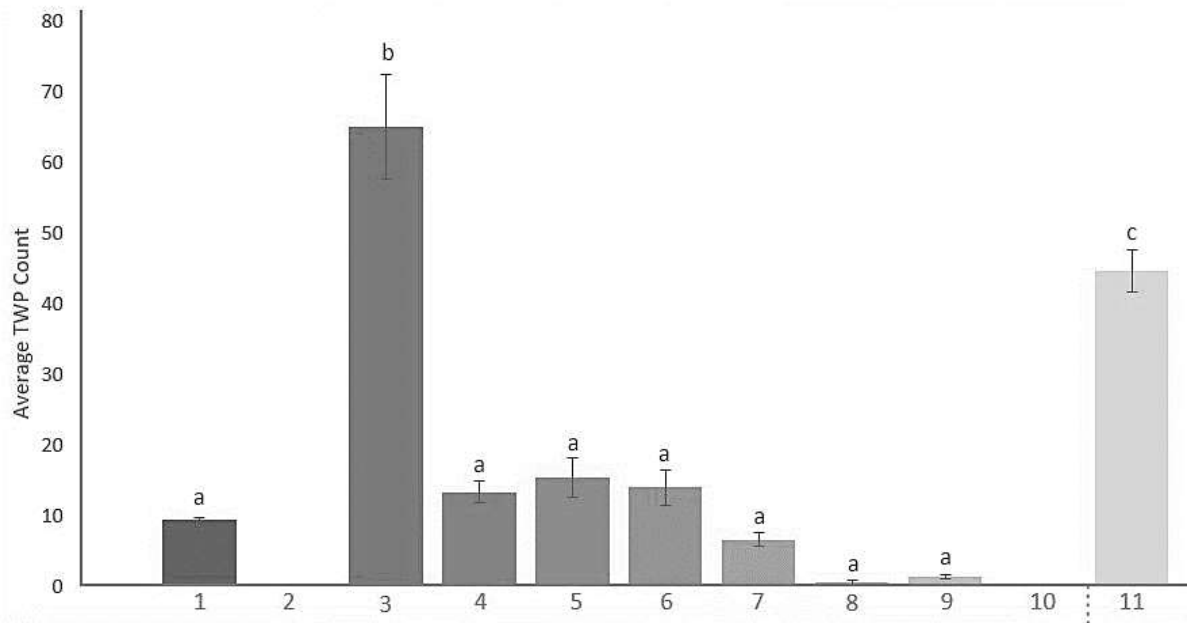

Figure 5. Average number of tyre wear particles (TWP ± SE) at the environmental sites (1-10) and roadside site (11) and identified by visual examination. Sites with the same letter (a, b or c) were not significantly different.

4. Discussion

The study found high levels of braking and acceleration to be the most influential variable in producing both larger and a greater number of tyre wear particles in excess of 50 µm. Although higher traffic loads did not produce significantly more particles, variability in terms of particle abundance between traffic densities was apparent. Our findings concur with Panko *et al.* (2019) who report no significant effect of traffic density upon tyre wear contribution to $PM_{2.5}$ but report the highest concentrations to correspond with areas of high breaking. In the current study it is possible that drains where high traffic loads occur are emptied more regularly, therefore less time for accumulation of tyre waste. Whilst sumps are routinely emptied in order to retain storage capabilities, it was not known how recently prior to sampling each drain was emptied or the intensity of the preceding rainfall events, hence the time over which particles had accumulated was not known. This would aid discussion if accounted for in future research future. Aronson *et al.* (1983) suggested sumps are subject to cleaning once or twice a year, although more recent data are not available. Furthermore, as it is likely that a proportion of tyre wear particles will be washed away through the drain, it is possible that the method used to isolate the particles (and only measuring down to 50 µm) will not represent the total abundance as tyre wear has been reported down to 0.1 µm (Cadle and Williams, 1978), with a reported mode <50 µm (Kreider *et al*., 2010). However, in this study the parameters used proved useful in indicating the presence of tyre wear in the environment. As sampling took place intermittently over

a two-year period, there is also potential that seasonal changes may have influenced our result. The findings in this study do reflect that of previous literature, which report the presence of tyre wear particles in roadside dust (Hopke *et al.,* 1980; Saito, 1989; Rogge *et al.*, 1993; Reddy and Quinn, 1997; Fauser, 1999; Kumata *et al.,* 2000; Kumata *et al.,* 2002), soils (Pierson and Brachaczek, 1974; Spies *et al.,* 1987; Fauser, 1999; Cadle and Williams, 1978) and river sediments (Spies *et al.*, 1987; Reddy and Quinn, 1997; Kumata *et al.,* 2002; Wik *et al.,* 2008).

The greatest abundances of tyre wear particles in the natural environment were found in the soil beneath the A38 Bridge, rather than the river or estuary sediment. As particles are less likely to be retained in the water than the soil, it could be suggested that tyre wear particles are carried away from the sediment at this site. The A38 is an evident point source, which may be a result of wash-off from impervious surfaces and/or via dispersal in the air. However more extensive sampling is required to confirm this. As a result, several primary pathways can be theorised; atmospheric fallout, direct road and storm water run-off, and treated wastewater effluent. Ultimately, these processes have the potential to carry tyre wear particles into the natural environment. The pathways for tyre wear particle transport in the environment requires further investigation. Furthermore, given their apparent abundance in the environment, greater understanding of the ecotoxicity of tyre wear particles is essential. Given the previous estimates that tyre wear particles are a major component of microplastics released to the environment, together with the novel data presented here on environmental accumulation, it would appear that tyre particles could be an important constituent of microplastic contamination and further work to evaluate potential toxicity is needed (Redondo-Hasselerharm *et al*., 2018; Marwood *et al*., 2011).

This study concludes that there are indications to suggest that tyre wear particles are a widely abundant microplastic, as shown by their prevalence throughout environmental samples and elevated abundance within close proximity to the road. These findings appear to concur with that of previous studies which have reported tyre wear to be a key source of microplastic emissions. In addition, this study empirically supports the observations that both driving behaviour and traffic density influence tyre wear particle generation. Therefore, empirical evidence regarding tyre wear presence, abundance and generation, as well as a novel methodology for particle isolation, has been determined. Nevertheless, the current literature indicates that few reports are available explicitly reporting tyre wear as a microplastic in environmental matrices. This study addresses key knowledge gaps, offering preliminary data regarding the generation and abundance of this under-reported microplastic.

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