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Health Impacts of Artificial Turf: Toxicity Studies, Challenges, and Future Directions

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Abstract

Many communities around the country are undergoing contentious battles over the installation of artificial turf. Opponents are concerned about exposure to hazardous chemicals leaching from the crumb rubber cushioning fill made of recycled tires, the plastic carpet, and other synthetic components. Numerous studies have shown that chemicals identified in artificial turf, including polycyclic aromatic hydrocarbons (PAHs), phthalates, and per- and polyfluoroalkyl substances (PFAS), are known carcinogens, neurotoxicants, mutagens, and endocrine disruptors. However, few studies have looked directly at health outcomes of exposure to these chemicals in the context of artificial turf. Ecotoxicology studies in invertebrates exposed to crumb rubber have identified risks to organisms whose habitats have been contaminated by artificial turf. Chicken eggs injected with crumb rubber leachate also showed impaired development and endocrine disruption. The only human epidemiology studies conducted related to artificial turf have been highly limited in design, focusing on cancer incidence. In addition, government agencies have begun their own risk assessment studies to aid community decisions. Additional studies in *in vitro* and *in vivo* translational models, ecotoxicological systems, and human epidemiology are strongly needed to consider exposure from both field use and runoff, components other than crumb rubber, sensitive windows of development, and additional physiological endpoints. Identification of potential health effects from exposures due to spending time at artificial turf fields and adjacent environments that may be contaminated by runoff will aid in risk assessment and community decision making on the use of artificial turf.

Graphical Abstract

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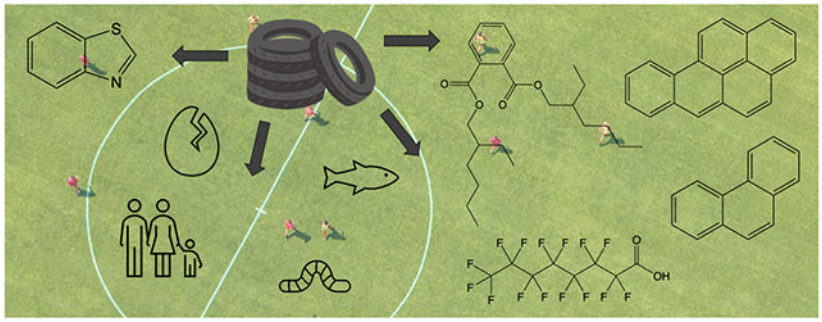
The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.



Keywords

artificial turf; crumb rubber; endocrine disruption; polyaromatic hydrocarbons; phthalates; perfluoroalkyl substances; environmental exposure; risk assessment

Introduction

A key feature of modern society is the drive to optimize and modify our environment with technological advances to improve our quality of life and adapt to changing environmental conditions. However, many such modifications come with increased risk to the natural environment and our own health. Replacing natural grass fields with artificial turf is one example of an "improvement" with unexplored health risks.

Artificial turf is a carpet of synthetic fibers that imitates the appearance of a natural grass field. It is widely used for recreational and professional athletics in the US and Europe. In 2020, the value of the artificial turf market was estimated at $2.7 billion and is experiencing massive growth with the market expected to more than double by 2027, with demand mostly driven by athletics and expanding to markets outside of the US and Europe (Industry Research 2021). As artificial turf is typically installed in areas that had previously been covered with plant life, this increase in coverage of the Earth's surface with synthetic materials that increase runoff and have been shown to cause heat island effects has important implications for climate change (Shi and Jim 2022). Proponents of artificial turf prefer the durable polymer surface to optimize limited playing space and time. Grass fields require maintenance, are sensitive to weather conditions, and the health of the grass suffers if fields are overused or improperly cared for (Cheng et al. 2014). Alternatively, opponents of artificial turf are concerned about exposure to hazardous chemicals such as polycyclic aromatic hydrocarbons (PAHs), phthalates, per- and polyfluoroalkyl substances (PFAS), and metals leaching from the synthetic materials, as well as the problematic environmental profile that can exacerbate local climate events (TURI 2019). In addition, artificial turf cannot be recycled and thus is consigned to a landfill after its useful life of 8-15 years, making it unsuitable for a circular economy.

Despite its increasing market share, the installation of artificial turf in communities around the US is highly controversial, in large part due to the sparce and mixed evidence for its safety. Importantly, the financial incentives of manufacturers to promote adoption of their products make this a prime target for manufactured doubt and scientific obfuscation (Goldberg and Vandenberg 2021). To date, the majority of scientific studies on artificial turf have focused on chemical components and leachates, identifying numerous carcinogens, neurotoxicants, and endocrine disrupting chemicals, many of which may have non-monotonic dose response curves that indicate there may be no safe level of exposure (Zoeller and Vandenberg 2015; Hill et al. 2018; Gomes et al. 2021). A few studies have attempted to estimate human exposure from inhalation and ingestion using surrogate biological fluids, environmental monitoring, and calculated estimates, generally finding low biological uptake and estimating low risk (Schilirò et al. 2013; Cheng et al. 2014; Peterson et al. 2018; Donald et al. 2019; Perkins et al. 2019; Pronk et al. 2020). Human epidemiology and laboratory toxicity studies are necessary bridge the gap between the established presence and release of hazardous chemicals by artificial turf and the current exposure estimates.

The purpose of this review is to examine research regarding the possible health effects from exposure to artificial turf and its components, both direct (athletics) and indirect (environmental contamination). Studies were identified from peer-reviewed literature and government-sponsored sources using Google Scholar and PubMed. Non-peer reviewed studies with a financial conflict of interest were excluded. We discuss ecotoxicology studies using invertebrate models, vertebrate animal studies, and human epidemiology studies of associations between artificial turf usage and disease. In addition, we discuss the areas where research is lacking and provide recommendations for future studies that will aid in decision making on artificial turf in communities.

Composition and Identified Chemicals

Artificial turf is made of several synthetic layers on top of natural soil (Figure 1). From the soil to the surface, there is typically a stone foundation layer made of compacted crushed concrete or granite, a plastic shock-absorbing layer to soften the ground, a synthetic fabric layer to prevent weeds, a plastic carpet layer to hold the artificial grass in place, a rubber infill layer to keep the artificial grass upright, and a layer of plastic grass fibers. These layers may be composed of nylon, polypropylene, polyethylene, polyurethane, synthetic rubber, and other polymers, including proprietary compositions. The most cost-effective infill is crumb rubber made from virgin rubber or shredded recycled tires; less common alternatives include thermoplastic elastomers, waste athletic shoes, acrylic coated sand, coconut fibers, cork, and sand (Massey et al. 2020).

Most analyses of the health and environmental hazards of artificial turf usage have focused on crumb rubber, although each synthetic layer can provide additional sources of exposure to hazardous chemicals. Crumb rubber is typically made from end-of-life automobile tires. It has been marketed as sustainable due to its status as a recycled material and alternative to the typical methods of tire disposal, burning or illegal dumping (Gomes et al. 2021). A single professional-size sports field requires crumb rubber from 20 – 40,000 tires at initial installation, with additional crumb rubber granules required for replenishment during the lifetime of the field as the granules migrate during use (Watterson 2017; Brandsma et al. 2019). In the US alone, tens of millions of tires have been used in artificial turf fields and to cover playground surfaces (Watterson 2017).

The widespread use of crumb rubber in the environment is particularly troublesome because of the large number of chemicals that have been identified in tires and rubber leachate. Tire rubber, which is composed of natural and synthetic rubber polymers, reinforcing agents, aromatic extender oils, vulcanization additives, antioxidants, and processing aids, has been widely shown to contain hazardous chemicals, most notably volatile and semi-volatile organic compounds, PAHs, heavy metals, phthalates, vulcanization agents, and antioxidants (Gomes et al. 2021; Armada et al. 2022). For example, an environmental transformation product of the rubber antioxidant N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine (6PPD) has been shown to cause acute low dose toxicity in juvenile coho salmon exposed through road runoff (McIntyre et al. 2021; Tian et al. 2021; Tian et al. 2022). As a ubiquitous tire chemical, 6PPD most likely leaches from crumb rubber in artificial turf fields and undergoes transformation into the extremely ecotoxic 6PPD-quinone in the local environment.

Recent chemical analyses of crumb rubber and other artificial turf components have identified hundreds of chemicals, including known carcinogens, neurotoxicants, and endocrine disrupting chemicals (Table 1) (Massey et al. 2020). Notably, recent studies of whole artificial turf and non-crumb rubber components have identified PFAS as an emerging class of contaminants to be considered alongside known rubber chemicals, emphasizing that although crumb rubber is notoriously hazardous, other components of turf should be studied as well (Naim 2020). Another recently recognized health hazard of artificial turf is the introduction of micro and nanoplastics into the environment, an emerging environmental concern (Wright and Kelly 2017). Infill, whether crumb rubber or other polymeric materials, is a loose component with a diameter of < 5 mm, meeting the definition of microplastics (Armada et al. 2022). Infill can wash off fields into the environment, collect in players' clothes, or be accidentally ingested during athletics or by babies and toddlers, resulting in additional sources of exposure (Lopez-Galvez et al. 2022).

Invertebrate Studies on the Health Impacts of Artificial Turf

The potential toxicity of artificial turf components has been studied most extensively from the perspective of ecotoxicology, focusing on organisms whose habitats are directly impacted by artificial turf installation. These studies have investigated only crumb rubber, which is also widely used in playgrounds and landscaping.

To model exposure to newly installed artificial turf fields, earthworms were housed in a tank containing a mixture of virgin crumb rubber and compost for 34 days. Exposed worms had reduced growth trajectory compared to earthworms living in only compost, but had the same mortality rate and susceptibility to light and stress (Pochron et al. 2017). To model exposure to fields containing aged crumb rubber, a follow-up study housed earthworms in a mixture of 7-year-old crumb rubber and compost. Exposed worms had significantly increased susceptibility to light and stress compared to earthworms living in only compost, but had the same mortality rate and growth trajectory (Pochron et al. 2018). Overall, the authors concluded that both new and aged crumb rubber pose risks to earthworms.

In another study of crumb rubber ecotoxicity, neonate *Daphnia magna* were cultured in aqueous extracts of newly shredded crumb rubber made from waste tires, crumb rubber cut from new tire tread, 6-year-old crumb rubber from a campus walkway, and 6-year-old crumb rubber from a playground (Lu et al. 2021). In addition, the samples of crumb rubber from new tire tread were irradiated with UV light to mimic outdoor aging. The *D. magna* exposed to the leachate of newly shredded crumb rubber had 100% mortality after 24 hours of exposure, whereas the *D. magna* exposed to new tire tread had significantly more deaths than the untreated control. The aged samples did not have increased mortality compared to the control. Exposure to new tire tread treated with UV light significantly increased mortality with increasing duration of UV treatment, indicating that newly installed crumb rubber has the highest toxicity risk. New tire particle leachate has also been shown to disrupt oyster development more than rubber leachate from aged tires (Tallec et al. 2022). Similar to the *D. magna* study, a study of mortality of zooplankton following exposure to seawater crumb rubber leachate revealed a dose-response relationship with increasing mortality with increasing leachate concentration (Halsband et al. 2020). In both studies, the only endpoint assessed was mortality, so non-lethal toxic effects from aged crumb rubber and low concentration leachates cannot be ruled out. Conversely, a study of the insect *chironomus riparius* and the worm *lumbriculus variegatus* in freshwater sediment contaminated with crumb rubber of various particle sizes did not identify any impact on growth, emergence, or reproduction (Carrasco-Navarro et al. 2022).

In Vitro and Vertebrate Animal Studies on the Health Impacts of Artificial Turf

Exposure of fish models to crumb rubber has identified potential ecotoxicity from leachate and granules that wash off fields and into the environment. Mummichogs and fathead minnows exposed to crumb rubber granules in artificial seawater environments ingested the granules, resulting in PAH adsorption into the bile and increase liver enzyme activity (LaPlaca and van den Hurk 2020). In addition, zebrafish embryos exposed to tire particle leachate developed malformations, whereas embryos exposed to nano-size tire particles had increased mortality and hatching delay (Cunningham et al. 2022).

Only one peer-reviewed study has used *in vitro* models or vertebrate animals as translational models for investigating the health impacts of artificial turf exposure on humans. This study assessed the reproductive toxicity of aqueous leachate from new crumb rubber in fertilized chicken eggs (Xu et al. 2019). Embryonic day 0 eggs were exposed by coating, dipping, or microinjecting and embryos were extracted at E3 or E7 for analysis. No significant morphological abnormalities were observed from dipping or coating. Eggs with leachate injected into the yolk had reduced growth, severe developmental changes, and impaired brain and cardiovascular system development. All the treatments showed signs of the disruption of thyroid hormone signaling, suggesting an endocrine mechanism of action (Xu et al. 2019).

The National Toxicology Program (NTP) has performed the only other human translational studies of crumb rubber, using rodents and *in vitro* models, which are published in two reports (National Toxicology Program 2019; Program 2019). In the rodent studies, adult female mice were exposed to new crumb rubber granules by oral gavage, dosed feed, or bedding for 14 days. Mice in the dosed feed group actively avoided consuming crumb rubber particles, but had statistically significantly lower ovary and thymus weights and altered hematology values at the end of the study. Mice in the crumb rubber bedding treatment group had statistically significantly increased liver weight. Overall, the authors of the study concluded that none of the changes were biologically relevant and that leachability of chemicals in crumb rubber is low in biological fluids. This is consistent with studies using simulated biological fluids (Pronk et al. 2020). NTP's epithelial cytoxicity studies exposed skin (HaCaT), lung (HPL-1D), and small intestine (FHs-74-Int) cells to culture media pre-incubated with crumb rubber granules and found that the pre-conditioned media was cytotoxic to all cell types. However, when crumb rubber was pre-incubated in artificial lung fluid and used for lung cell culture, toxicity was reduced, suggesting that cell culture media may not be an appropriate model for biofluids. In both of the NTP studies, the routes of exposure modeled were direct dermal and oral exposure to crumb rubber. These studies did not consider other routes of exposure, including from runoff, or other components of artificial turf.

Human Studies on the Health Impacts of Artificial Turf

In 2014, a professional soccer coach released anecdotal evidence to suggest that artificial turf exposure could be causing cancer in soccer players, particularly goalies, causing a media frenzy on artificial turf and cancer risk (Bleyer 2017). Although multiple athletes and coaches have blamed crumb rubber on incidents of cancer, the human epidemiology evidence for an association is scant and preliminary. In response to the soccer coach's claims, an investigation of incidences of cancer among skilled female college soccer players in Washington compared to other residents of the state found no significant association (Washington State Department of Health 2017). However, this study was limited to a single university and did not include most female soccer players in the state. An investigation of the association between turf field density and incidences of cancer in counties in California also found no significant association (Bleyer and Keegan 2018). A 2022 simulation of cancer risk in children due to PAH exposure from rubber playground surfaces estimated a ten times higher risk compared to soil surfaces (Tarafdar et al. 2020). No human epidemiology studies on artificial turf or crumb rubber have investigated any endpoints other than cancer.

Future Directions

More Research is Needed

As this review reveals, few studies have investigated the potential health effects of artificial turf exposure using actual samples of artificial turf or its components. All of the studies reported above used crumb rubber, a popular infill material. Crumb rubber is considered to be one of the riskiest components of artificial turf as it is known to contain high levels of PAHs and metals. However, artificial turf contains many additional components that may leach harmful chemicals. Of note, artificial glass fibers have been shown to leach multiple phthalates, which are known reproductive toxicants, and various PFAS have been identified in artificial turf samples (Glüge et al. 2020; Naim 2020; Gomes et al. 2021). Additional studies that incorporate all components of artificial turf are strongly needed.

With the exception of ecotoxicology, the studies discussed in this review have focused on athletic exposure to artificial turf. Children and adults utilize turf fields for recreational purposes with regularity and for long periods of time, resulting in acute and chronic inhalation, dermal, and oral exposures. Although some of these exposure routes have been modeled, future studies should consider all routes of exposure various exposure durations. In addition, epidemiology studies have only investigated cancer in athletes and have been limited in scope. Additional studies are strongly needed to consider associations in young children and other sensitive populations, developmental and reproductive endpoints, and community exposures. Laboratory studies should also consider community exposures through runoff and water and soil contamination. Multiple studies have collected rainwater from turf pitches for measuring chemical leachate from artificial turf, indicating that contaminated runoff is highly likely (Gomes et al. 2021). In addition, the partitioning relationship of organic leachate or emissions from artificial turf into local air, soil, and water has not been studied (Donald et al. 2019).

Research Challenges

The paucity of health and toxicity studies on artificial turf stands in stark contrast to the large body of literature that has identified chemicals in crumb rubber and other artificial turf components and leachate. A major research challenge for future studies is bridging this gap to incorporate knowledge of chemical components to expand toxicity studies beyond crumb rubber. To be most representative, studies should extract exposure samples from artificial turf pieces, both virgin and from existing fields, and collect runoff from fields, for use in *in vitro* and *in vivo* studies, especially in vertebrate models. Chemical mixtures determined from extraction studies and representing leachate may also be useful for determining the most active toxicants and identifying synergistic mixture effects. There is also a wide range of brands and manufacturers of artificial turf, each with their own structure and layers that may include proprietary materials. Studies should incorporate samples from major companies in all markets around the world.

Implications for Risk Assessment

Due to the controversy over artificial turf usage in communities, regulatory agencies at local, state, and national levels have relied heavily on the scant available data. In addition, the NTP, Environmental Protection Agency (EPA), and some state governments have commissioned and performed their own studies. The relevant studies with publicly available data are discussed above. In addition, the EPA has ongoing studies to collect information for risk assessment on synthetic turf playing fields, although only on crumb rubber (Environmental Protection Agency 2019). Due to the paucity of health-focused studies on artificial turf, risk assessors have not been able to make confident recommendations and communities have come to a wide range of conclusions about installation of artificial turf in parks and schools.

Conclusions

In conclusion, few laboratory and epidemiology studies have been performed on the potential health impacts of artificial turf in athletes and communities, despite the abundance of evidence of carcinogens, neurotoxicants, mutagens, and endocrine disruptors in its components. The existing studies have focused exclusively on a single component, crumb rubber infill, neglecting the complexity of the mixture caused by simultaneous exposure to all components. Peer-reviewed studies using I systems, translational animal models, and ecotoxicology models would greatly benefit both risk assessment and consumers as the installation of artificial turf fields is a controversial and ongoing issue in communities and school districts.

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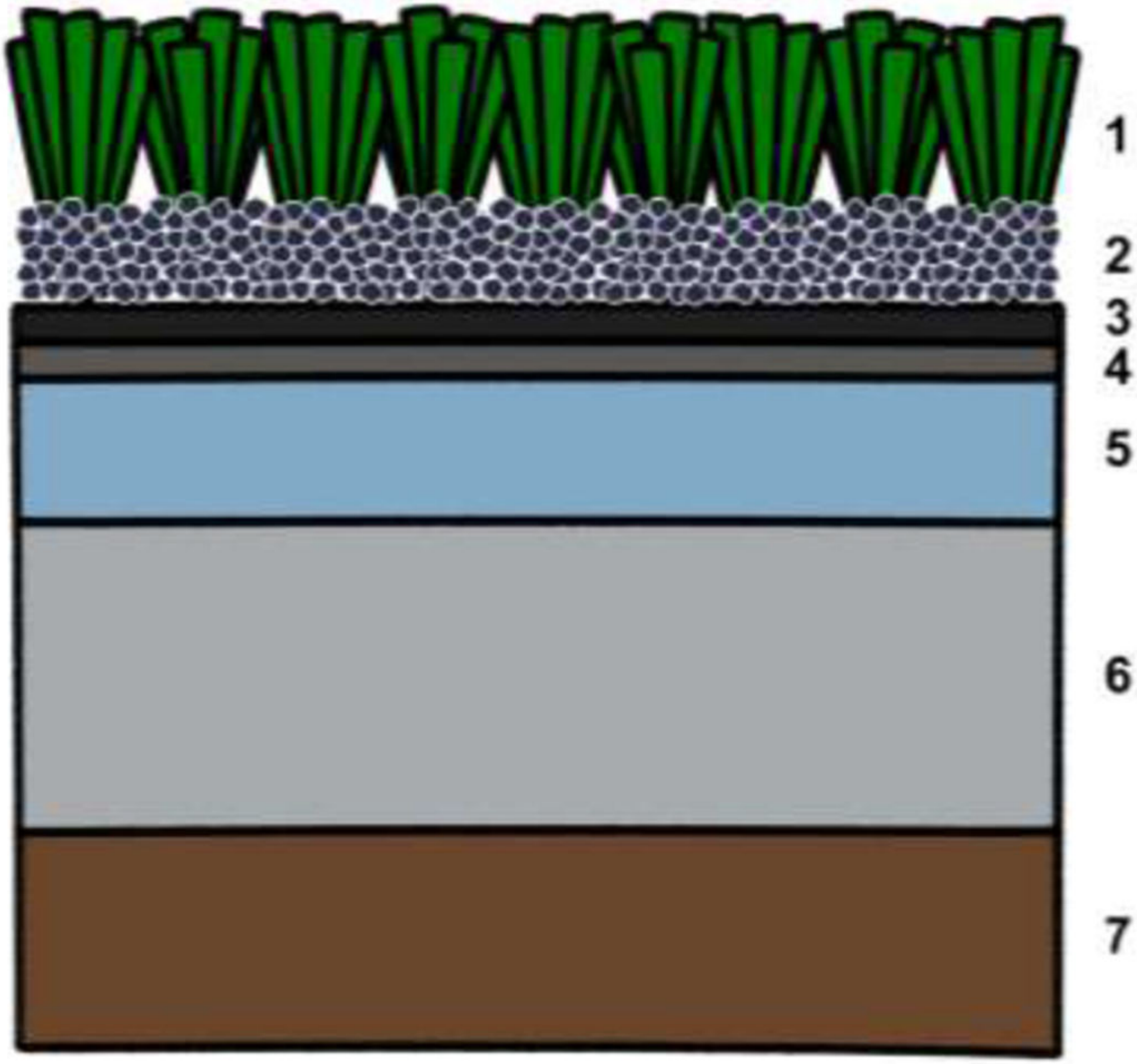

Figure 1: General structure of artificial turf layers.

On the surface, plastic fibers (1) are surrounded by infill, usually crumb rubber (2), at the base. These rest on top of additional layers of synthetic, engineered, and natural materials which may include a plastic carpet (3), an anti-weed barrier (4), a shock absorbing pad (5), crushed concrete (6), and finally natural soil (7).

Table 1:

Chemicals Identified in or Released from Artificial Turf and Its Components*

Class	Individual Chemicals	Class	Individual Chemicals
Polycyclic aromatic hydrocarbons (PAHs)	naphthalene acenaphtalene acenaphthene fluorene phenanthrene anthracene fluoranthene pyrene benzo[a]anthracene chrysene benzo[b]fluoranthene benzo[k]fluoranthene benzo [a]pyrene indeno[1,2,3-cd]perylene dibenzo[a,h]anthracene benzo[g,h,i]perylene	Polychlorinated biphenyls (PCBs)	PCB18 PCB28 PCB31 PCB33 PCB49 PCB52 PCB66 PCB70 PCB74 PCB91 PCB95 PCB99 PCB101 PCB110 PCB118 PCB128 PCB138 PCB141 PCB146 PCB149 PCB151 PCB153 PCB170 PCB174 PCB177 PCB180 PCB183 PCB187
Volatile organic compounds (VOCs)	toluene ethylbenzene propylbenzene iso-propylbenzene m-butylbenzene xylenes p-isopropyltoluene 1,2,4-trimethylbenzene 1,3,5-trimethylbenzene trichloromethane cis-1,2-dichlorthene benzene methyl isobutyl ketone 4-methyl-2-pentanone acetone chloroform chloromethanie methylene chloride carbon tetrachloride aniline cyclohexane methane		
Plasticizers and other semi-volatile organic compounds	benzyl butyl phthalate dibutyl phthalate di(2-ethylhexyl)phthalate diisononyl phthalate dimethyl phthalate diethyl phthalate dicycylohexyl phthalate di(2-ethylhexyl) adipate diisobutyl phthalate dinonyl phthalate dipheylphthalate bisphenol A	Rubber additives and antioxidants	4-t-octylphenol iso-nonylphenol 4-n-nonylphenol benzothiazole 2-hydroxybenzothiazole 2-mercaptobenzothiazole 2-methoxylbenzothiazole 2-aminobenzothiazole n-cyclohexyl-1,3-amine butylhydroxytoluene 4-tert-butylpyridine butylated hydroxyanisole 2-propyl-methyl pentanoic acid methyl 2alpha-D-xylofuranoside 2-ethyltetra-hydrothiopene 4-methyl-4-heptanol 2-butyl tetrathydrothiopene N-N-diethyl-3-methyl benzamide 2-2-7 trimethyl-3-octyne

Class	Individual Chemicals	Class	Individual Chemicals
PFAS	general PFAS content(Naim 2020) perfluorooctanoic acid(Naim 2020) perfluorooctane sulfonate(Naim 2020)	Metals	zinc calcium magnesium aluminum iron barium cobalt copper manganese lead strontium arsenic cadmium mercury nickel chromium berellium lithium selenium barium molybdenum titanium

*Chemicals from the comprehensive review by Gomes (Gomes et al. 2021) unless otherwise cited. Not an exhaustive list of all chemicals measured in artificial turf and crumb rubber.