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Microplastic emissions and degradation mechanisms, in artificial turf systems – analytical detection and future directions

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The environmental impact of artificial turf systems is receiving increasing attention, particularly in relation to the release of microplastics. Here, our aim is to review recent studies on microplastic emissions from artificial sports fields, with an emphasis on environmental factors such as ultraviolet radiation, temperature fluctuations, rain, and mechanical wear, which all contribute to the fragmentation of synthetic fibres and infills. This study also reviews the leaching of toxic chemicals and microplastic sources in artificial turfs. We summarise and discuss various analytical techniques, including Fourier transform infrared spectroscopy, scanning electron microscopy, and pyrolysis-gas chromatography-mass spectrometry, employed to detect and quantify the release of microplastics and different contaminants from artificial turf to the environment. We identify significant gaps in current research, specifically determining degradation rates of artificial turf, and the detection and release characterisation of harmful substances like microplastics, heavy metals and polycyclic aromatic hydrocarbons from it. We highlight a need for further standardised methods and comprehensive long-term and accelerated studies to accurately assess the full ecological impact of microplastic release from artificial turf systems.

Environmental significance

Artificial turf's emission of microplastics is a timely topic with limited research. Here, we systematically study the factors affecting microplastic release and the analytical methods used for qualitative and quantitative sample analysis. We have carefully selected the most recent literature to provide a review of the current state of the art in this area. We highlight that weathering factors, including UV radiation, temperature changes, precipitation, and mechanical wear, all play a part in the fragmentation of synthetic fibres and infills. These are becoming increasingly relevant with the occurrence of extreme weather events induced by climate change. We advocate for the establishment of standardised methods of sample collection and adequate instrumental analysis for qualitative and quantitative characterisation of the samples.

1. Introduction

The synthetic turf system, or artificial turf, has become a popular sports surface, undergoing drastic changes over the past 50 years, since its introduction.[1] Artificial turf was first introduced during the 1960s as a long-lasting replacement for grass when it was installed at the Astrodome in Houston, Texas.[2] First-generation turf consisted of short plastic fibres, an artificial grass surface that provided a low-maintenance option for indoor sports venues where natural grass was nondurable and fragile.[3] Improvements were made during the 1980s with second-generation artificial turf. These included sand infill, which improved stability and shock absorption, allowing for outdoor games on these surfaces.[4] However, the first transformational advancement in turf technology came along in the late 20th century with the introduction of rubber granules as an infill for a more grass-like surface. Infill rubber is commonly produced from recycled tyres and marketed as crumb rubber. This third-generation system set the durability standard to support high-traffic use in professional and recreational sports venues and became the most widely used.[5] Artificial turf surfaces are commonly used for baseball, American football, Canadian football, cricket, hockey, association football, rugby, tennis, golf, and motor racing.[5] When compared with natural turf, they show greater durability under heavy use and harsh weather, lower water consumption, and low maintenance.[1] Most of these properties arise from the use of synthetic fibres, predominantly polyethylene (PE) and polypropylene (PP), which can replicate the appearance and functionality of natural grass.[5,6] The synthetic turf market has grown with the increasing demand for artificial turf installations. Nearly 181.45 million sq.

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meters were installed worldwide by 2021, with the forecast that this figure will increase to 266.03 million sq. meters by 2027.[7] The global market was valued to be worth USD 8.105 billion in 2021 and is predicted to reach USD 12.68 billion by 2027, with a compound annual growth rate (CAGR) of 7.7%.[7]

Artificial turf's impact on the environment has become a concern in recent years.[8] Toxic compounds such as toluene, zinc (Zn), lead (Pb), arsenic (As), cadmium (Cd), polycyclic aromatic hydrocarbons (PAHs), polyfluoroalkyl substances (PFASs) and microplastics (MPs) are gradually released into the environment from artificial turf over time.[8] Turf is exposed to environmental

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stressors such as ultraviolet (UV) radiation, temperature changes, or mechanical wear, resulting in gradual degradation.[8] Over time, these factors contribute to the breakdown of synthetic fibres.[8,9] The number of MPs released from artificial turf reported in the literature ranges from 0.1 kg to 5 tons per year per field.[1–5] Artificial turf fibres can account for over 15% of the mesoplastics in the marine world, with up to 20 000 fibres flowing through rivers daily and up to 213 200 fibres per km^2 found in nearshore sea surfaces.[9] Recent data from the UK government department of Environment, Food and Rural Affairs (DEFRA) underscore the wider environmental impact, estimating an annual burden of 16 866 tonnes in the UK, a figure aligned with EU estimates and 300 million fibre loss in a year.[10] This emphasises the urgent necessity for specialised monitoring tailored to the domain. As these MPs are transported through ecosystems, they can release harmful chemicals that pollute the soil, water, and air, leading to significant and potentially irreversible damage to the environment.[4] In wildlife, MPs can cause oxidative stress, endocrine disruption, and reproductive toxicity.[11] In addition, MP ingestion by animals may lead to gastrointestinal problems accompanied by decreased feeding rates and, in some instances, starvation.[11] MPs preserved in water for a long period can cause a potential hazard to water ecosystems and human health.[12–14]

To detect and quantify MPs in the environment from various sources, different analytical methods are used. Techniques like Raman spectroscopy, mass spectroscopy, and pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS) help detect and quantify MPs and associate pollutants, providing high recovery rates.[12] Fourier transform infrared spectroscopy (FTIR) and liquid chromatography tandem mass spectrometry (LC-MS-MS) are employed to identify hazardous substances.[14–16] However, there is no standardised method for MP sampling and characterisation from various environmental samples. In addition, limited research has addressed MP emissions and degradation from artificial turf specifically[6,15] caused by environmental factors (*e.g.* UV exposure, rainfall, temperature fluctuations, and pH variations) and biological stressors, but also due to mechanical wear. Moreover, there is a lack of information on the effects of weathering on grass wear, the breakdown of MPs, and their fate in different environmental media, such as water, soil, and air.[8,15–17] Similarly, the deficient quantification of field release ranges of MPs is crucial for understanding their mobility in immediate environmental matrices, such as soil, air, and wash-off water from the artificial turf system.[8,9]

This article specifically identifies MP release from artificial turf during their degradation due to environmental exposure, and the qualitative analysis methods to identify the best practices for sampling and characterising the MP release from the current database. Furthermore, the research gaps and future research areas are also highlighted with their importance to gain a complete understanding of MP release from synthetic sports surfaces during degradation.

2. Methodology

The methodology for this review followed a structured approach to ensure comprehensive article selection. The main keywords, including artificial turf, synthetic sports surface, artificial turf degradation, environmental impacts, environmental stressors, MP release, and analytical methods, were used to conduct searches in Scopus, ScienceDirect, and Google Scholar databases within a publication period from 2014 to March 2025. Additionally, broader searches were conducted using terms such as artificial turf impacts, outdoor weather impacts, thermal degradation, UV degradation, hydrolytic degradation, mechanical degradation, MPs in soil, MPs in water, MPs in air, athletes' MP inhalation, player risk, football pitch, FIFA regulations, fake grass, turf maintenance, sports field management, synthetic surface health risks, MP pollution in sports, and environmental policy in sports facilities.

Initially, a total of 248 articles, including research articles, review articles, book chapters, and industrial reports, were listed, with some duplicates and irrelevant articles. The latter were removed, resulting in 167 articles for further review. After evaluating relevance by linking the review goals and research gaps, 104 articles were selected. These focused on detection methods, degradation, release mechanisms, and environmental stressors in pollutant release from artificial turf. Then, they were organised into several categories; MP detection methods (66 articles), MP identification techniques (11 articles); turf degradation (8 articles), exploring the breakdown of artificial turf (3 articles), MP release from artificial turf (7 articles) and environmental stressors (9 articles), addressing the impact of external factors on MP degradation and release.

3. Structure and chemical composition of artificial turf

3.1 Turf fibre

Synthetic grass is constructed with multiple layers to provide durability and functional support to the playground. The structure generally includes fibres in layers, a layer of infill (sand and rubber granulates), a backing layer to hold the fibre and a solid layer of crushed limestone or granular material to provide drainage for the whole system. Fig. 2 depicts the main components of the artificial turf.

Fibres used in various types of artificial sports surfaces differ in their appearance, texture, and mechanical properties. In most cases, these fibres are manufactured from synthetic polymers.[9] Due to the soft texture, durability, and resistance to UV degradation,[18] they can withstand wear and tear while retaining their original appearance. Polyethene (PE) is the most popular turf polymer. Notably, linear low-density polyethene (LLDPE) has become the material of choice for grass blades in ‘third-generation’ pitches.[19] The robustness of PE under severe use makes it a suitable material for high-traffic areas, such as soccer, rugby, and multifunctional sports grounds, where comfort and safety are of utmost importance.[20,21] Compared to PE, PP is more cost-effective. It is also stiffer and more rigid, making it suitable for landscaping or low-traffic areas where softness and high durability are less critical.[3,22] Its structural stiffness helps give density and support, but it compromises durability.[19,22] The most resilient fibre, nylon (polyamide), holds its shape even when subjected to high stresses, which makes it appropriate for tennis courts and professional sports grounds. However, it is only used in high-end applications because of its higher cost.[23] Hybrid turfs, which combine polymers such as PE and PP with natural grass, offer a mix of resilience, comfort, surface stability and safe playing. They provide a better replication of the playing experience of natural grass and withstand more frequent use, and have grown popular for specialised sports pitches such as football, golf, hockey, rugby, and others.[24] Monofilament fibres, made up of individual, dimensional strands, provide a more natural appearance and remarkable durability suitable for high-performance sports fields. In installations for multiple uses, fibrillated fibres with a net-like structure are used as they increase turf density and stability.[17]

3.2 Infill materials

Infill materials are essential for the stability and performance of synthetic grass, positioned in between the turf fibres (Fig. 1). They safeguard player safety and enhance the overall system's performance under heavy foot traffic, rough play, and extreme weather conditions. Infill materials absorb impact, reducing the risk of player injuries, especially in high-intensity sports like soccer and rugby. Beyond their functional benefits, infills significantly impact the surface's tactile feel and aesthetic attractiveness.[20,24,25] Various infills are used in artificial turf, including synthetic polymeric materials like rubber and thermoplastics, as well as natural materials like sand and organic materials like cork, coconut fibre, walnut shells, or olive pits.[26,27] Crumb rubber is one of the most common infill materials, made of styrene-butadiene rubber (SBR). It offers superior shock absorption, enhancing turf elasticity and making it ideal for high-traffic athletic fields like soccer and rugby. Chen *et al.*,[8] Hua *et al.*[22] and Massey *et al.*[28] confirmed that infill is used to enhance the elasticity of sports turf, and the spaces between artificial grass blades are filled with small granules. Initially made from recycled car tyres, most rubber infill particles are now made of ethylene propylene diene monomer (EPDM) due to health concerns about potential exposure through skin contact, ingestion, and inhalation, which were studied by Alijagic *et al.*[29] and Ghosh *et al.*[30] Infill rubber granules easily stick to sports gear and are displaced by heavy rains, spreading into surrounding vegetation.[31,32] Lassen *et al.*[33] reported that an estimated 1.5–2.5 tonnes are released annually from each artificial football field in Denmark. Thermoplastic elastomers (TPEs), including thermoplastic polyurethanes (TPUs) and polyolefin elastomers (POEs), are alternatives used in high-

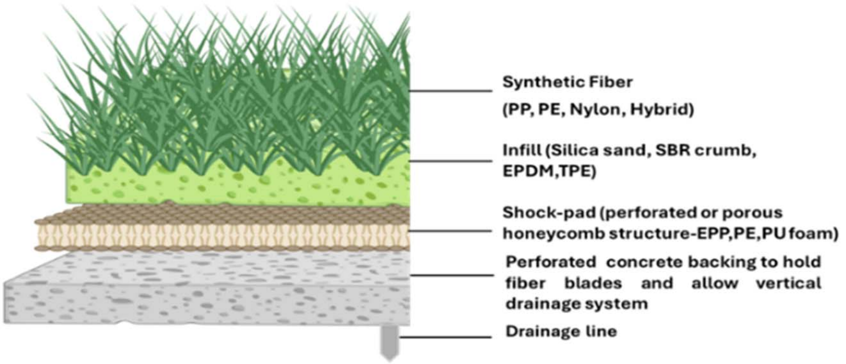
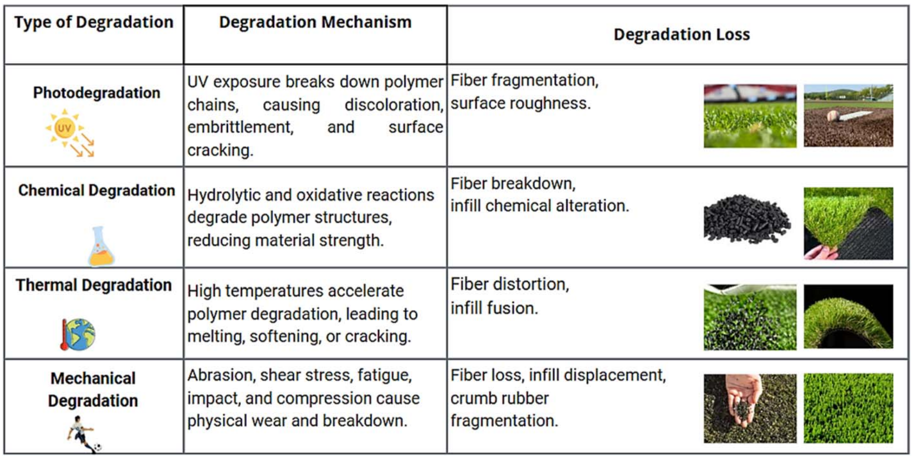


Fig. 1 Schematic of the major components of artificial turf.



Type of Degradation	Degradation Mechanism	Degradation Loss
Photodegradation	UV exposure breaks down polymer chains, causing discoloration, embrittlement, and surface cracking.	Fiber fragmentation, surface roughness.
Chemical Degradation	Hydrolytic and oxidative reactions degrade polymer structures, reducing material strength.	Fiber breakdown, infill chemical alteration.
Thermal Degradation	High temperatures accelerate polymer degradation, leading to melting, softening, or cracking.	Fiber distortion, infill fusion.
Mechanical Degradation	Abrasion, shear stress, fatigue, impact, and compression cause physical wear and breakdown.	Fiber loss, infill displacement, crumb rubber fragmentation.

Fig. 2 Different types of degradation in artificial turf materials and their associated mechanisms and losses.

Table 1 Properties and applications of different infill materials used in artificial turf

Infill material	Sports/applications	Chemical composition	Physicochemical properties	Other features	References
Recycled SBR	Soccer, American football, and rugby (general sports with high-impact needs)	Styrene-butadiene, carbon black, and sulphur	Elastic, durable, high heat retention, and potential for toxin leaching	Cost-effective but less environmentally friendly; releases MPs	9, 34–40
EPDM	Tennis courts, golf, and professional-grade sports surfaces	Ethylene, propylene, and diene monomers, pigments, and additives	Elastic, UV-resistant, and durable under extreme conditions	Expensive, appropriate for specific applications with required specifications; releases MPs	2, 23, 38–41
TPE	High-performance sports fields, multipurpose sports, and recreational areas	Thermoplastic polymers (TPU and POE)	Consistent performance, versatile, tuneable hardness, recyclable, and improved traction and safety	Engineered for performance, recyclable, expensive, long durability, and releases MPs	28, 38, 42 and 43
Organic infill	Low-impact fields, children's playgrounds, and eco-friendly applications	Natural materials (*e.g.*, cork and coconut fibre)	Biodegradable, natural heat dissipation, softer and less durable	Eco-friendly, lower durability, and applicable for heat-sensitive areas	5, 6, 8 and 23

performance sports fields and multipurpose recreational areas. Though they are recyclable, they come at a higher cost due to the processing cycle, and EPDM is more expensive as it is made of synthetic rubber.[28]

Table 1 presents a comparative analysis of the chemical composition, physicochemical properties, applications, and expenditure of different artificial turf infill materials, highlighting their strengths and limitations in various sports and environmental contexts. SBR presents high heat retention and MP release, raising environmental and player discomfort concerns. EPDM is preferred for tennis courts and professional-grade surfaces due to its elasticity, durability, and UV resistance. It is more expensive but customizable in performance properties, making it a popular choice in infill, but it also releases MPs during playing due to abrasion and tear as well as weathering exposure.[21] Similarly, TPE releases MPs from the high traffic areas of the pitch.[44] Organic infills, such as coconut and cork, are biodegradable options with good heat dissipation, but their low durability makes them unsuitable for high-impact sports.[23,27]

4. Degradation mechanisms and microplastic generation

Artificial turf components are susceptible to degradation due to wear and tear, as well as environmental exposure. Key contributors to the latter are UV radiation, temperature fluctuations, mechanical stress, and weathering, *e.g.*, rain.[45,46] Decaying turf can lead to the release of MPs and hazardous chemicals such as PFASs, PAHs, heavy metals, and volatile organic compounds (VOCs).[46,47] The different polymers which are used in artificial turf may degrade at different rates and through various mechanisms, depending on their chemical structure and the presence of additives or impurities.[45,48–50]

4.1 Thermal degradation

The temperatures of artificial turf surfaces can increase considerably, surpassing those of natural grass. On hot and sunny days, the surface temperature of artificial turf can reach up to 70 °C, compared to less than 40 °C for natural turf.[49,51] This is mostly because the materials used to make artificial turf have a poor albedo and absorb most of the sunlight radiation.[48–51] The type of infill and fibre used are two of the many variables which affect artificial turf's temperature. For example, Villacañas *et al.*[50] reported that surfaces made of fibrillated fibres and SBR often reach higher temperatures than surfaces made of thermoplastic rubber and monofilament fibre. The low thermal conductivity of materials like PE and rubber granules prevents heat dissipation, while their ability to absorb intense radiation further increases the surface temperature.[49,50] Li *et al.*[14] found that substances were released from the crumb rubber material used on artificial turf fields at high ambient temperatures during the first two weeks of exposure, and the volatilisation accelerated with high-vapour–pressure compounds, reducing their concentrations to initial levels. This rapid loss by stabilised emission of volatile compounds indicates that the behaviour of crumb rubber was influenced by thermal impacts and other weathering conditions.[52,53] Elevated temperatures accelerate thermal degradation of polymers like PE and PP, which are commonly used in artificial turf, leading to a higher release of MPs.[54,55] Villacanas *et al.*[50] studied turf fields older than five years, and those used for over 35 hours weekly exhibit increased thermal degradation, with SBR fields exceeding five years attaining temperatures of 63 °C. Conversely, TPE fields exhibit a marginal decrease in temperature with increased usage, indicating superior heat resistance.[50] Crumb rubber releases volatile and semi-volatile organic compounds under different thermal environmental conditions, along with other factors.[8,14]

4.2 UV degradation

PE and PP undergo photodegradation when exposed to UV light. The photodegradation process takes place at wavelengths in the UV-B and UV-C regions of the spectrum, typically between 280 and 320 nm.[56–58] UV light excites bonds in the polymer chains, leading to chain scission and the formation of free radicals and other reactive species (22, 50, 59).[18,59,60] At different UV

Table 2 Effects of different UV wavelength ranges on artificial turf degradation[56,58]

UV type	Wavelength (nm)	Impact on turf
UV-A	315–400	Minor impact, *e.g.*, gradual fading in colour and fibre wear
UV-B	280–315	Significant degradation, weakened backing, delamination and fibre loss
UV-C	<280	Highly destructive; not present in natural sunlight

wavelengths, this chain scission can eventually lead to the formation of smaller fragments, such as MPs, as listed in Table 2.

The process starts with the absorption of UV light by the polymer. This can provide the energy needed to excite the polymer backbone and break C–H and C–C bonds.[49,61,62] PP breaks apart at the tertiary carbon site, where the bond is the weakest, resulting in the formation of stable tertiary alkyl radicals. This radical formation plays a key role in the reaction process, increasing the reactivity at the tertiary carbon:

$$CH_3–CH(CH_3)–CH_2–CH_3 \rightarrow CH_3–C^{\bullet}(CH_3)–CH_2–CH_3 + H^{\bullet}$$

These radicals then react with atmospheric oxygen (O_2) to form peroxy radicals, triggering oxidative degradation.[63]

$$C^{\bullet}\ (CH_3)–CH_2–CH_3 + O_2 \rightarrow C(O^{\bullet}O)(CH_3)–CH_2–CH_3$$

The peroxy radicals can then remove a hydrogen from another PP chain, forming hydroperoxides. As mentioned earlier, oxidative chain scission can lead to polymer fragmentation, creating MPs. Both photolysis (effective bond breaking by short wavelength UV light) and photo-oxidation (oxidative reactions following radical formation) are critical in the degradation process.[63,64] This process is significantly accelerated at higher temperatures. UV degradation leads to surface microcracking in recycled plastics due to oxidative reactions and polymer chain scission, which is the first step in MP formation.[63] As the turf degrades, it becomes more brittle, and the fibres become more susceptible to mechanical wear, particularly in high-traffic areas. The increased brittleness and fragmentation of the fibres are further exacerbated by the combination of high temperatures and UV exposure, which accelerates the deterioration of artificial turf surfaces.[58,65]

Nylon and polyester fibres are particularly vulnerable to UV-induced degradation. The amide (–CONH–) group of nylon is polar, forming a dipole that makes it more likely to absorb UV light. Similarly, the ester (–COO–) group in polyesters is polar, creating a dipole due to the electronegativity difference between oxygen and carbon, which allows it to absorb UV radiation. This results in significant fibre release and deterioration of their mechanical properties over time.[45,65] UV exposure can cause changes in the surface morphology of the fibres, including the formation of microvoids that contribute to their overall breakdown.[58] The breaking strength of nylon 6 fabric was reported to decrease from 1008 N to 425 N after UV irradiation (100 W cm^{-2}) for 8 min.[66] It is important to consider the angle of incidence of UV light in environments where the durability and longevity of fibres are crucial, as long-term exposure, even at reduced angles, can still lead to significant degradation.[67,68]

FTIR spectroscopy has been used to prove the changes in the chemical structure of SBR after UV exposure, including the increase in carbonyl and sulfoxide groups. Zadshir *et al.*[52] and Andrady *et al.*[60] found that UV exposure leads to the formation of cracks and a reduction in mechanical properties such as tensile strength and elongation at break. The breakage of chemical bonds, such as C–C, C–O, and C–H,[69,70] results in a decrease in the cross-linking density of the rubber. The degradation is often more pronounced on the surface, eventually leading to the detachment of heavily degraded layers, accelerating the release of MPs.[48,55] SBR's C═C double bonds in butadiene make it highly vulnerable to UV degradation, especially above 40 °C, causing it to lose elasticity, harden, and crack.[53] While UV stabilisers and coatings help delay degradation, they add to maintenance costs, making alternative infill materials like EPDM or TPE more attractive for longer durability in artificial turf surfaces.[70–72] The fully saturated polymer main chain of EPDM explains the excellent resistance against heat and UV light compared to the polydiene rubbers with very high unsaturation in the main chain. The low amount of unsaturation in the side groups of EPDM facilitates sulphur vulcanisation and enhances peroxide curing.[72] Liu *et al.*[73] found that during the ageing process, the molecular main chain of the peroxide-cured EPDM was broken, resulting in a double bond and C═O structure. TPEs combine hard and soft segments to provide enhanced UV stability. The hard segments, such as polystyrene (containing phenyl groups, $–C_6H_5$) or polyolefins (with $–CH_2–$ groups), are relatively non-reactive and promote crystallinity, which helps resist UV degradation. The soft elastomeric segments, typically based on styrene-butadiene with –C═C– double bonds or ethylene-propylene with –C═C– bonds in the diene structure, are designed to be flexible and less prone to UV-induced degradation, making TPEs more resistant to UV exposure than unsaturated rubbers such as SBR.[74]

Numerous studies[69–71,73,75] have been conducted on polymers, composites, and their structural degradation. However, there remains a lack of experimental datasets specifically investigating UV-induced degradation and morphological deterioration over time in different wavelength ranges. The formation of cracks, free radicals, and MPs due to UV radiation, as well as the specific rates of degradation across different turf materials (such as PE, PP, and rubber) at various UV wavelengths, is not well established. Additionally, the effects of different UV exposure angles, along with environmental factors like humidity and temperature fluctuations, on degradation rates remain underexplored. Although some studies focus on chemical changes in the polymer matrix, the broader ecological impacts of these changes, particularly regarding MP release into the environment, are not fully quantified. This gap in understanding hampers the development of more durable and environmentally sustainable turf materials.

4.3 Hydrolytic degradation

Another weathering exposure is rain, leading to the formation of cracks and defects, allowing water to penetrate deeper into the artificial turf materials. In addition to MP release, compounds such as Zn and PAHs can leach from the turf materials, contributing to contamination in surrounding soil and water systems,[14,76] posing risks to aquatic life and human health. Hydrolysis rates increase in warm (>30 °C), humid environments. Acid rain, with typical pH values ranging from 3.5 to 5.0, accelerates the degradation of polymers due to the presence of sulphur dioxide (SO_2) and nitrogen oxides (NO_2) in the atmosphere, which react with water vapor to form sulfuric acid and nitric acid. This leads to the deterioration of functional materials such as high-voltage outdoor polymeric insulators.[5,74] Polyacrylamide-based polymers undergo rapid hydrolysis under alkaline conditions, and long sufficient rain and higher humidity can both induce hydrolysis of weak bonds such as those found in esters. In addition to simulating field conditions, turf is specifically engineered to induce mechanical stress, potentially leading to material fractures.[77] Likely, the degradation of wood-plastic composites, including those featuring polymers like high-density polyethene (HDPE) and PP, is accelerated under acidic conditions, reducing their mechanical strength and wear properties.[78,79] Hydrolysis can be either slowed or accelerated depending on acidic or slightly alkaline conditions. In acidic environments, the degradation rate may slow down due to the limited availability of hydroxide ions and neutral to slightly alkaline conditions can accelerate polymer breakdown.[76] Volker *et al.*[77] reported that the degradation *via* hydrolysis can occur through either acid or base catalysis. UV irradiation is not necessary for hydrolysis; rather, it enhances hydrolysis by degrading the surface, exposing fresh surfaces for hydrolytic processes. The chemical mechanisms behind these processes involve the protonation of ester or amide linkages, which makes them more susceptible to hydrolysis in the presence of water.[74] The long-term flow of rain could increase the runoff issues seen with artificial turf, leading to increased stress on the fibres and potential fragmentation. In artificial turf, unlike natural grass, the lengthy rain could weaken the fibres, making them more vulnerable to fragmentation.[80,81] This is consistent with the study of Song *et al.*,[78] that prolonged exposure to environmental conditions (photothermal-oxidation), can lead to the degradation and fragmentation of materials, including MPs and fragmentation. The mechanical damage to artificial turf fibres caused by stormwater carrying physical debris is a multifaceted problem involving abrasion, expansion, and contraction due to moisture, temperature, and weathering.[82] These factors collectively contribute to the fast wear and tear of artificial turf surfaces, highlighting the need for improved materials and maintenance practices to enhance the durability and longevity of artificial turf installations.

Despite several studies investigating the degradation under hydrolytic weathering, there are gaps in the current literature concerning MP release and its specific impacts under different environmental conditions. While some studies discuss the degradation of polymers under specific environmental stressors, the long-term cumulative effects of exposure to varying pH levels or seasonal temperature fluctuations on MP fragmentation remain unexplored. Hence, further research is required to produce improved standardised methods to measure MP emissions and to assess their environmental and ecological impacts under accelerated weathering conditions.

4.4 Mechanical and physical degradation

Abrasion from player interaction on the surface and foot traffic is a primary factor in producing fibre splitting and thinning, particularly in the playing areas compared to outer areas.[83] Condense loads, such as running and jumping, compact the infill materials and deform elastic layers, hence reducing cushioning and resilience. Tensile stresses from repeated bending and stretching of fibres during gameplay lead to material fatigue, weakening their structural integrity.[84,85] Studies have shown that artificial turf fibres can detach from the basal cloth due to mechanical wear and migrate to surrounding areas, including ditches connected to sewage pipes. This indicates that mechanical wear directly contributes to the release of MPs into the environment.[78]

Infill migration, where sand or rubber granules shift under traffic, accounts for a certain performance decline, leading to uneven surfaces and increased fibre wear.[84] The elastic layer, engineered to absorb the stress, gradually loses its flexibility because of compaction and continuous mechanical wear.[1] Player interaction contributes significantly to degradation, with rapid and compact movements causing fast abrasion in the pivoting and sliding action areas. These reduce playabilities and surface hardening and increased the risk of injuries. Bridge *et al.*[74] discussed the outdoor fields' crumb rubber or SBR being subjected to mechanical wear, direct UV radiation, changes in temperature, and water in different types of weather, like hot summer, snowy winter and humid rainy weather. Consequently, the fibre shedding further leads to environmental pollution, with up to 250 kg of MPs potentially released annually per field.[16,39] Mechanical wear, like shock absorption and vertical deformation, deteriorates over time due to wear.[80,85] Optimising elastic layers, infill materials, and maintenance protocols is critical to extending turf lifespan and mitigating environmental impacts.[25,37,54] These processes gear up the fragmentation of crumb rubber into smaller pieces, which eventually adds to the environmental contamination caused by MPs.[82] In addition to forming MPs, crumb rubber degradation also releases toxic chemicals such as Zn, Cd, Pb, Cr, benzene, toluene, and xylene, which harm human health and ecosystems.[8,86,87] These chemicals can leach into surrounding soil and water systems, further exacerbating environmental contamination.

4.5 Biological degradation

The biological decomposition of plastics is crucial for ecological health.[88] Artificial grass fibres provide environments favourable for biofilm development, fostering the attachment and growth of bacteria and fungi. These organisms may expedite deterioration through enzymatic processes.[87] Later on, biofilm-coated NPs and MP fragments may serve as microbial transporters after release.[86] The involvement of biofilms in NP and MP degradation and transport is currently underexplored. Insect species possessing gut bacteria that may degrade synthetic polymers could provide alternative breakdown mechanisms for MPs.[88] Some microorganisms can break the long polymer chains into short oligomers, dimers, and monomers.[89] HDPE exhibited modified surface topography, colouration, and novel functional groups during weathering, consistent with biodegradation.[90,91] Nylon components have more hydrophilicity than PE or PP, promoting microbial adhesion. Nonetheless, enzymatic breakage of amide bonds is still limited.[92] Enzymatic pretreatments, namely laccase-mediated oxidation, have been experimentally demonstrated to diminish the hydrophobicity and molecular weight of PE and nylon, hence improving their potential for microbial biodegradation.[87]

Infills, including SBR, TPE, and EPDM, exhibit minimal biological degradation in the environment.[8] For these materials, degradation mostly involves surface oxidation and fragmentation rather than full mineralisation, leading to an increase in MP debris with an elevated potential for environmental release.[89] Indeed, biological degradation may intensify microplastic pollution originating from synthetic grass.[93] The biological ageing of turf fibres and infills constitutes a significant, yet inadequately regulated source of MPs and NPs, highlighting the necessity for focused research and enhanced mitigation strategies to diminish the environmental and health hazards associated with artificial turf-derived MPs.

5. Microplastic leaching from artificial turf

The main sources of leaching in artificial grass are the synthetic fibres, which are usually made of PE, nylon, or PP, and the crumb rubber infill, which is manufactured from recycled tyres. Over time, these materials release organic pollutants, including PAHs and heavy metals like Zn, Pb, and Cd, into the environment, as reported by McMinn *et al.*[94] Vulcanisers, plasticisers, and antioxidants are among the complex mixture of chemical compounds found in crumb rubber, which is made from used tyres, as discussed by Mayer *et al.*[95]

Artificial turf systems incorporate crumb rubber infill, plastic fibres, and carpet backings, which may release chemicals into the environment through volatilisation and leaching.[96,97] These processes introduce inorganic and organic compounds, and other contaminants into air, water, and soil systems, raising environmental and health concerns. Table 3 describes leaching of different chemicals under different environmental stressors.

Depending on the environment, crumb rubber infill can degrade over time and emit a variety of MPs, organic pollutants and heavy metals into the environment because of physical wear, moisture, and UV exposure.[61,79]

Environmental hazards also arise from leaching from the synthetic fibres used in artificial turf, which are mostly composed of PE, nylon, or PP.[8] Heavy metals like Pb, which were once utilised as a colour in some grass goods, may be present in these fibres. Older turf fields may continue to leak lead over time as the fibres deteriorate, even though the usage of lead-based dyes decreases. UV deterioration and mechanical wear are the main causes of these pollutants leaking since they break down the fibres, releasing toxic dust or particulate matter into the surrounding area.[58] Over time, these contaminants can accumulate in the soil, water, and air, contributing to environmental pollution. Bohne *et al.*[102] argued that, while the leaching of contaminants from these materials is localised, their environmental impact is widespread, and their cumulative effects over the field lifetime (10–20 years) are concerning. According to Celerio *et al.*[35] and Surana *et al.*[59] Pb, Cd, and other toxic compounds from both the fibres and infill can increase the pollution in the soil and water.

Penetration of the rainwater through the porous structure of artificial turf into the infill layer enables contaminants to leach into surrounding soils or groundwater through the drainage line and layers (illustrated in Fig. 1). Infill rubber, such as crumb, contains a blend of chemical additives, including vulcanisers (sulphur and ZnO), plasticisers (dioctyl phthalate, diisononyl phthalate, polymeric plasticisers, and di-*n*-butyl phthalate), and antioxidants (butylated hydroxytoluene), which can leach into the environment, as found in experimental results of Armada *et al.*[103] Organic compounds typically

Table 3 Infill material released chemical substances under different environmental stressors

Infill material	Thermal degradation	UV degradation	Rainwater exposure	pH degradation	References
Crumb rubber	Zn, Pb, Cd, and VOCs (benzene and toluene)	PAHs, benzothiazole, and MPs	Heavy metals and organic compounds	Enhanced leaching of Zn, Cd, and Pb	5,14, 78, 91, 93 and 94
Organic infill	Organic acids and lignocellulosic	Cellulose and hemicellulose	Tannins and organic acids	Hydrolysed fibres and organic acids	8, 12, 16 and 98
TPE (thermoplastic)	Plasticisers and stabilisers	MPs and chemical additives	Plasticisers and phthalates	Accelerated leaching of phthalates (dibutyl phthalate)	5, 11, 31, 40, 78 and 99
EPDM	Stabilisers and organic residues	MPs and minor leachates	Small organic residues	Slight increase in metal (Zn and Pb) and stabiliser (benzotriazole) release	73, 77, 100 and 101

identified at trace levels contribute to long-term toxicity. Crumb rubber's environmental impact is particularly pronounced under acidic or alkaline conditions, which accelerate leaching rates of plastics and other chemicals. Efforts to mitigate these effects include better treatment of recycled tyres and exploring alternative infill materials.[40,104]

EPDM rubber is a synthetic option favoured for its durability and weather resistance. While it releases fewer contaminants than crumb rubber, Zn leaching remains a concern, at trace levels. Additionally, the outer layer of EPDM and other infill materials, which are exposed to the elements, undergo wear and tear through weathering and oxidation, releasing MPs, heavy metals and PAHs, potentially increasing the toxicity of the altered EPDM.[8,105] TPE infill is designed to minimise the leaching of harmful substances. However, when comparing SBR with TPE, TPE has higher concentrations of sulphur (S) and calcium (Ca), whereas SBR contains more carbon (C) and oxygen (O). These differences in elemental composition suggest that the two materials have distinct chemical structures and properties, which influence their performance in turf. TPE typically offers better UV resistance, durability, and lower susceptibility to degradation, while SBR is more prone to wear and tear. From an environmental impact perspective, Magnusson *et al.*[101] demonstrated that TPE is considered more eco-friendly due to its lower tendency to leach harmful substances and MPs, whereas SBR can release toxic chemicals, such as heavy metals and PAHs, during weathering, raising concerns about contamination of soil and water.[106,107] The chemical leaching from both synthetic turf fibres and infill materials, particularly crumb rubber, represents a significant environmental challenge. The release of heavy metals such as Zn, Pb, and Cd, along with organic pollutants like PAHs, has the potential to contaminate soil, water, and air, posing long-term ecological and public health risks. Given the persistent nature of these contaminants and their cumulative effects over the lifespan of artificial turf, there is an urgent need for the development of safer, more sustainable infill materials and more effective management strategies to mitigate these environmental hazards.

Nanoplastics derived from the relatively pure inner EPDM layer are considered non-toxic. Although EPDM rubbers might vary in composition, they all contain the same EPDM polymer. The precise composition of the EPDM granules is proprietary to the manufacturer. MP sizes and exposure to acidic or alkaline conditions, which improve the mobility of metals and organic compounds, increase the leaching of these pollutants, according to research by Zhang *et al.*[104] However, the immediate effects of this leachate are usually lessened when it is diluted with rainfall.[77,108] Leaching factors across all infill types are influenced by temperature, pH variations, water exposure, and mechanical wear, which can accelerate contaminant release over time.

Biodegradable organic materials pose very low risks due to minimal leaching of natural compounds. Crumb rubber releases MPs as it is worn down by foot traffic and other mechanical stress. Additionally, the plastic coatings on the turf fibre and infill layer, and backings that support the turf fibres, may degrade with ageing.[45,109]

Additionally, irrigation and rainfall contribute by washing MPs into drainage systems from the surface. Through surface runoff or drainage systems, MPs can find their way into adjacent rivers, lakes, and oceans in aquatic ecosystems. Aquatic species may consume them, causing bioaccumulation, the movement of tiny particles up the food chain. Smaller crumb particles leach at higher rates due to their increased surface area. MPs have the power to change the physical composition of soil, decreasing permeability and water retention.[8,21,82,110,111] They can also carry toxic chemicals, including heavy metals and plasticisers, which pose long-term risks to plant and animal life.[38,82] Additionally, MPs that become airborne through wind or human activity can be inhaled, leading to potential respiratory issues for humans and animals.

The process is exacerbated by UV light, which speeds up the emission of MPs by breaking down plastic fibres into smaller particles. Brushing, power brushing, vacuuming, and washing are examples of maintenance tasks that might damage the surface and release additional MP particles into the environment.[102,112]

5.1 Environmental distribution of MPs from artificial turf systems

The extent of artificial turf-induced MP pollution has been brought to light by research. Studies have indicated that drainage from artificial grass fields contains significant amounts of Zn and other pollutants.[111] Particularly, crumb rubber infill was found to be a major source of MPs as well as leachates of hazardous chemicals such as heavy metals, PFEs and PAHs. Particularly in places where artificial grass is widely used for playgrounds and sports fields, the environmental impact is significant, and there is a chance that ecosystems will get contaminated over time.[91,94]

Rainfall runoff from artificial turfs contains a high concentration of MPs, ranging from 8.26×10^6 to 4.08×10^7 MPs per L, as listed in Table 4. Polyurethane, polyethene, silicone-modified polyurethane, and rubber particles make up most of these MPs, which are smaller than 0.5 mm and mostly manifest as fibres and pieces.[111] MPs are present in the soil next to artificial turfs in considerable amounts, especially in agricultural terrain. Yoon *et al.*[110] reported a concentration of 5047 particles per kg, and these particles range in size from 20 μm to 500 μm.[110] In residential areas, parks, roads and forest they were found in slightly lower concentrations. The most prevalent forms of MPs found in soil include fragments, fibres, films, and spheres made of PE, PP, and polymethyl methacrylate.[110] Although precise levels of airborne MPs close to artificial turfs have not been reported, it is known that there are MPs in the atmosphere that are smaller than 5 mm.[113,114] These particles can have a variety of forms and are affected by both human and meteorological variables.[113,114]

Furthermore, MP emissions might be greatly decreased by enhancing turf maintenance procedures, such as collecting and reusing rubber granules during field maintenance. It is feasible

Table 4 Distribution, composition, and characteristics of MPs in different environmental media

Environmental medium	Microplastic concentration	Particle size range	Polymer composition	Morphological forms	References
Surface water	8.26×10^6 to 4.08×10^7 items per L	<0.5 mm	PU, PE, silicones, PU, and rubber	Fragments and fibres	111
Soil	5047 particles per kg-agricultural land 4987 particles per kg: roadside 1097 particles per kg: forest 3646 particles per kg: residential areas 2673 particles per kg: parks	20 μm to 500 μm	PE, PP, and polymethyl methacrylate	Fragments, fibres, films, and spheres	110
Air	0.93 ± 0.32 items per m^3 outdoors, 4.34 ± 1.93 items per m^3 indoors)	<5 mm	Various polymers; polyethylene terephthalate, PP, and PE	Various shapes	113 and 114

to create focused solutions that lessen the hazards artificial grass systems pose to the environment and human health by comprehending the origins and pathways of MP pollution.[9,115,116] Notably, in Table 4, surface water shows the highest contamination levels, while airborne MPs remain largely unquantified, indicating a gap in research. Quantitative atmospheric concentrations of MPs and fingerprints of chemicals can fill these gaps, along with a ratio of airborne MPs from fibres and infills with standardised mass count per metrics. Furthermore, comprehensive field-based research is required to assess MP concentrations across diverse environments and under varying meteorological conditions to enhance the accuracy and representativeness of the data.

6. Microplastic sampling and analysis techniques

6.1 Sampling techniques

The precision of MP analysis is significantly influenced by the sampling techniques used; proper sampling is essential for detection and quantification. Sampling methodologies are tailored to the environmental matrix, whether it is marine water, freshwater, sediments, soils, air, or biological tissues, to enhance recovery and minimise contamination.[13,117–119] Manta trawl tools are used to gather MPs from both marine and freshwater systems, but sediment sampling needs instruments like shovels, trowels, spades, scoops, and spatulas for sampling.[120] A Van Veen grab is usually used for deeper sediment levels.[13] Lusher *et al.*[119] conducted a study using a Van Veen grab, collecting sediment samples at depths of 10–15 cm from lakes in Norway, including Lake Mjøsa and Lake Femunden, and found small MPs >1 mm, such as fibres, films, and filaments, primarily PE and polystyrene (PS) in lake sediments. Soil sampling utilises related instruments and corers to reach various soil levels. Airborne MPs are collected *via* specialised high-volume air samplers or deposition collectors engineered to capture particles suspended in the atmosphere.[121] MPs from artificial turf systems vary in size, shape, colour, and polymer composition. They range from large fibres to small granules and irregular fragments. The size range overlaps with organic debris, making visual or automated identification unreliable in complex matrices such as soil or stormwater.[122]

The extraction of MPs from solid matrices, including sediments, soils, and biota, typically employs density separation, leveraging the disparity in density between polymers and mineral particles. Sodium chloride (NaCl) solutions are used for freshwater samples for their accessibility and safety, but they are less effective for denser plastics such as PET or PVC.[13] To address this constraint, denser solutions like zinc chloride ($ZnCl_2$) or sodium polytungstate can be used, although they are expensive and cause environmental risks.[123] Magnetic separation and flotation methods have also been studied for MP separation from environmental samples.[124,125]

Filtration is an important step in sampling MPs from water samples or to avoid extra fluid that is left over after density separation. Non-plastic filters, like glass fibre or aluminium oxide filters, can prevent contamination during analysis. Filters with a pore size as small as 0.45 μm are commonly used, but smaller pores can cause blockage and extended processing durations. To mitigate this issue, filter cascades and sample subdivision can be used; however, these methods prolong processing time and underscore the necessity for consistency, particularly as filter pore size affects the detection threshold of MPs.[98,123,126]

Size fractionation is generally executed using sieving or filtration, focusing on a prevalent MP size range of 0.5 to 5 mm, while also accounting for smaller fractions down to 62 μm.[123] For liquid samples, encompassing marine and freshwater, non-plastic filters, such as glass fibre membranes with pore diameters as tiny as 0.45 μm, are used to prevent contamination and facilitate subsequent polymer-specific analysis.[122]

Biological samples, encompassing marine organisms (*e.g.*, mussels and fish), terrestrial organisms, and soil fauna, necessitate dissection to extract pertinent tissues, such as digestive tracts, before visual inspection and, if warranted, microscopic examination.[98,127] This guarantees more precise quantification, preventing both underestimation and overestimation of MP concentration.[98] The purification of samples is important to remove any organic materials that can cause obstructions in detection. Nuelle *et al.*[127] experimented with chemical digesting techniques by incorporating oxidative treatments using hydrogen peroxide or Fenton's reagent for MPs, which decompose organic substances while preserving polymer integrity.[127,128] Alkaline digestion with potassium hydroxide provides a milder and more economical option, which has been confirmed in six digestion methods by Li *et al.*[128] The reagents used in the digestion analysis comprised potassium hydroxide (KOH, 10% w/v), sodium hydroxide (NaOH, 10 M), hydrogen peroxide (H_2O_2, 30% w/w), nitric acid (HNO_3, 69% w/w), a binary acid mixture of nitric acid and hydrochloric acid ($HNO_3 : HCl$, 1 : 1 v/v), and a ternary acid mixture of nitric acid and perchloric acid ($HNO_3 : HClO_4$, 4 : 1 v/v). Purification can be complicated for artificial turf samples due to the presence of additives, colourants, and organic debris on the surface of fibres and infill, which can interfere with chemical digestion steps and potentially damage the integrity of some plastic particles.

Karlsson *et al.*[129] studied enzymatic digestion for MPs in biota, resulting in 97% recovery of spiked particles and exhibiting good selectivity and maintaining MP properties, rendering them advantageous for delicate biological and soil specimens. Hybrid methodologies that include enzymatic and chemical digestion can enhance efficiency, yet the effects of different purification procedures on the contaminants associated with MPs remain a question.[125,127,130] Artificial turf matrices often contain a mixture of synthetic and natural materials, making the optimisation of enzymatic or hybrid digestion protocols more challenging.

Various methodologies have been devised to enhance recovery rates and hence prevent the underestimation of microplastic quantities in environmental samples. The Micro-Plastic sediment separator, named HYDRO-BIOS, developed from the Munich Plastic Sediment Separator, segregates various ecologically significant size categories of plastic particles from sediment samples.[122] The Sediment-Microplastic Isolation (SMI) unit is a bespoke device that is used by Coppock *et al.*[131] to reliably extract microplastics from sediments in a single operation. The sampling and extraction of MPs require a multi-faceted, matrix-specific methodology that combines manual collection from different sources (marine and freshwater environments, sediments, soils, air, and biota) with density or

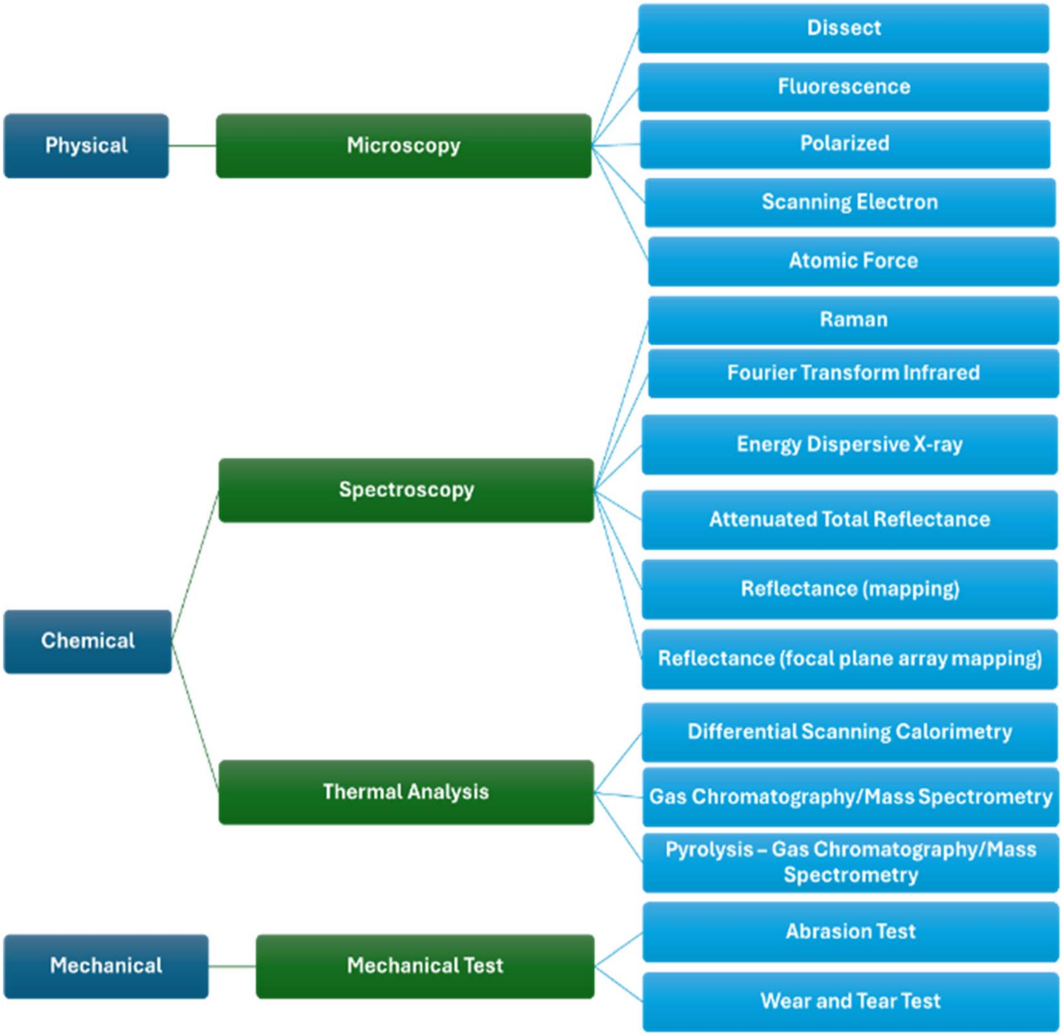


Fig. 3 Current methods using physical, chemical, and mechanical characterisation for analysing microplastics.

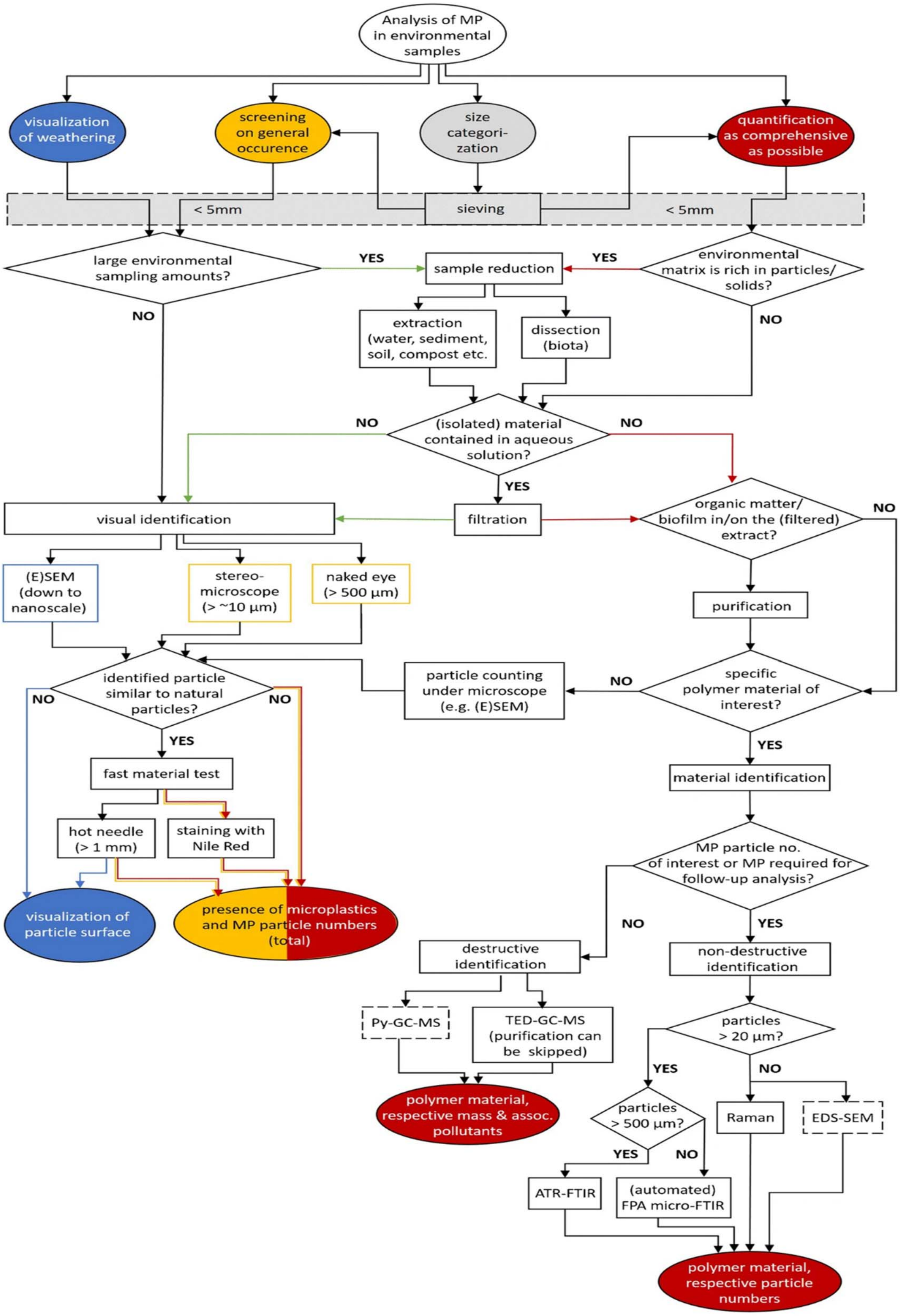


Fig. 4 Analytical methods decision tree of MP detection from an environmental sample.[122]

flotation separation, size fractionation, and purification. In artificial turf fields, the use of such extraction devices must account for the unique mix of long fibres, rubbery infill, and fine particulates that may behave differently during separation. These require modifications and tailored protocols for accurate MP quantification.[122]

6.2 Analytical techniques

MPs are present in every medium of the environment, oceans, rivers, lakes, soils, and even in the air, with estimates suggesting that billions of MP particles are released into the environment each year,[59,110] raising concerns about their environmental and health impacts. The shedding of synthetic fibres from textiles and the breakdown of larger plastic detritus are the sources of these small particles, which are frequently less than 5 mm in size.[49,78] Physical, chemical, physicochemical, and mechanical characterisation studies are required for identifying MP release from turf degradation (Fig. 3). The analytical method flow decision tree of MP detection from an environmental sample is shown in Fig. 4, which depends on the research question and boundary conditions, providing a systematic overview of the methodological flow integral for accurate MP analysis.

The accuracy and efficiency of the visual analysis method for identifying MPs are relatively low due to various factors, such as the environmental medium, impurities in samples, and the colour, shape, and structure of the MPs. Additionally, individual subjective judgment can influence results. Visual analysis becomes ineffective when MP particle sizes are too small, below 500 μm and when environmental samples contain other particulate impurities not retained by the standard sieving and need density separation or filtration, as reported by Hidalgo *et al.*[98] As a result, visual analysis is typically used as an auxiliary method, rather than a standalone technique. The naked eye can identify larger MPs (1–5 mm),[132,133] while microscopy is used to analyse smaller particles, typically 100 microns and above. Microscopy methods include optical microscopy and electron microscopy.[133] Optical microscopy is a simple and cost-effective method, but has a relatively high error rate, especially when identifying transparent MPs or those smaller than 100 μm, and is time consuming.[98] Optical microscopy is often combined with electron microscopy to eliminate the error rate. Electron microscopy offers higher magnification and high-resolution imaging, which allows it to distinguish MPs from impurities. Scanning electron microscopy (SEM) can identify MPs as small as 1–5 μm, but it cannot analyse colour or chemical composition. Transmission electron microscopy (TEM) can examine fine structures smaller than 0.2 μm that optical microscopy cannot detect.[46,134] SEM can provide extremely clear and high-magnification images of plastic-like particles. High-resolution images of the surface texture of the particles facilitate the discrimination of MPs from organic particles. Further analysis with energy-dispersive X-ray spectroscopy (EDS) provides the elemental composition of the same object.[127]

Fluorescence staining is often used to enhance the accuracy of visual analysis. This technique progresses using hydrophobic fluorescent dyes to stain MPs[134] which are then illuminated under light beams in a fluorescent or confocal laser microscope scan.[127] The limitation of fluorescence microscopy is that fluorescent dyes require specific wavelengths of excitation light, and some bioorganic compounds in the samples may also be stained with the dye. Additionally, some environmental samples naturally fluoresce,[134] which can interfere with the analysis results.

Laser diffraction particle size analysis can analyse the particle size distribution of MPs in soil and sediment. Blott *et al.*[135] claimed that it is a highly accurate and non-destructive technique that identifies particles ranging from 0.04 to 2000 μm. Although impurities in environmental samples may disrupt the results, this method requires prior extraction and separation of MPs from the samples.[98]

Dynamic light scattering is another promising method for analysing nanoplastics (NPs) in a range of plastic particles smaller than 1 μm. Sorasan *et al.*[136] found that solar photochemical ageing can convert secondary microplastics into NPs through dynamic light scattering tests. Nonetheless, certain pollutants in environmental samples may influence the experimental outcomes, as the limitation is the same as that of the laser diffraction technique.[13] As technology advances, both laser diffraction and dynamic light scattering are expected to play an increasingly important role in MP detection and analysis.

Furthermore, atomic force microscopy (AFM) has been applied to analyse MP particles at the nanometre scale, providing insights into their surface properties and any nanoscale roughness that might affect pollutant absorption. AFM studies have shown how surface characteristics of MPs change over time with UV exposure, potentially enhancing their ability to adsorb environmental toxins.[133]

Spectroscopic techniques such as FTIR and Raman spectroscopy are extensively used for identifying the polymer types of MPs and assessing chemical changes caused by environmental exposure.[98] FTIR is non-destructive and can provide rapid analysis of MP composition. It requires relatively clean samples because contaminants may interrupt the readings of the analysis. Correspondingly, Raman spectroscopy works by analysing the back-scattered light from a laser beam to generate a unique spectrum based on the molecular structure, which is also non-destructive. Raman spectroscopy offers high specificity in identifying polymer types and their chemical composition.[133] FTIR is typically more sensitive, but it has difficulty analysing small particles and requires particles to be at least 10 μm in size for micro-FTIR (μ-FTIR). On the other hand, Raman spectroscopy can detect much smaller particles, down to 1 μm, but its signals tend to be weaker, and it can be affected by interference from fluorescence.[137] It has been found that Raman spectroscopy can detect MPs from artificial turf with great precision, even in environmental samples containing organic matter. Araujo *et al.*[138] paired the optimised software with Raman spectroscopy technology, which made it possible for microplastics with particles ranging in size from 1 μm to 500 μm to be automatically found. This made Raman spectroscopy efficient at detecting MPs.

However, fluorescence interference from other materials can complicate the identification of MPs in complex environmental matrices.[120] FTIR spectroscopy is commonly used for identifying MPs by analysing their chemical bonds. It detects carbon-based polymers, with different bond compositions producing unique spectra to differentiate plastics from other materials. μ-FTIR is used for analysing smaller MPs, and it has different modes such as transmission and reflectance.[126,139] Attenuated total reflectance (ATR) is particularly useful for irregular or unclear muddy MPs, as it doesn't require extensive sample preparation. However, ATR-FTIR has limitations with smaller particles <20 μm and may require multiple trials to obtain accurate spectra, especially for weathered or fragile particles. The identification process can be long and requires experience to obtain the spectra accurately.[125,133] FTIR is beneficial for identifying polymer composition and assessing MP weathering. FTIR's spatial resolution limit of around 10 microns, combined with complex data interpretation and manual selection, makes it less effective for detecting smaller MPs and slows down routine analysis.[137,140] With the sequential measurement of IR spectra at manually chosen and spatially isolated spots on the sample surface, Levin *et al.*[140] employed the μ-FTIR mapping technique. However, this method is quite time-consuming and only allows for the analysis of small portions of the filter paper.

Significant methods for characterising MPs involve thermal analysis, which includes techniques like Pyrolysis-Gas Chromatography-Mass Spectrometry (Py-GC-MS), thermogravimetric analysis (TGA), and differential scanning calorimetry (DSC).[13] DSC is commonly used to study the thermal properties of polymers. It requires reference materials for polymer identification, as different plastic types exhibit distinct characteristics in DSC analysis. This method is particularly useful for identifying specific MPs, such as PE microbeads, where reference materials are available. However, DSC combined with TGA has limitations in identifying certain polymers like polyvinyl chloride (PVC), polyamide (PA), and PE due to overlapping phase transitions.[127] To improve identification, TGA can be combined with solid-phase extraction (SPE), followed by thermal desorption gas chromatography-mass spectrometry (TDS-GC-MS), allowing for better resolution and larger sample sizes compared to DSC alone. This method has successfully identified PE and PP in environmental samples.[127,141] Py-GC-MS is another thermal analysis technique where polymers are decomposed at high temperatures, and the resulting gases are analysed. This method is particularly effective for identifying a range of plastics, such as PVC, PS, PE, PP, and others, as discussed by Shim *et al.*[133] Py-GC-MS provides more detailed chemical information compared to DSC and is useful for analysing smaller plastic samples, typically in the range of 0.35–7 mg.[142] However, thermal analysis methods are destructive, meaning that MP samples cannot be further analysed once processed. While DSC is relatively simple and fast, it has limitations in identifying a broad range of polymers in environmental samples. Combining thermal analysis with GC-MS allows for the simultaneous detection of additives present in MPs, though this technique is more time-consuming and requires skilled operation.[141,143] Furthermore, while bulk samples can be analysed, thermal analysis does not provide information about the number, size, or shape of the MPs. Although not yet suitable for routine MP analysis, these thermal techniques are valuable for screening bulk samples and complementing other analytical methods, like spectroscopy, in the characterisation of MPs.

Mechanical wear analysis is also crucial for understanding how MPs are released from artificial turf due to physical forces such as foot traffic or maintenance equipment.[78] Micro hardness testing is a technique often used to assess changes in the mechanical properties of MPs after exposure to UV radiation or mechanical stress.[47,84] Nasri *et al.*[45] revealed that MPs become more brittle and susceptible to fragmentation after prolonged use or exposure to UV light using this technique, which contributes to the release of smaller particles into the environment. Turf abrasion testing is an essential evaluation to assess the durability and performance of artificial turf surfaces under mechanical wear conditions. The standard test method for synthetic turf abrasion resistance helps determine the turf's resistance to surface degradation caused by repetitive foot traffic and sports activity.[144]

Despite the extensive research and analytical methodologies available for the characterisation of MPs, the overall practicality and efficacy of the latter for artificial turf systems remain significantly limited. The majority of current methodologies have been formulated and refined for environmental matrices, including marine sediments, soils, water, and biota, which are fundamentally distinct in composition, complexity, and contamination characteristics when compared to artificial turf systems. The diverse and composite nature of artificial turf, comprising polymer fibres, granular infill, backings, and additives, create intricate interferences that complicate the direct use of conventional MP analytical techniques. This intricacy results in contamination, overlapping particle sizes, and spectral interferences that diminish technique accuracy and repeatability. Moreover, the extensive size range and weathering variability of turf-derived microplastics hinder consistent identification.[145] Therefore, a strong analytical decision tree, as shown in Fig. 4 is crucial for guiding technique selection, integrating complementary methods, and attaining thorough, reliable MP characterisation tailored to artificial turf matrices.

6.3 Challenges in microplastic characterisation

One of the main challenges in characterising MPs from artificial turf degradation is the complexity of sample collection, processing, and analysis.[18,19] As turf is often located in areas with other types of plastic pollution, contaminants in environmental samples can interfere with the identification and quantification of MPs. This issue is particularly pronounced when dealing with mixtures of MPs from various sources. Additionally, there is a clear need for standardisation in analytical methods focused on targeted sample collection. While several techniques, such as FT-IR, Raman spectroscopy, and Py-GC-MS, are widely used for MP detection and characterisation, differences in protocols, sample preparation, and data interpretation between studies hinder direct comparisons.[89,120,127,133,146] Considering the heterogeneous polymers of infills and fibres, shock pads, and environmental matrices with overlapping densities and sensitive chemical digestion, sampling of MPs from artificial turfs requires a dedicated, turf-focused multi-stage separation and filtration standard protocol set. Moreover, this protocol should encompass and be tailored for runoff, infill, adjacent soil, and

Table 5 Sampling and processing framework for artificial turf-derived MPs

Matrix	Primary targets	Sampling strategy	Lab processing	Key notes
Active air (aerosolized)	Fine fibres, rubber dust, and infill fragments[147]	Time-integrated active sampling at 1.0–1.5 m during play/maintenance to capture peak emissions[148]	Inorganic or metal filters (quartz, glass fibre, and silver) with thermal desorption or Py-GC-MS and μFTIR or μRaman spectroscopy[148]	Non-polymer filters avoid spectral and thermal interference from polytetrafluoroethylene (PTFE) or polyethersulfone substrates (PES) and improve polymer identification in airborne MP studies[147]
Passive dust (settled)	Coarse fibres, backing flakes, and urban dust with tyre-/road-wear[147]	Passive fallout or vacuum dust collection on and around the pitch to quantify leakage[147]	Dry, homogenise, density separation (NaCl, $ZnCl_2$, and NaI), filtration and spectroscopic identification[12]	Density separation is essential for removing the mineral or soot background[147]
Surface infill	SBR, TPE, EPDM granules, fibre or backing fragments[145]	Deep samples (*e.g.* 0–10 cm, 10–20 cm deep) at multiple pitch locations[149]	Dry sieving into size ranges, density separation, FTIR, Raman spectroscopy, and Py-GC-MS[120,126]	Require stainless steel sieves; validated multi-size fractions distinguish wear debris from native infill[126,132]
Runoff or drainage effluent	Suspended flakes, fibres, and rubber particles	Event-based sampling at outlets, focusing on rainfall or irrigation first flush	Pre-screening, Fenton oxidation of organics, density separation, filtration and polymer identification[120]	Fenton compatibility with rubber polymers is required[120,150]
Adjacent soil	Migrated infill, fibres, and secondary MPs in top soil[150]	0–10 cm top soil transects perpendicular to pitch (*e.g.* 0, 1, 2, 5, and 10 m)[149–151]	Dry, sieve, then high-density $ZnCl_2$, NaI separation, filtration and spectroscopic or thermal analysis[137,152]	Requires specified functional modelling like Fit exponential or a power law to test hypotheses[153,154]

dust. Similarly, analytical workflows demand a standard protocol, which needs to be validated through inter-laboratory research for achieving consistency.

As shown in Table 5, we propose an integrated framework for the sampling and processing of MPs released from artificial turf to air, dust, infill, runoff, and soil. Matrix-specific sampling strategies, including breathing-zone air sampling, depth-stratified infill coring, first-flush runoff collection, and perimeter soil transects, are coupled with established extraction techniques like density separation and Fenton oxidation and polymer identification methods, such as FTIR, Raman spectroscopy, and Py-GC-MS. Thus, the process aligns with standard

Table 6 MP detection techniques, methods, and limitations

Technique	Particle size range	Identification method	Identifications	Limitations	References
ATR-FTIR spectroscopy	>500 μm (ATR); 20–500 μm (μ-FTIR)	Infrared absorption of functional groups	Polymer type and functional groups	Low resolution for small particles; affected by pigments and matrix effects	34
μ-FTIR	10–20 μm	Infrared absorption (localised; high-resolution)	Polymer type and weathering patterns	Time-intensive; requires clean and flat surfaces	34
Micro-Raman spectroscopy	1–20 μm, down to 1 μm	Raman scattering spectra of vibrational modes	Polymer type and additive influence	Fluorescence interference; sensitive to contaminants and matrix complexity	34
Pyrolysis-GC-MS	Bulk mass >500 μm	Thermal decomposition products matched to the polymer database	Polymer type and additive content	Destructive; no shape or count info; requires extensive calibration	132
Optical microscopy	>100 μm	Direct visual observation and image analysis	Shape, size, and color	No polymer ID; subjective; limited for small or transparent	133
SEM	1–5 μm	High-resolution surface imaging using an electron beam	Morphology and surface texture	No chemical info; needs complementary methods	135 and 155
Micro-SEM	∼1 μm	Surface imaging at micro-scale resolution	Fine surface detail and shape	Suitable for morphology only	156

analytical practices while addressing MPs from specific matrix-related constraints.

6.4 Analytical method comparison

The identification and characterisation of MPs require a combination of various analytical methods, chosen based on parameters such as particle size, shape, and chemical composition, and the contamination of the surrounding matrix. The selection of the methodology depends on the precise objectives of the analysis, such as identifying polymer types, evaluating environmental degradation, or detecting additives, though each technique entails specific limitations, including susceptibility to contaminants, interference from pigments, resolution constraints for MPs, and the requirement for extensive sample preparation.

Table 6 presents a comprehensive review of various studies to identify the best practices for MP identification methods, highlighting their limitations. FTIR and μ-FTIR are effective for identifying polymer types and functional groups, but their resolution for small particles like MPs and sensitivity to matrix effects can hinder their accuracy in complex turf materials. Micro-Raman spectroscopy provides high spatial resolution, ideal for identifying small MPs, but fluorescence interference and sensitivity to contaminants limit its effectiveness in the heterogeneous turf matrix. Py-GC-MS offers precise polymer identification through thermal decomposition, but it is destructive, lacks information on particle size or morphology, and requires extensive calibration. Optical microscopy is limited by its inability to identify polymers and struggles with small or transparent samples, while SEM and micro-SEM excel at detailed morphological analysis but require complementary methods for chemical identification. While each technique contributes valuable insights, a combination of methods is essential for comprehensive MP detection in artificial turf, balancing morphological and chemical characterisation.

7. Knowledge gaps and future directions

The uncertainty about artificial turf degradation processes and their MP release patterns is a significant research gap that needs to be addressed. The main current challenge stems from capturing MPs from environmental matrices and weak quantitative measurements regarding real-world MP emission rates, which are identified and listed in Table 6. The production of MPs from PE, PP, nylon, SBR, EPDM, and TPE materials remains largely unexamined. Laboratory experiments that mimic environmental stressors, including UV radiation, temperature changes, and humidity, together with rainfall and pH levels, are essential for building predictive models across different turf arrangements.[15,17,74,82]

Research has insufficiently defined the mechanisms that lead to artificial turf degradation when multiple environmental stress conditions act simultaneously. Scientific research about artificial turf degradation primarily investigates isolated effects, with no studies of the combined impact of different factors at present. The kinetics of polymer breakdown and contaminant leakage need a deeper understanding through combined stress assessments using advanced microanalytical methods.[26,110,114,157]

The investigation techniques of generated MPs from turf degradation need improved characterisation methods. Most studies present insufficient data about the complete details of particle sizes, along with surface appearances and polymer types, with information about their environmental reaction rates. The implementation of advanced techniques, including μ-FTIR, Raman spectroscopy, Py-GC-MS, and atomic force microscopy, should become standardised for the precise identification of MPs throughout environmental media.[34,133,142]

Standard approaches to capture MPs during sampling procedures, together with their laboratory processing, sampling, and measurement techniques, remain essential for proper research.

Methodological differences between studies prevent researchers from having comparable findings and reproducing results. This hinders the advancement of dependable environmental monitoring procedures and analytical workflows, which needs to be validated through inter-laboratory research for achieving consistency.[126,137,158]

Research investigating the extended lifetime of MPs from manufactured turfs and their path of movement, as well as environmental outcomes, has not received sufficient attention. Current research fails to provide quantitative data about how MPs are spread by air and move through runoffs into aquatic environments build up in turf field adjacent soils. MPs require a thorough toxicological examination because they actively affect soil microbial populations and both aquatic and plant life.[38,57,82,115] Both scientific researchers and manufacturers have paid very limited attention to creating and validating eco-friendly turf products and reusable infill materials. Policy and sustainable design strategies need complete environmental assessment results from comparative lifecycle evaluations between artificial and natural turfs, specifically regarding MP pollution.[25,59,159,160] Several approaches can be adopted to lessen the negative effects artificial turf's MP emissions can have on the environment. One of them is the creation of biodegradable turf substitutes, which would break in to ecologically less harmful components than synthetic turf. Also, programs for recycling grass materials, particularly crumb rubber, can reduce the number of MPs released into the environment.

Research should separate the combined impact of UV radiation with thermal cycling and hydrolytic stress, mechanical abrasion and biodegradation on polymer breakdown affecting PE, PP, and SBR matrix materials. The combination of analytical instruments, including μ-FTIR imaging, Py-GC-MS, and nano-FTIR, should be utilised systematically for assessing size-specific fragmentation results, surface-level oxidation conditions, and sorption behaviour. Environmental scientists need more accurate instruments to measure the movements of MP and NP fractions and their availability to plants in soil and roots and exposed ecosystems. Systems-based investigation of alternative biopolymer-based turf systems must be conducted to determine their operational achievements as well as their breakdown patterns and environmental hazards. The implementation of standardised testing methods and LCA-based comparative evaluations should inform regulatory policies while guiding environmentally friendly turf infrastructure development.

8. Conclusion

The practical and performing nature of synthetic turfs makes them a major but generally overlooked contributor to environmental MP contamination. This review has thoroughly discussed synthetic turf material degradation patterns when exposed to UV radiation that interacts with temperature cycles and mechanical deformation, as well as hydrolysis conditions. Multiple environmental processes cause turf fibres and infill elements to fragment, which ultimately releases both MPs together with their chemical pollutants into land-based and water ecosystems.

To date, the accurate characterisation of MP generation and release from artificial turf systems has been constrained by the lack of validated, turf-specific measurement standards. In response, we propose an integrated, matrix-specific sampling and analytical methodology that accounts for the heterogeneity of turf components and receiving environments. By providing harmonised protocols for air, dust, infill, runoff, and soil, this framework could enable more selective separation, robust quantification, and improved comparability of MP emissions across materials, geographic locations, and climatic conditions, while laying the foundation for future inter-laboratory validation.

Author contributions

All authors contributed to the study's conception, design, and methodology. Literature search, critical analysis, and data organisation were performed by Afsana Sharmin, who also wrote the original draft of the manuscript. Mansoor Ahmad Bhat contributed to the review & editing of the manuscript. Ignacio Martin-Fabiani and Tanja Radu contributed to the conceptualisation, investigation, supervision, resources, and review & editing of the manuscript. All authors reviewed and commented on previous versions of the manuscript and approved the final version.

Conflicts of interest

The authors declare no competing financial interests.

Abbreviations

MPs	Microplastics
NPs	Nanoplastics
PE	Polyethylene
PP	Polypropylene
PAHs	Polycyclic aromatic hydrocarbons
VOCs	Volatile organic compounds
UV	Ultraviolet
Zn	Zinc
Pb	Lead
Cd	Cadmium
Cr	Chromium
SBR	Styrene-butadiene rubber
EPDM	HDPE ethylene propylene diene monomer high density polyethylene
TPE	Thermoplastic elastomer
TPU	Thermoplastic polyurethane
POE	Polyolefin elastomer
PVC	Polyvinyl chloride
PU	Polyurethane
PET	Polyethylene terephthalate
PMMA	Polymethyl methacrylate
FTIR	Fourier transform infrared spectroscopy
μ-FTIR	Micro-Fourier transform infrared
ATR-FTIR	Attenuated total reflectance Fourier transform infrared
Raman	Raman spectroscopy
GC-MS	Gas chromatography-mass spectrometry
Py-GC-MS	Pyrolysis gas chromatography-mass spectrometry
LC-MS-MS	Liquid chromatography tandem mass spectrometry
AFM	Atomic force microscopy
SEM	Scanning electron microscopy
TEM	Transmission electron microscopy
XPS	X-ray photoelectron spectroscopy
TDS-GC-MS	Thermal desorption gas chromatography-mass spectrometry
SPE	Solid phase extraction
LCA	Life cycle assessment
PCBs	Polychlorinated biphenyls
PCDDs	Polychlorinated dibenzo-*p*-dioxins
PCDFs	Polychlorinated dibenzofurans
μm	Micrometre (micron)

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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