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REVIEW

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Fate of recycled tyre granulate used on artificial turf

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Abstract

The production of granulates as infill for artificial turf is able to process 21% of the end-of-life tyres in Europe, approximately 600 million kg per year. In doing so it avoids an annual CO_2 emission comparable with the amount that could be absorbed by around 30 km^2 of forest. However, dispersal of rubber infill to the environment is perceived as a problem. An amount of 3000–5000 kg granulate per field per year is currently used as underpinning for a European proposal to ban rubber infill as part of the intended restriction on intentionally added microplastics in 2021. By reviewing grey research reports, we found out that the dispersal rates are based on the false assumption that the annual granulate demand for refilling is necessary because of granulate losses to the environment. However, it has been ignored that part of the refill is needed because the infill layer settles and becomes more dense (compaction) and that part of the lost infill is collected and reused on the fields. In combination with unawareness and improper piling of snow in the past, these are the causes of the high estimates of infill dispersal per year. This paper shows the current state-of-knowledge about ELT granulate dispersal and shows that approximately 600–1200 kg refill is required annually to compensate for compaction and for some infill waste on pavements and in drainage sinks. Recommended mitigation measures are containment through optimized field and drainage construction, suitable maintenance equipment and practices and good-housekeeping rules for players and groundkeepers and handling end-of-life pitches. If these recommendations are implemented, the emission of ELT granulates to the environment can be reduced to virtually zero.

Keywords: Rubber granulate, Dispersal, Maintenance, Emission, Duty-of-care

Background

As a consequence of population growth and wealth a huge amount of end-of-life products is waiting for secondary use, recycling of the contained materials or recovery of energy. End-of-life tyres (ELT) are such a product. One billion tyres reach the end of their useful lives worldwide every year [39]. Since in 2005 the European Landfill Directive [1] has put a ban on land-filling of ELT, new applications were needed that could absorb the used tyres. This challenge has resulted in 58% material recycling, 35% energy recovery and 3% use in civil engineering ([12], see Fig. 1).

Major destinations of ELT are rubber granulate and powders; they absorb 43% of the total ELT [12]. Granulates come in different size fractions. Depending on the size fraction, the granulates are used as filler in for instance asphalt (0–1 mm), as infill in sports fields (1–2 mm), rubber tiles (2–4 mm) and as an elastic layer beneath sports fields (4–8 mm). Approximately half of the granulates (21% of total ELT) is used as infill on sports pitches [30]. ELT granulates contain approximately 46% polymers [21] comprising natural and synthetic rubber, and therefore they are classified as microplastics [19].

Plastic recycling in general and recycling of ELT are important goals of the European Union [13]. The recycling of ELT to rubber granulate prevents the mining of virgin resources (rubber, oil, metals). It has been estimated that the recycling of 1000 kg ELT avoids the emission of 838 kg carbon dioxide [25]. The annual recycling of 21% of the European ELT to rubber infill for sports fields thus leads to an avoided CO_2 emission of

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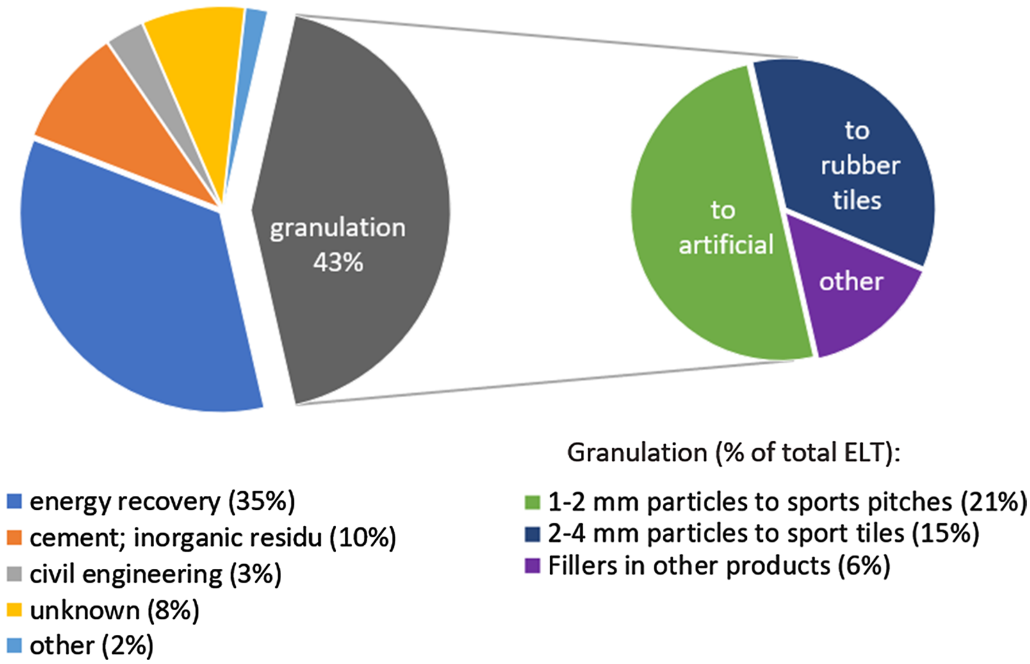

Fig. 1 Destinations of ELT in EU27 (+UK, Serbia, Norway, Switzerland and Turkey), expressed as a percentage of the total collected mass of ELT. Total ELT released by these countries is 3.424.500 tonnes; data 2017 [12]. * Other use of ELTs comprises use in steel mills and foundries (0.3%) as well as use as dock fenders, blasting mats (1.2%) pyrolysis (0.4%). The material recycling in cement concerns the inorganic fraction of the tyres. ** Energy recovery includes ELTs sent to cement kilns (29%) as the energy fraction of co-processing ELTs in cement kilns and ELTs used in district heating/power plants (6%); *** unknown also includes collected tyres waiting for treatment. Distribution over granulate fractions has been adopted from [30]

600 million kg, which equals the amount that would be absorbed by approximately 30 km^2 of forest per year [2].

ELT granulate appeared to be a suitable filler in sports floors, because it is elastic, durable and relatively cheap. The presence of affordable rubber infill enabled a rapid growth in the number of artificial turf pitches. ECHA estimated that there are more than 13,000 large synthetic turf fields in European Union (data 2017) and even a higher number of mini-pitches [34]. These pitches are mainly used for football. Compared to natural grass, these pitches allow year-round playing irrespective of the weather conditions. Because artificial turf tolerates intense playing, less fields and thus less land suffices to facilitate outdoor field sports.

However, despite of these positive characteristics the use of ELT, and plastics in general, is currently approached with criticism. Small fractions of plastics, the microplastics, are dispersed to the environment and enter the food-chain [27, 41], although the exposure and effects to humans seems to be very limited to date [33]. Because the rubber particles are heavier than water (specific density ≈ 1.16 g/cm^3), they tend to end up in soils and sediments. A common freshwater benthic organism (*Gammarus pulex*) has shown to ingest tyre-derived particles (< 500 μm), when offered in a laboratory setting [31]. However, there were no significant effects on the growth and reproduction of *G. pulex* and three other types of aquatic benthic organisms up to a dosage of 10% tyre particles in the sediment.

To reverse the growing release of microplastics in the environment, the EU intends to adopt a restriction proposal on intentionally added microplastics, including ELT granulate, in 2021 [9]. ECHA's Risk Assessment Committee has proposed a total ban on the use of rubber granulate in artificial turf pitches, with a 6-year transition period [10]. However, an exception to this ban, provided that the dispersal of microplastics is kept below 7 g/m^2 (equivalent to approx. 40 kg on a pitch measuring 100 × 60 m), has been brought forward as an alternative option during the public consultations and the socio-economic assessment [11]. A policy decision that determines the future of rubber infill is expected in 2021 and will be taken by the European Commission and its member states.

In support of policy measures, the EU had conducted a study to quantify the most important sources of microplastics [18]. The study indicates that ELT granulate is a very small and local source, compared to other sources of microplastics such as tyre wear and paint, preproduction pellets and textile fibers. Besides these sources, fragmentation of plastic litter and cosmetics are more relevant than ELT granulate [28]. The quantities in these studies are not directly comparable because they focus on different environmental compartments and the geographical coverage is not identical, but overall it can be stated that ELT granulate comprises << 1% of the microplastic emissions. The EU-study estimated, leaning on assumptions, a granulate dispersal of 1500–5000 kg per field per year. In their restriction proposal ECHA assumed that 10% of the refill, that is up to 500 kg per field per year ends up in the environment. Around the same time, new studies have been published that actually measured dispersal along different pathways [26, 32, 40]. The results enable adjustment and refinement of the existing estimates.

Besides polymers, tyre tread rubber contains approximately 19% carbon black (filler), 19% plasticizers and oils, and 16% minerals, mostly silica, sulfur and zinc [21]. Previous human health concerns, based on the presence of heavy metals, polycyclic aromatic hydrocarbons and other organic substances in ELT granulate, have shown to be unnecessary. Several extensive risk assessments [8, 29, 34]), established that the chemical risk for humans, playing on artificial turf with ELT granulate, is negligible. However, ecosystems may be at risk because environmental quality criteria to protect ecosystems in soil have been exceeded for zinc, cobalt and mineral oil in several occasions [37]. In this paper, we focus on the emission of particles in view of the microplastics debate and do not address chemical issues again.

In order to prevent that a beneficial recycling option is discarded because of negative perceptions or worst-case assumptions, it is of the utmost importance that facts and figures about ELT granulate are made available. The research questions of this paper are: (1) what are the pathways, processes and factors that influence the amount of infill loss; (2) what is the variation of granulate dispersal from artificial turf fields to the environment; (3) what are the mitigation options? Information concerning these topics is currently scattered in several grey research reports that contain useful experimental data and measurements. Because some of the reports have been written in Dutch, Danish, Norwegian or Swedish, we translated the studies and included the essential details in this review in order to make the information accessible to a broader community.

Dispersal processes and routes

The distribution of granulates to the environment can be assessed in several ways, and both ways are represented in the literature:

1. Based on inquiries to the use of infill material, with subsequent assumptions about the dispersal routes. The uncertainty is high and depends on the extent and details of the sales inquiries, and about the assumed dispersal routes.
2. Based on actual measurements in the environment. The main uncertainty here is related to local variations in field construction, maintenance practices, field age, and weather conditions.

Emission of ELT granulate comes from unbound outdoor applications, mainly from football (soccer). During construction of soccer fields approximately 100–120 thousand kg ELT granulate is applied on the fields to support the synthetic grass fibers and to optimize playing conditions. In the use phase, periodical refills are necessary, because the thickness of the infill layer decreases over time, particularly on intensely agitated zones, such as the goal, penalty, corner and midpoint area.

The annual granulate refill is required to compensate for compaction and for losses (see Fig. 2). Studies that quantified these processes have been reviewed in the "Annual refill", "Compaction" and "Infill loss" section. Compaction of infill layers occurs through natural weathering by sunlight, through the presence of dirt and agitation by players and through gravitational force by [15]. Compaction and infill loss lead to a higher unsupported fiber length (free pile height) and deterioration of the field performance (such as vertical ball rebound, ball roll distance, rotational traction resistance, vertical deformation and force reduction [16]. Several maintenance methods are available to reverse the effects of compaction: drag brushing, also referred to as grooming (one to several times per week), powerbrushing (6–12 times per year), deep cleaning (once per 1 or 2 years), deep decompaction (once per 3 to 4 years) and rubber top-up when the infill layer becomes low. Also leaf blowing and snow clearance need to be done, depending on the season and local conditions. Rubber granulates can be dispersed to the environment during construction, maintenance and use of artificial turf fields. The amount of dispersed granulates depends on the construction of the fields, the methods and frequency of maintenance and awareness of constructors, caretakers and players.

Although dispersal of granulates to the environment can be prevented, this has unfortunately not been the case in the past two decades. Uncontrolled and mostly unintentional dispersal of granulates to soil and surface water might have occurred in the past decades when awareness about microplastics was not widespread.

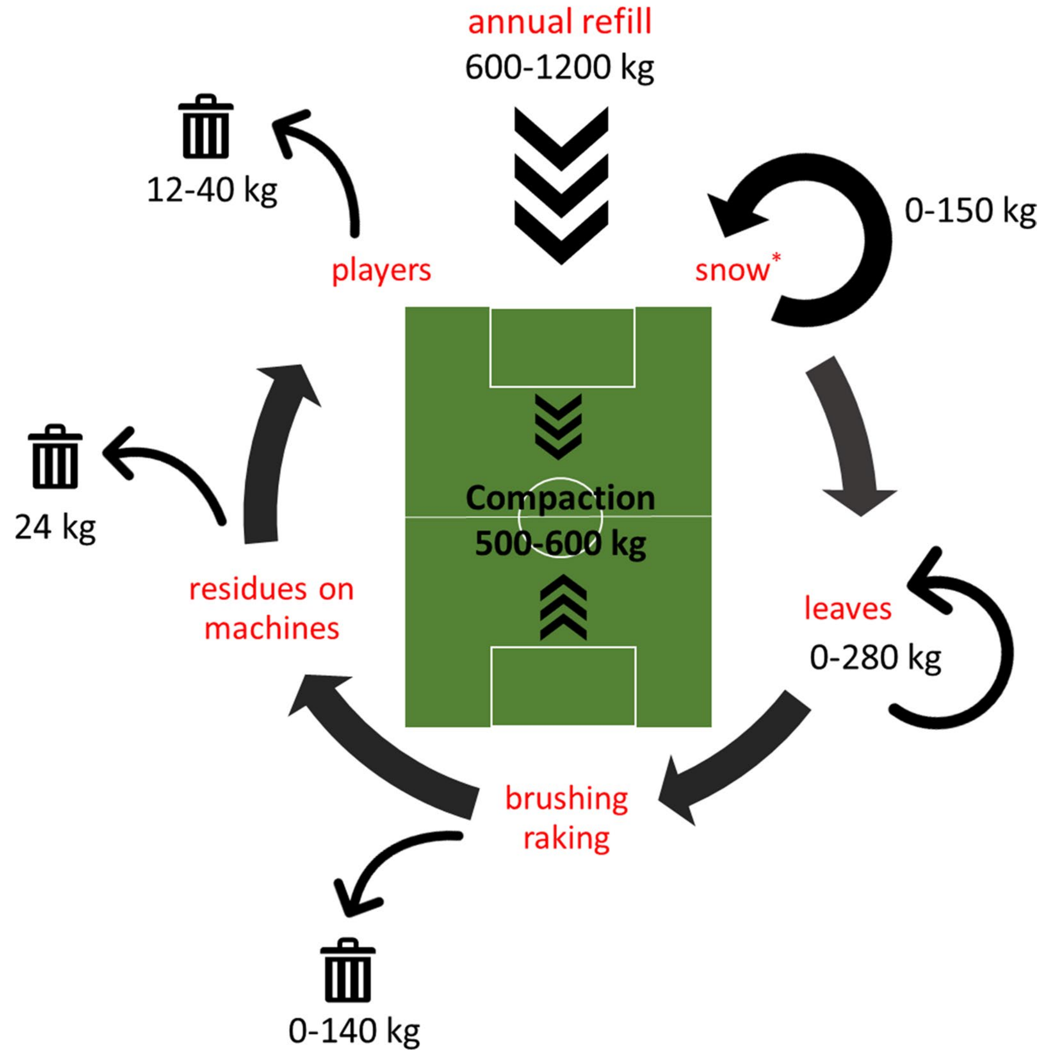

Fig. 2 Approximated annual input and output of ELT granulate on artificial turf. * Snow clearance is dependent on climate zone. Actual exact amounts depend on management and mitigation

Annual refill

The first estimates of environmental exposure were solely based on inquiries on the total annual use of ELT granulate. Early Scandinavian reports mention annual refill of 3000 to 5000 kg per year, which can be traced back to a recommendation of the Danish Football Union to guarantee optimal playing conditions [7]. The Danish recommendation of a refill of 3000–5000 kg/field/year is adopted by later studies [20, 22, 24] and in 2018 it formed the basis of an extrapolation to the European scale [18], which inspired ECHA to include ELT granulates in the restriction proposal from microplastics [9].

A study from Norway [36] assumed a refill of up to 12,000 kg per field per year for officially sized soccer pitches, based on an undocumented assumption of 10% loss of infill per year. A rationale for such a high amount has not been provided, although the Norwegian study adopted the Danish amount of 3000–5000 kg in the overall assessment, based on the fact that infill is also used on smaller pitches, such as playing grounds and school and kindergarten pitches. However, the previous recommendation of the Danish football association was meant for officially sized soccer fields and did not mention playgrounds. A Swedish study, based on inquiries at one football club, mentioned an amount of 3000–4000 kg granulate refill per year [38].

A later study estimates an annual refill of 2200 kg/field and seems to be based on more solid data, because more than 89 Danish clubs were asked about their infill use (Lindberg International, 2018 cited by [23]. A small inventory amongst three Dutch fields resulted in annual refill of 0, 590 and 2200 kg/field [40]. The inventory is too small to derive a reliable average amount. Data from other countries were not found.

Refilling a whole field is seldomly done. In practice, caretakers mentioned that usually not the whole field needs refill, only certain intensively exposed zones, such as penalty and goal area (16.5 × 40.3 m) and around the center mark (9.15 m ф). These areas account for approximately 1400 m^2, equal to 20% of the total pitch area (105 × 68 m) [14].

Compaction

Compaction can be measured in a laboratory under controlled conditions or in field set-ups where the results are more realistic, but may be influenced by the specific local weather conditions and field maintenance regime. Data are available from both type of experiments, which are described below.

Laboratory measurements

Laboratory testing has been conducted to investigate controlled density changes in the rubber infill simulating compaction due to pressure of players and decompaction by raking [15]. A 65 mm monofilament carpet (0.5 × 0.75 m) was filled with sand (13 kg/m^2) and SBR rubber (14 kg/m^2, diameter 0.5–2.5 mm). The sand layer was applied first and was conditioned with 50 cycles of a weighted studded roller (40 cm wide and 43.6 kg). The sand layer thickness was measured on 24 points, a deviation ± 1 mm was allowed. SBR granulate was added in portions of 2 kg batches with raking in between. The system was installed in triplicate; the compaction was tested after either 0, 200 or 500 cycles of rolling with the weighted studded roller. One cycle was equal to two passes of the roller, one outward and one return. Measurements of the total infill depth were done on 3 points on the field, on midpoint and 15 cm distance apart towards the short edges.

During the experiment, the infill depth decreased from 31.0 mm in the beginning to 27.4 mm at 50 cycles and 22.4 mm at 500 cycles. These data imply a compaction of, respectively, 11 and 27%. The study shows that compaction can be partly reversed by raking, also under field conditions. It is not clear how the cycles of the weighted studded roller can be translated to realistic outdoor conditions.

Field measurements

The compaction under outdoor conditions was determined on two football pitches in The Netherlands [40]. The first field (located in Hoogeveen, installed in 2007) was a well-maintained 11-year-old pitch where leaf blowing has always been done in an inward direction. The second field (located in Amsterdam, installed in 2008) was not well maintained, refill had not taken place for years and leaf blowing was done in an outward direction. Samples of the infill layer were taken in March 2017 on each pitch on the penalty spot and in the goal areas and on two reference points in the strip just outside the field markings. The spot dimensions were 30 × 30 cm, where all the loose material, including the sand, was recovered until the carpet was visible. The mass of the infill was determined undried. The results are shown in Table 1 section A.

A compaction of 8.5 kg/m^2 has occurred over a period of 11 years on the well maintained Hoogeveen field. This equals a compaction of 2.7% per year. This implies that an amount of 0.8 kg/m^2 per year was used to compensate for compaction in high-use areas.

A compaction of 2.7% per year was also found on the Amsterdam field. The total amount of recovered infill was only approximately 4 kg/m^2, which is very low, considering that a new field is constructed with an initial amount of 15 kg infill/m^2. This field is therefore considered to be not representative for current maintenance practices. An infill amount of only 4 kg/m^2 could imply that 11 kg/m^2 may have been disappeared to the surrounding environment, an amount that equals 78.5 thousand kg for this particular field (≈ 8000 kg/year) in the past 9–10 years. Poor maintenance practices, in particular leaf blowing in outward direction, which unintentionally also transports granulate off-field, may be responsible for this loss.

If we adopt compaction rates of 2.7% per year from the abovementioned studies and an initial infill amount of 100–120 thousand kg, this would imply that approximately 500–600 kg ELT granulate is needed to compensate compaction.

Infill loss

Dispersal by players

Three studies are available that describe results of measurements to ELT granulates in shoes and socks.

A first study was a citizen science project in 2017 in Norway, where 12,591 participating school children collected data about infill loss through shoes and clothing [26]. A number of 286 schools of 144 municipalities studied 592 soccer matches on 343 soccer fields, 99% were outdoor fields, 70% of the fields were regular 11-player pitches. The students were asked to play a football match of 2 × 15 min and to collect granulate from shoes and clothing on a large white sheet. They recorded volume of the infill and infill type, field size, playing duration, number of players per match, the weather conditions as well as the type of environment at 10 m distance from

Table 1 Measurements of the fate of ELT infill on three Dutch fields [40]

	Rotterdam	Amsterdam	Hoogeveen
General information			
Year of construction	8–2016	2008	2007
Research period	Winter 2017–2018		
Field age (years)	1	10	11
Maintenance	n	Poor	Well
Leaf-blowing direction	Not described	Outwards	Inwards
Sides with trees	2	3	2
A. Infill compaction (% per year)		2.8	2.7
Infill recovered from high-use areas (kg/m^2)		4.3	31.4
Infill recovered from low-use area (kg/m$^{2)}$		3.1	22.9
Net compaction (kg/m^2)		1.2	8.5
B. Infill loss in brushing waste (kg/field/year)	21–140	9–60	0
Number of brushing events/year	7	1	0
Amount of collected waste (L)	80 ± 20	240 ± 60	0
Infill content in brushing waste (%v/v)	7.6	50	n.d
Density of infill (kg/L)	*0.5*	*n.d*	*0.6*
65% as suspended mass (kg/field/year)	*1.0*	*n.d*	*1.1*
C. Infill loss to pavement (kg/field/year)	1.2	60	16
Total paved surface (m^2)	1258	310	522
Time since last brushing (weeks)	14	4	1
Mean infill (g/m^2)	0.8	38	2.2
Weekly spread (g/m^2/week)	0.1	10	2.2
Leaf blowing (weeks per year)		*13*	
Dispersal by other means (weeks per year)		*40*	
90% by leaf blowing (kg/field/year)	*0.8*	*44*	*12*
10% by other means (kg/field/year)	*0.3*	*15*	*4*
D. Infill loss to drainage sinks			
Number of sinks	8	0	20
Time since last cleaning (years)	3	–	10
Mass flux to sludge (kg/field/year)	1.5	–	1.7
E. Infill to ditches (kg/field/year)		4.3	6.1
Distance to ditch (m)	No ditch	3	4
Thickness of sediment layer (m)		0.1	0.05
Width of ditch (m)		1.5	0.5
Length of ditch (m)		64	100
Time since last dredging		3	10
% infill in sediment		0.26	4.9
F. Infill to grass strip (kg/field/year)	256	269	279
Infill concentration in sod (0–0.02 depth) g/kg soil	28–70	190–220	250–610
Infill concentration in soil (0.02–0.05 depth) g/kg soil	< 0.1	130	90–200

Assumptions are italic

the field. During the experiment, only 14% of the players wore football shoes (the others wore regular shoes). Before computing average infill loss, the outliers were removed.

On more than 81% of the fields the type of infill was ELT granulate (see Fig. 3a); other types of infill were EPDM, TPE, sand and organic infill. The humidity of the pitch appears to have a major impact on the amount of rubber granules that stick to the players. If the pitch is wet, more than twice as much granules will stick to shoes and clothes than if it is dry (Fig. 3b). On 11-player pitches under dry conditions an average of 0.6 g granulate per player was collected (in 187

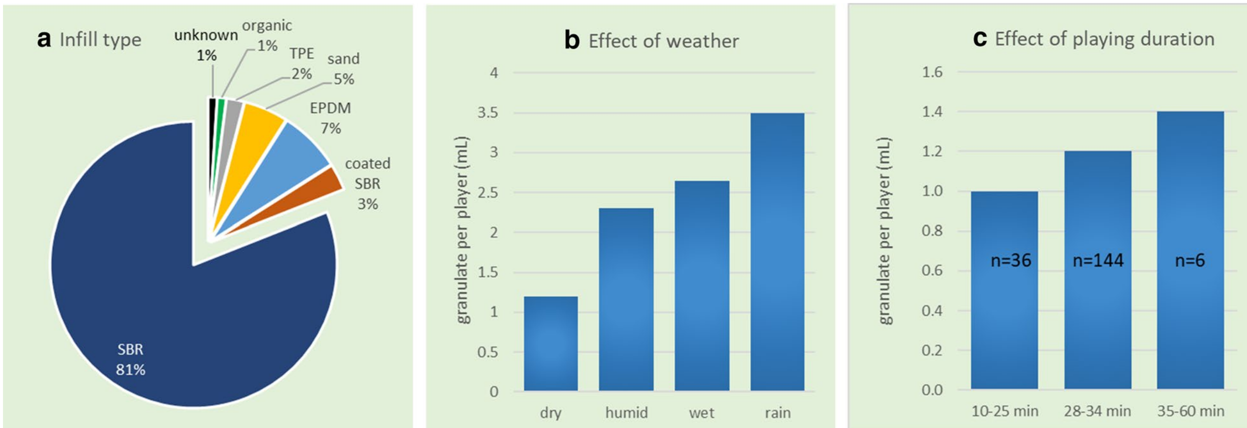

Fig. 3 Norwegian Citizen science project on infill loss via players shoes and clothing (data: [26]). **a** Percentage of fields with certain infill types; **b** effect of weather on the amount of collected granulate on 11-player pitches; C. effect of playing duration on the amount of collected granulate during dry weather

matches) and under wet conditions (damp, wet field or during rain) 1.35 g per player was collected (in 192 matches).

The actual playing duration varied from 10 to 100 min per match, on average 29.3 min. The data were grouped in three time intervals to investigate if the amount of collected particles is related to the playing duration. It seemed that the amount of rubber increased slightly with the length played (Fig. 3c).

In a second case study, in Kalmar in Sweden in 2019, the amount of granulate that has clung to shoes and socks of players has been quantified through weighing [32]. After a playing duration of 60–120 min (average 93 min), players and coaches from various football teams had to brush off clothes and shoes, and also empty their shoes, in a special tub. The total number of players included in the survey was 376 (an average of 16 per occasion). Measurements were taken on 23 occasions during the period Oct 2018–Apr 2019. In this study, the weather conditions have also been taken in to account. Under wet conditions significantly more granulate was collected than under dry conditions (one-sided t-test, $p=0.02$). Median amounts of collected granulate was 0.7 g/player/occasion under dry conditions ($n=12$) and 2.2 g/player/occasion under wet conditions ($n=12$). The overall mean under all weather conditions is 1.5 g/player/occasion.

A third study investigated the amount of granulate on shoes and socks of one 90-min match during dry weather conditions in The Netherlands [40]. After the match, players walked about 200 m to the dressing rooms, were they handed over socks and shoes to the

Table 2 Estimation of infill loss by clinging to shoes, socks and clothes determined in three studies

Country	Amount of granulate clung to socks/shoes (gram per person)			Playing duration (minutes)	N players tested	Loss per field per year (kg)
	Dry	Wet	Mean			
Norway[a]	0.54	1.6	1.1	29	12,591	40[a]
Sweden[b]	1.1	2.5	1.7	93	645	26.8[b]
The Netherlands[c]	0.9	–		90	11	12[c]

[a] [26]

0.88 g per player × 22 players per field × 2200 h (occasions) per year

Bulk density of ELT rubber = 0.45 g/mL

[b] [32]

1.66 g per player × 21 million players/1300 fields per year

[c] [40]

0.9 g per player × 321 players per field per week × 40 weeks per year researchers, who quantified the amount of granulate by weight. This single observation resulted in an average amount of 10 g for the whole team. Assuming 11 players, this accounts for 0.9 g per player.

In Table 2, the infill losses by shoes and clothing determined in the 3 investigations are compared. Although the Norwegian study is by far the most extensive study, the average test playing duration was only 29 min. The Dutch study only concerned one occasion. Therefore, the Swedish mean value of 1.5 g per player is the most representative value for regular 90-min matches.

The estimated amount per field in the reports varied between 12 and 40 kg per field per year. Each study applied different extrapolation methods to assess the total loss per field, and the assumptions and actual situation vary between countries. Based on the data in Table 3 and the given fraction of wet and dry days in each countries, estimates can be made for countries in different climate zones.

Dispersal by maintenance

Brushing waste

Brushing is done to level the field. Infill loss in brushing waste has been determined in the Netherlands in 3 fields with ELT infill [40]. The amount of dirt and the granulate content in the dirt was determined in 2 ways: (1) based on interviews with caretakers and (2) based on measurements after density separation of samples. In Table 1 section B, the field characteristics and results are summarized. The amount of dirt was between 1 and 3 wheelbarrows per occasion (one wheelbarrow has a volume of 80 ± 20 L). The measured infill content in a sample from a field with ELT granulate was 7.8% v/v (3.8% m/m). However, one caretaker mentioned that the content of ELT granulate can be as high as 50%, which was demonstrated by photographs.

It appeared that the actual brushing frequency of 0–7 times per year is lower than the recommended frequency of once in 1 or 2 weeks. The annual rubber infill collected by brushing is estimated to be between 0 and 140 kg per field per year. Dispersal to the environment by brushing can be minimized if the residue is disposed of as waste.

Table 3 Granulate (gram) removed from a maintenance machine after employment on wet and dry field [32]

Field conditions	Cleaning method	
	Brushing and blowing	Blowing only
Dry	1775 ($n = 1$)	15 g ($n = 3$)
Wet	5100 ($n = 1$)	1765 ($n = 2$)

[26, 32, 40]

Snow clearance

Snow clearance is commonly done in Nordic countries. Snow blowers, snow brushers or snow ploughs can be used. Which one is most suitable depends on the snow conditions. If snow is unlawfully dumped on adjacent soil or ditches, significant amounts of granulate could end up in the natural environment. Moreover, snow clearance with losses of infill is also a financial burden to communities, as new infill needs to be purchased for top-up. Increased awareness about microplastics dispersal had led to better instructions and development of new machineries that remove snow and leave or return the granulate on the field.

The amount and frequency of snow clearance and the infill that comes along with it vary enormously from one field to another, depending on the climate conditions and on the intensity of maintenance and the way the snow is stored. A Swedish study [38] estimated that every time when snow is removed using a snow plough, approx. 20–30 L of infill is removed. The study is based on interviews with caretakers for artificial turf fields in different Swedish local communities. Assuming 10 snow removals per year and a bulk density of 0.5 L/kg, 100–150 kg/year ELT granulate is removed from the field during snow clearance. This amount can be reused on the fields once the snow has melted, if the snow is properly piled.

It can be noted that also within the Nordic region, the need for snow clearance is highly variable. Maintenance of artificial turf fields in Norway is a very important factor in relation to the spread of microplastics in the form of infill material, especially in the winter [3]. Whether the fields are located in the cold or the warm part of Norway is of considerable importance. The fields close to the coast receive the least snowfall and lost the least infill, whilst the northerly, inland fields lost granulate due to snow clearance. Four coastal field were studied which have been in operation for 10 years, and still weighed exactly the same when recycled as when they were new, while infill was never added. The amount of infill additionally used on fields in relatively warm, coastal areas is therefore low. The cold, northerly fields need 10–20 times more infill added as a result of snow clearance. Both studies indicate that weather conditions are of importance for the dispersal of infill. However, the maintenance practices are the decisive factor.

Leaf blowing

To our best knowledge, no studies are available about the effect of leaf blowing on the dispersal of ELT granulate. Nor are there reports available about transport of rubber granulate by wind. Because of the size and specific density (1.16 kg/m^3) of rubber particles, transport by wind is unlikely.

There are several types of equipment with large differences in the potential spread of rubber granulate. Leaves and dirt can be removed by sweeping and picking up by hand, by leaf blowers or by several types of power brushes and vacuum cleaners. For example, a simple hand-held leaf blower, when applied in an outward direction, is powerful enough to spread leaves and granulate to the grass strips adjacent to the fields. Blowing in an outward direction, where leaves were left to decompose outside the field, used to be an efficient way to clean the field. Currently, more modern equipment is on the market to sieve the leaves and granulate mixture that is collected during operation. In this way almost all of the granulate is reused on the field. An unknown amount of granulate remains in the collected mixture, which should be disposed of as waste and not be composted.

Cleaning of equipment

Granulate may be spread as well when maintenance equipment is cleaned by brushing or by high pressures water streams. A Swedish study determined how much granulate is released during cleaning of brushing maintenance equipment [32]. The study did not describe the exact type, brand or model of the equipment. The equipment was used on several occasions during dry and during wet field conditions; afterwards the machines were cleaned. Cleaning of the machines with compressed air with and without prior brushing was compared. The results are shown in Table 3.

It appeared that brushing was very effective in removal of granulate from the machines; on average > 6 times more granulate was removed by a combination of brushing and air blowing than by air blowing alone. When fields were wet more granulate (> factor 3) stuck to the equipment, which is visible in the higher amounts removed from the machines. For the extrapolation of an occasional to an annual loss by the equipment, the author assumed 70 brushing maintenance occasions per year under 50% dry/wet conditions, and 10% release from the equipment during off-field time. During off-field time, granules that stuck to brushes, the wheels or the machine can be washed away by rain, blown away by wind or can fall from the machine through vibrations. The resulting potential total loss of granulates by a maintenance vehicle is approximately 24 kg/field/year.

Environmental concentrations

Paved surfaces

The spread of infill to paved surfaces can be caused by dragging along granulates with shoes or maintenance machines, but according to Weijer et al. [40], the major cause (in The Netherlands) is leaf blowing. In Nordic countries it can also be caused when snow clearance is deposited on paved surface.

In The Netherlands, the amount of infill on paved surfaces has been determined near 3 artificial turf pitches with ELT infill. The selected fields did not have precautionary measures in place, such as boardings along the sides. The spread of granulates to pavement has therefore not been prevented. Repeated observation plots of 1 m^2 were marked on paved surfaces at 20 m distance from each other at the north, south, east and west side of the fields, implying that 12 observations were taken per field. The amount of infill was determined by visual comparison with reference plots with known amounts of infill. The results are summarized in Table 1 section C. The measured amount of infill spread to paved surfaces varied from 0.01 to 2.9 kg/m^2/week (mean 0.4, median 0.2 kg per m^2 per week), which equates to 1 to 60 kg lost per pitch per year. The variation in the amount of infill found on paved surfaces is high, and there is no statistically significant effect of the geographic orientation. The highest amounts have been found on pavements in Amsterdam. This may be caused by the fact that there are more trees surrounding the pitch (so the need for leaf blowing is higher) than on the other locations (trees on 3 versus 2 sides of the field) in combination with an outwards blowing direction.

In the same study, the amount of infill in cattle grids and walk-in mats was determined and equated on average 11 kg per mat ($n = 10$).

Drainage system

Through stormwater run-off granulate that has not been swept from the pavement, can end up in the drainage system. The amount of granulate that is captured in drainage sinks will depend largely on the infrastructure around the pitches (boarding, cattle grid), on the maintenance equipment and on the awareness of caretakers and players. Two studies attempted to quantify the mass of infill that could end up in drainage sinks.

In the first study [40], sludge in 28 drainage sinks in the vicinity of 2 artificial turf pitches was sampled in January/February 2018. The amount of infill in the sludge was determined by a combination of visual inspection, sieving, washing, drying and weighing. In Rotterdam (field was 1.5 years old), eight sinks that were cleaned yearly, contained 62 g rubber granulate per sink. In Hoogeveen (field was 11 years old), 20 sinks contained on average 341 g rubber infill each. According to the caretaker, the sinks have never been cleaned before. Based on these two fields the maximum loss of infill to the drainage system is 2 kg per field per year (see Table 1 section D).

In the second study [32], stormwater traps and collecting wells were installed at a new football pitch with ELT infill in Sweden (constructed in September 2018). The field was surrounded by boarding to prevent spread of infill, special lining to pile up snow on the pitch and filters of respectively 100 and 200 µm to collect microplastics in, respectively, the drainage system and stormwater traps. The traps were installed beneath the field, in the pavement surrounding the field to collect stormwater, in collection wells and in the drainage system of an asphalt road (for comparison). Traps were sampled at 7–8 occasions for up to one year after construction. The samples were analyzed on 5 plastic categories: (1) PP, PE, PS; (2) PMMA, PUR, PE; (3) rubbery particles (with silicon); (4) particle with chlorine, such as PVC; (5) particles with fluorine such as PTFE. Microplastics have been identified with the analysis methods SEM–EDX and FTIR. The method was able to detect microplastics > 10 µm. The analytical method was not able to specify ELT rubber specifically, but these are included in the category "particles containing silicon". The results are shown in Fig. 4.

Run-off from pavement was the major dispersal route with 15.5 kg microplastics per field per year. The amount of rubbery compounds in the stormwater was 26% containing, maximally 4–5 kg ELT granulate per field per year. This seems a relatively high amount, compared with the 1 kg mentioned above [40]. The study of Weijer concerned older fields and there were no filters installed in the drainage wells, so particles might have been moved further downstream in ditch sediment (see "Sediment" section). The stormwater traps in the study of Regnell [32] seem an effective mitigation measure, because further downstream, in the collection wells, the percentage of rubbery compounds is similar to the background of road run-off. It is striking, that even so close to the artificial turf, rubber granulate is a minor component in the overall microplastic mixture.

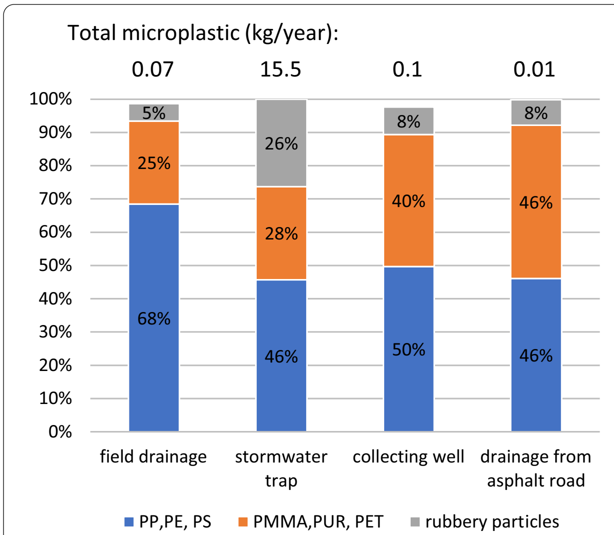

Fig. 4 Percentage of different types of microplastics in drainage and run-off water of an artificial turf field, compared to an asphalt road [32]. Microplastics particles measured after construction of an artificial turf field in September 2018 in Sweden. Infill was ELT granulate. Rubbery particles were determined based on the presence of silicon. Particles containing chlorine (such as PVC) or fluorine (such as PTFE) were below the limit of detection

Sediment

Granulates can enter the ditches through the drainage system, surface run-off or improper leaf-blowing and snow clearance. Two Dutch studies describe measurements of rubber granulate in ditch sediment. ELT granulate are hydrophobic and heavier than water and as a consequence it will precipitate close to the discharge point. However, it is common practice that ditches are cleared from precipitated debris and dead plant materials periodically. Information about this practice is necessary to interpret the measurements.

In the first study [40], the ditches are only 3–4 m away from the 2 artificial turfs under investigation. A mixed sample was composed from 10 sediment sub-samples from ditches adjacent to the field. Sediment contained, respectively, 0.26% v/v of ELT granulate in the Amsterdam ditch, and 4.9% v/v in the Hoogeveen ditch (see Table 1 section E). Considering previous dredging and the ditch dimensions, the annual loss of infill from the artificial turf to the ditch is estimated 4–6 kg infill per field per year. This amount is approximately equal to the amount found by Regnell [32] in the drainage traps (see "Drainage system" section).

In the second study [37], the distance from the ditches to the artificial turf fields varied from 8 to 72 m. Fields constructed between 1990 and 2009, containing ELT infill, were selected from 10 different municipalities. The ditches contained on average 0.22 (0–2.8) g ELT granulate per kg dry sediment. The granulate concentrations are in the same order of magnitude as the lowest value measured by Weijer et al. [40]. Information about the time lapse since last dredging is incomplete.

Soil

Two studies in The Netherlands have sampled (independently from each other) with a grass plot sampler the topsoil around artificial turf football pitches for analysis of the rubber granulate content. The granulate content was based on a gravimetric separation of granulate and soil particles and is described in more detail in the Additional file 1. The sampling positions relative to the artificial turf field of both studies are indicated in Fig. 5.

In the study of Verschoor et al. [37], 20 samples were taken of the upper 10 cm of the grass strip surrounding the artificial turf. Samples were taken every 10 cm at a

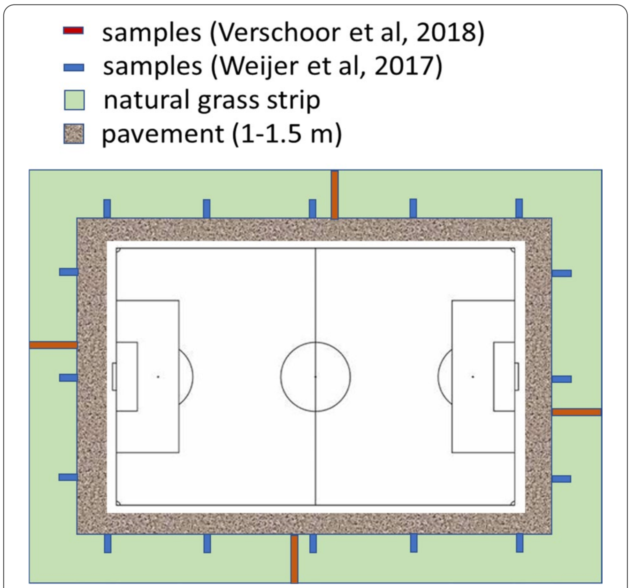

Fig. 5 Sampling scheme of soil in grass strips surrounding the artificial turf fields

distance of 0–2 m from the pavement. A median rubber infill concentration of 13 g/kg soil (range 1–35 g/kg) in the upper 10 cm at a distance of 0–2 m from the field was determined in 10 fields of approximately 10 years old [37].

In the study of Weijer et al. [40] three sports field were investigated, one in Amsterdam and one in Rotterdam and one in Hoogeveen. The grass sod (upper 2 cm) and the 5 cm beneath the grass sod were sampled separately to gain insight in the vertical distribution of the granulate. Samples were taken over a perpendicular line of 0–0.5 m distance from the surrounding pavement at every 20 m on each side of the field and combined and mixed into one homogeneous samples per side. Quantification and tentative identification have been done with a gravimetric method. The results are shown in Table 1 section F.

From the findings in sod and subsoil in Rotterdam it can be deduced that 97% of the infill that has spread to the surrounding soil, was found in the sod of 2 cm thick. Only 3% was found in the 5-cm layer underneath. However, this was in a new field; soil processes and organisms have had only half a year to spread the infill vertically. In Hoogeveen, on the other hand, 78% of the infill was found in the subsoil and 23% in the sod. Construction works in 2006 over a longer period of time caused mixing and homogenization granulate over a thicker soil layers. The same might have happened in Amsterdam in 2007. Since 2010 the awareness has grown that dispersal of granulate needs to be limited as much as possible, also during the construction phase.

Granulate concentrations in the study of Verschoor et al. [37] are lower than in the study of Weijer et al. [40]. The difference is most likely caused by the larger strip (0–2 m versus 0–0.5 m) and the thicker layer (0–10 cm versus 0–7 cm) that has been sampled in the respective studies.

Mass balance

The principle of circular economy is that materials can endlessly be reused and recycled. Losses to the environment are undesirable. Loss to the environment has been perceived as one or the most important reason for refill [18]. It is difficult to derive general values for the amount of environmental loss, because it depends on the housekeeping rules, on behavior of players and caretakers, on available maintenance equipment and on infrastructure. On top of that, wet weather and especially snowy conditions may accelerate the dispersal of infill.

In Fig. 2 the material cycle of ELT granulate on artificial turf is drawn. Improper snow piling is potentially the most important reason for granulate loss from the field. However, large parts of Europe have a temperate or warm climate, where snow clearance is not an issue. It is probably not a coincidence that most of the studies to the fate of rubber infill have been conducted in Scandinavian countries, because of the high visibility of granulate in melting snow piles near the sport premise. It was assumed that up to 100–150 kg of ELT granulate per field per year could be lost due to snow clearance (see "Snow clearance" section). A way of preventing large-scale loss is better control of snow clearance [3]. With the right measures and procedures, the ELT that remains after the snow has melted, can be reused on the field.

When snow clearance is done on the whole field, refill is needed for the whole pitch (7140 m^2). In countries where snow clearance is not needed, only locally worn-out high-usage areas need refill. So in contrast to whole-field refill, in temperate zones it is likely that only local hot-spots are treated with additional infill, which requires lower amounts of granulate.

Based on the literature review we estimate that approximately 600–1200 kg infill per field is needed annually. Although there are examples of sports fields that never received refill. Under good and responsible management practices, environmental dispersal can be avoided. The most important reason for annual refill of artificial turf fields is compaction (500–600 kg). During compaction, no dispersion of infill to the environment occurs. The remaining part could be collected from pavements and drainage sinks and disposed of as waste (see Fig. 2).

Mitigation

Not all the losses of ELT infill necessarily end up in the environment. There are many options to mitigate the dispersal of granulates to the environment. With current awareness on microplastic contamination, new protocols have been developed. The European Committee for Standardization has recently published guidance on how to minimize infill dispersion into the environment [6]. The guidance pays attention to the field design, installation, maintenance with special attention for snow clearance, changing rooms, retrofitting and the end-of-life stage of the artificial turf. Guidance is also offered by producers of infill materials [17] or field contractors [5].

Recommendations that can easily be implemented concern good-housekeeping practices, such as to blow leaves inwards and transport the leaves as solid waste instead of composting them. Granulates dispersed to paved surfaces, buildings and in drainage systems can be collected and disposed of as solid waste. In the recent years, new equipment has been developed to remove leaves by vacuuming. By immediate filtering, granulate falls back on the field whereas the leaves are contained in the machine.

To remove dirt that has already entered the infill layer and to reverse compaction, power brushing and raking are recommended 3–4 times per year [35]. In order to prevent dispersal of rubber granulate to the environment, collected residues should be considered as waste.

In case of snow clearance, it is recommended to store the snow in designated areas with paved surface and linings around. When the snow has been melted, granulate can either be reused on the fields or disposed of as solid waste. Common practice is to clear parts of the artificial turf area and when snow melts use regular maintenance machines to redistribute the infill over the cleared field. Many fields have dedicated, paved areas for snow clearance that are used in winter time or parts of the area for spectators are used. Although the snow piles are an unwelcome sight, they can be isolated from the natural environment.

The dispersal of granulate to the environment due to the cleaning of equipment can be completely prevented, if the cleaning is done on an (isolated) paved surface, that enables collection and recycling onto the fields or disposal of the granulate as solid waste.

The drainage system in the paved surfaces surrounding the artificial turf is designed to quickly move excess water to surface water or sewerage systems. Sinks are a constituent of a drainage systems and prevent clogging of the drainage tubes, with material that could precipitate, such as sand, rubber granulate or debris. The sinks not only protect against clogging, but also prevent the release of these materials to the surface water. These sinks need to be cleaned on a regular basis, and if rubber granulate is present the residue need to be disposed of as waste. The placement of filters in the drainage systems to capture microplastics has shown to be an effective measure; only 1 kg per field per year has been shown to pass the filter and reach the ditch [32].

Discussion

Far-reaching European wide policy to restrict ELT infill on sports field is proposed as part of a policy to reduce microplastics. In this paper we explained that rubber fill dispersal can be controlled and reduced to virtually zero. As a result, policy to ban rubber granulate will be ineffective to solve the microplastic issue and may even be counterproductive on another important issue such as the circular economy.

There are no scientific peer-reviewed publications about the fate and dispersal of ELT granulate used on outdoor artificial turf fields, and relevant grey studies have been published in foreign languages. This paper collected the grey literature, that contributes to the knowledge base by provision of measurements and experimental data. Studies were translated and used in the review to give an overview of the current state-of-knowledge with respect to ETL granulate dispersal. The fact that other sources (traffic related polymer particles, textile, microplastic pellets) are much more relevant was already mentioned in the introduction. The study of Regnell et al. [32] showed that even close to an artificial turf field, rubber infill comprised only a small fraction of the total microplastics present in drainage water, stormwater traps, and collecting wells (see Fig. 4).

The number of studies with measured data is small. We've found four studies that described monitoring results under outdoor conditions. The aims and the studies differed, which is reflected in the set-up and the accuracy and usefulness of the results. Aims varied from mass balance [40], environmental impact [37], infill loss by shoes [26], to efficacy of mitigation measures [32]. Sampling methods, analytical methods and reporting differ, which complicates comparison of the studies. Sampling methods differ in sample size, depth and/or distance to the field, most analyses have a physical nature, and chemical confirmation of the polymer has rarely been done. Reporting endpoints vary from number of particles to weight, volume or percentages. We have attempted to transform the outcomes of these studies to one uniform unit: kg infill dispersed to the environment per field per year. The dispersal of rubber granulate from artificial turf shows a huge variation. It appears that local conditions in field age, field maintenance, and geographical and meteorological conditions are the dominant factors. The studies that attempted to quantify the dispersal of ELT granulate and the annual infill demand were all conducted on fields that were constructed and maintained in a period when mitigation measures were not in practice, except for the study of Regnell [32]. Hence, the estimated quantities must be considered as to reflect a worst-case situation. Worst-case situations especially seem to occur by unawareness about granulate dispersal and the need and way how to mitigate microplastic dispersal. High infill demands, as estimated by Scandinavian sources, suggest that loss by snow clearance is particularly risky, while compaction as an in-field sink is ignored. It is striking that there are no measured data about the actual dispersal by snow. Only one Swedish study [38] estimated an ELT granulate removal of 20–30 L infill per snow removal occasion, based on interviews with caretakers. The representativity and reliability of this value cannot be assessed because the conditions (wet or dry) during snow clearance and the type of equipment have not been described.

One data seems to be particularly influential and that is the estimation of 3000–5000 kg of annual infill demand. This data traces back to 2009, although this original Danish source is not available. However, a similar reference from the same source of 2012 can be found [7]. Due to a lack of better data, this value has been adopted by many review studies, who extrapolated it to other countries and the EU as a whole [18, 20, 22, 24, 36]. Ultimately, this value still forms the basis of the ECHA restriction proposal.

The question can be raised if these Scandinavian values are representative for all countries within the European Union. Scandinavia belongs to a colder climate zone, whereas western and southern Europe belong to a more temperate climate zone with less snowfall [4]. With snow removal, a significant amount of rubber infill may be removed from the fields and, if not stored in a proper way, this may lead to environmental dispersal.

Snow removal is not common or not necessary in countries with temperate or warm climate. Data are only present from Scandinavia and The Netherlands. No studies have been found from Southern European countries. It makes sense that countries were infill dispersal is not (perceived as) an issue, have not invested into monitoring studies. Still it would be valuable if such data were collected, in order to differentiate the infill demand per country and to test the hypothesis that climate contributes to the infill demand.

Awareness about microplastic dispersal has risen in the past few years, which has led to adjustment of infrastructure, standard procedures for maintenances and rules for behavior of players. The annual refill demand can be reduced to 600–1200 kg per field, and is mainly needed to compensate for compaction on high-usage spots and to minor losses that can be collected as waste.

Besides the abovementioned recommendations and developments, the use of other infill materials or the construction of non-infill synthetic turf is under debate. A shift to common alternative infill materials like EPDM and TPE is not effective, because they are also considered microplastics. The use of natural infills may be considered, though they are usually only recommended for residential use because they are more susceptible to wear. Also, the availability, quality and certification of natural materials are more uncertain. Moreover, the light natural materials may float away during heavy rainfall. Finally, non-infill turfs consisting of fibers that are supported by smaller fibers may be considered. However, non-infill turf is more susceptible to increased wear and tear of the polyethylene fibers. While rubber granulate can be collected and reused, the worn fibers of a non-infill field are hard to collect and cannot be reused on the field. Because of their size and weight rubber particles tend to precipitate rapidly, in drainage sinks and sediment of nearby ditches. With frequent sweeping of paved surfaces and filters in the drainage system, the dispersal to ditch sediment can effectively be prevented [32]. The studies in this review indicate that dispersal of rubber granulate is a local issue, that can be minimized to virtually zero with the proper infrastructure and maintenance procedures.

Conclusion

This paper shows the current state-of-knowledge about ELT granulate dispersal and shows that approximately 600–1200 kg refill is required annually to compensate for compaction and for some infill waste on pavements and in drainage sinks. Recommended mitigation measures are containment through optimized field and drainage construction, suitable maintenance equipment and practices and good-housekeeping rules for players and groundkeepers and handling end-of-life pitches. If these recommendations are implemented, the emission of ELT granulates to the environment can be reduced to virtually zero.

Supplementary Information

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Additional file 1. Quantification of rubber granules in soil and sediment.

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Authors' contributions
AvG was involved in the set-up and critical reading of the manuscript. AJV wrote the first and final draft. AJV and UH were involved in some of the underlying experimental studies.

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Consent for publication
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The authors declare that they have no competing interests.

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