Crumb Rubber Use in Artificial Athletic Turf

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CRUMB RUBBER USE IN ARTIFICIAL ATHLETIC TURF

Concerns for Public Health

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Introduction

Brooklyn Park

Brooklyn Park, a growing and diversifying suburb of the Twin Cities, offers the community 62 parks with more than 2,000 acres of park land and environmental areas. Of these parks, 30 have athletic fields available to the public, accommodating a wide variety of sports including, football, soccer, cricket, rugby, and lacrosse. These outdoor fields become available in the late spring, and are used heavily throughout the summer into the early autumn season. This heavy usage compacts the soil, degrading its quality, and therefore requires on-going maintenance, as well as the occasional closure of a field for recovery. With their diversifying community, and high usage of their athletic fields, Brooklyn Park's Department of Recreation and Parks is dedicated to the equitable distribution of their park resources, and is seeking to re-evaluate their outdoor fields in order to develop multi-purpose fields that enable multi-season usage and long-term sustainability. In response to this issue, the Department of Recreation and Parks is considering converting two of their athletic fields to synthetic turf. Although, artificial turf is widely utilized, controversy has arisen in recent years over the potential adverse health effects due to exposure to its crumb rubber infill.

Crumb Rubber

Waste Tire Recovery

Each year, the United States produces a large volume of waste tires. In 2013, the U.S. Environmental Protection Agency (EPA) estimated that 4.77 million tons[1] of waste tires had been generated, of which only 40.5% had been recovered through recycling, approximately 1.93 million tons[2]. When tires reach the end of their serviceable life, they may be recycled and reused for beneficial purposes. With waste tire recycling, end-use markets for scrap tires is growing, such that in 2015, 87.9% of scrap tires by weight generated in the U.S. were consumed[3]. The ground rubber applications market alone, which includes playground and sports surfacing, consumed 1,020 thousand tons of scrap tires, accounting for over 25% of the total volume of scrap tires repurposed[3]. Prior to tire recycling, scrap tires were stored in stockpiles, or dumped illegally, posing environmental problems, potential health risks from vector borne diseases, and fire hazards as stockpiles are prone to catastrophic fires[3,4].

Tire Crumb Rubber Manufacturing

Crumb rubber is any material derived from reducing scrap tires or other rubber into uniform granules. During the manufacturing process, the inherent reinforcing materials, such as steel, are removed from the tires, along with any other inert contaminants (dust, glass, rock)[5]. Crumb rubber is manufactured by two tire recycling processes, ambient and cryogenic processing. Ambient grinding takes place in granulation or cracker mills. During the mechanical shredding process, respirable fine particles are generated, but are recovered by air pollution control devices[6]. Cryogenic processing utilizes liquid nitrogen to freeze tire chips below -112 ˚F, causing the rubber to become brittle, allowing size reduction to be accomplished by crushing or breaking[6]. Both processes reduce scrap tires down to sizes ranging from 10-20 mesh (0.84 – 2.0 mm) size particles that can then be used as infill for synthetic turf[1].

Synthetic Turf Fields

Manufacturers emphasize that artificial turf is environmentally friendly as it uses recycled tire rubber. Artificial turf utilizes large amounts of scrap tires with an average soccer field containing approximately 100 tons of crumb rubber[7]. According to the U.S. EPA, as of 2016 there are approximately 12,000 to 13,000 synthetic turf athletic fields in the United States, of which 95% utilize recycled rubber infill, and it is estimated that each year there are nearly 1,200 to 1,500 new installations[1]. Synthetic turf fields are typically constructed by using a gravel or stone base for drainage, and a multi-layered polypropylene and urethane backing material. Attached to the backing material are polyethylene fiber blades, which are placed over the base. For the lower layer of infill, sand or a sand/crumb rubber mix is often used, while the top layer of infill material will consist largely of crumb rubber, natural materials (ground coconut husk), ethylene propylene diene monomer (EPDM), or thermoplastic elastomers (TPE) granules[1].

Benefits of synthetic turf fields with crumb rubber include reduced water use, increased number of playable days per year, and minimum maintenance. It has been estimated that replacing a full-size sports field with artificial turf can result in an annual savings of 0.5 to 1 million gallons of water, and in 2011 it has been claimed that use of artificial turf conserved 5 billion gallons of water in the U.S. alone[7]. Routine maintenance for artificial turf fields includes brushing for infill redistribution, raking or vacuuming for infill de-compaction, and sweeping to remove debris[1].

Chemicals of Concern

In spite of the environmental benefits of artificial turf, there is potential risk to human health due to the contaminants released by the crumb rubber infill. Due to the tire manufacturing process, tires contain a range of chemical vulcanizers, oil-based plasticizers, antioxidants, antiozonants, and fillers in the blend of natural and synthetic rubber[7]. The substances involved in rubber formulation, consisting of chemically reactive and unreactive materials are listed in **Table 1**. During the manufacturing process many of the reactive materials are consumed or transformed into less reactive chemicals, while others become chemically bound into the elastomeric matrix[6]. As a result of these chemical and physical transformations, the finished product contains a very small amount of reactive chemicals, such that very low detection limit analytical techniques are required in order to detect the presence of these chemicals, if possible[6].

Table 1: Chemicals used in Tire Manufacturing[6]

Unreactive Materials	Reactive Materials
Polymer	Silane (coupling agent)
Carbon black (filler)	Reactive resins (adhesion, reinforcement)
Silica (filler)	Accelerators (cross linking)
Oil (plasticizer)	Sulfur (cross linking)
Resins (uncured adhesion)	Stearic acid (activator)
Wax (protection)	Zinc oxide (activator)
Fatty acids, esters, glycol derivatives (processability)	Retarders (cross linking)
	Antioxidants and antiozonants (protection)

During the tire manufacturing process, the rubber is vulcanized resulting in a material with many highly toxic additives and compounds. The hazardous substances identified in crumb rubber infill are primarily heavy metals, volatile organic compounds (VOCs), phthalates, benzothiazoles, and polycyclic aromatic hydrocarbons (PAHs) (**Table 2**)[8]. The zinc in tires is due to zinc oxide used as a vulcanization aid in the rubber production process[8]. However, lead, along with other trace metals are contaminants commonly found in carbon black, which is used as a filler. Nitrosamines are formed during the vulcanization process, while xylene is used as a solvent. PAHs are impurities in aromatic extender oils, and phthalates are plasticizers used to control elasticity of the rubber[6]. Finally, the benzothiazoles used in tire manufacturing are accelerators in the vulcanization process.

Table 2: Contaminants Identified in Crumb Rubber

Volatile Organic Compounds (VOCs)
Nitrosamines
Xylenes
Heavy Metals
Zinc
Lead
Other
Polycyclic Aromatic Hydrocarbons (PAHs)
Benzothiazoles
Phthalates

Though these chemicals are bound within the finished product, environmental breakdown through volatilization and/or leaching under natural conditions is possible, resulting in the release of organic compounds and heavy metals from the rubber matrix[7]. These substances may be released into the air from the crumb rubber, posing potential exposure to the user via inhalation as well as ingestion and skin contact.

These contaminants will have varying concentrations within crumb rubber infill depending on the composition and age of the parent material[9]. As crumb rubber ages and weathers, the concentration of contaminants will decrease due to leaching and off-gassing. Volatile compounds in the vapor phase have been detected in high concentrations over crumb rubber fields, however the concentrations of VOCs have been shown to level off significantly after 2 weeks under natural weathering conditions[7]. Temperature, rain, and irrigation have also been shown to reduce the concentrations of contaminants in crumb rubber. Chemicals such as zinc and PAHs have been widely detected in the leachate from tire rubber[10]. The high temperatures observed in artificial turf athletic fields has been shown to loosen contaminants from the bond within the rubber matrix. Therefore, when high field temperatures are followed by rain or irrigation to reduce the surface temperature, increased leaching will occur[11].

Exposure Assessment

The following provides a review of current literature on studies evaluating the impacts of crumb rubber on human health as associated with oral, inhalation, and dermal exposure to artificial turf or its leached contaminants. Though there are many hazardous substances that have been identified within crumb rubber (see Appendix Table A1), not all chemicals have been evaluated in regards to exposure through crumb rubber, often due to concentration levels found to be below regulatory standards or below the limit of detection. Also, many of the substances have been grouped into categories such as PAHs, and VOCs, rather than investigating one specific chemical. As a result, there are currently many data gaps within the available literature.

Oral Exposure

Oral exposure to crumb rubber or its associated chemicals may occur through the ingestion of crumb rubber (intentional or incidental), and intake of drinking water contaminated by leaching.

The oral ingestion of crumb rubber infill is unlikely to represent a major exposure pathway. Birkholz, et. al. determined oral ingestion to have a low overall hazard based on the unlikelihood of crumb rubber being ingested, and that even if it were to be ingested the gastrointestinal tract is inefficient in extracting toxic chemicals from crumb rubber[12]. Therefore, the chemicals will remain within the rubber matrix and pass through the body without being absorbed. However, consideration of this pathway is necessary given the high usage of artificial turf by children who are more sensitive to chemical exposure.

Lead

Exposure to heavy metals through ingestion is of great concern, especially as one of the main impurities in crumb rubber is lead. Lead is toxic even when only a small amount is present within the human body, with children under the age of 6 being especially susceptible as approximately 40 to 50% of ingested lead is absorbed in their gastrointestinal tract, which is significantly higher than that absorbed in adults (3-10%)[40]. The absorption rate of lead within the body is dependent on two factors, particle size and age of person exposed, such that when the human body is exposed to lead, the smaller the particle size and the younger the age of the exposure group, the higher the absorption rate[13]. Therefore, children are more sensitive to lead toxicity, which may induce damage to the kidney, liver, nerves, and immune system. Low levels of lead in the blood of children has also been shown to result in behavior and learning problems, lower IQ, hyperactivity, slowed growth, hearing problems, and even anemia[21]. Since toxicological effects can occur at low concentrations in children, the U.S. Environmental Protection Agency (EPA) does not publish a reference dose for lead[22]. However, the EPA has set guidance levels for lead concentrations in residential soil at 400 ppm in play areas and 1200 ppm in non-play areas[23]. Also, the Centers for Disease Control and Prevention (CDC) recommends that children's blood lead level not exceed 5 μg/L [23], while the South Korean Ministry of the Environment has set a children's tolerable intake reference dose of 0.001 mg/kg-day[13].

Though there is a possibility of children directly ingesting crumb rubber, recent research has indicated that rubber powder may be unconsciously swallowed from artificial turf during exercise, which is of greater concern due to the higher bioavailability of smaller particles[13]. In order to determine the bioavailability of lead in children due to oral ingestion of crumb rubber powder, Kim et. al. evaluated the human risk level of lead through ingestion through an exposure assessment.

Evaluating exposures to lead in crumb rubber with particle sizes of less than 250 μm representing unconscious ingestion and greater than 250 μm representing conscious ingestion, Kim et al. analyzed the rubber powder of artificial turf filling in three ways: total content, acid extraction and artificial digestive extract methods. Extraction analysis results showed that lead concentration from crumb rubber powder's total content, acid extraction, and digestive fluid for particles below 250 μm was 2.42 mg/kg, 1.40 mg/kg, and 0.53 mg/kg respectively, which were all considerably higher lead concentrations compared to that of the particles above 250 μm[13]. Kim et al. then assessed the extraction analysis by calibrating constant bioavailability, then assessed the exposure by calculating the hazard quotient (i.e. the ratio of the potential exposure to a substance and the level at which no adverse effects are expected. HQ = LADD/RfD where LADD is the lifetime average daily dose (mg/kg/day), and RfD is the reference dose, the maximum acceptable oral dose of a toxic substance) for low elementary, middle and high school students according to particle size. A substance was judged to be hazardous when the hazard quotient exceeded 1, according to the standard suggested by Environmental Health Law[13]. For particle sizes less than 250 μm, the hazard ratio for the digestion extraction was calculated to be 0.260, and 0.081 for the low grade elementary, and middle/high school students respectively. For particles sizes greater than 250 μm, the hazard ratio for the digestion extraction was calculated to be 0.093 and 0.029 for low elementary and middle/high school students respectively. Both the digestion and acid extraction revealed that the hazard quotient was over 2 times more in particle size of 250 μm than in particles greater than 250 μm, thereby concluding that lead ingestion exposure and risk level increases as the particle size of crumb rubber decreases.

A similar study Zhang et. al. evaluated the bioaccessible fractions of metals in synthetic digestive fluids, which included saliva, gastric fluid, and intestinal fluid. Zhang first determined the concentration of lead in crumb rubber. Analysis of lead in artificial turf revealed that there was no clear decay of lead concentration with field age. Concentrations of lead in the crumb rubber samples of three of Zhang's samples were low (5.76, 4.63, and 3.12 ppm), but one sample had a much higher lead concentration of 53.5 ppm, which is below the EPA standard of 400 ppm for residential use[14], but is close to reaching the unrestricted use soil cleanup objective of 63 ppm set by the Department of Environmental Conservation of New York State[24]. Further analysis revealed lead to have a bioaccessibility of 24.7 – 44.2% in the synthetic gastric fluid regardless of the low concentrations found in crumb rubber[14]. However, lead was only bioaccessible in the gastric fluid. There was no bioaccessibility of lead observed in the synthetic saliva or intestinal fluid.

Conclusion

Though concentrations of lead in artificial turf has been detected below EPA soil standards (400ppm), the bioavailability of lead at these low concentrations via oral ingestion is of great concern as particle size decreases, especially in regard to children (below the age of 6) who are more susceptible to lead toxicity harming their neurocognitive development. However, further investigation is required in order to determine whether the micro-scale particles released from crumb rubber during play on artificial turf actually contain lead.

Zinc

Zinc is an essential element to the human diet, as it functions as a component of various enzymes in the maintenance of the structural integrity of proteins and the regulation of gene expression[25]. The recommended dietary allowance for adults has been set at 8 mg/day for women and 11 mg/day for men[25]. Although no adverse effects have been observed from intake of naturally occurring zinc in food, adverse effects have occurred in response with chronic intake of supplemental zinc. Such adverse effects include suppression of immune response, decrease in high-density lipoprotein (HDL) cholesterol, and reduced copper status[25]. Acute adverse effects have also been reported with excess zinc consumption, including epigastric pain, nausea, vomiting, loss of appetite, abdominal cramps, diarrhea, and headaches[25]. Given the potential adverse health effects of excessive zinc ingestion, a tolerable upper intake level (UL) has been established for multiple age groups with children having the lowest UL as seen in **Table 3**. However, according to the California Office of Environmental Health Hazard Assessment (OEHHA) there has been no evidence to suggest children are more sensitive to zinc than adults as they are with lead[20]. The EPA has also derived an oral reference dose (RfD) for zinc, currently set at 0.3 mg/kg/day based on the decrease in erythrocyte superoxide dismutase (a sensitive indicator of body copper status), and changes in serum ferritin[26, 27].

Table 3: Tolerable Upper Intake Level[25]

Age	UL (mg/day)
1-3 years	7
4-8 years	12
9-13 years	23
14-18 years	34
Adult	40

Zinc occurs naturally in small amounts in igneous rocks, and it has been estimated that the natural zinc content of soils ranges from 1 – 300 mg/kg[15]. When within soil at a pH 5 or greater, zinc ions will be strongly adsorbed and are expected to have low mobility in most soils[28]. As to date the EPA has not established a soil concentration limit for zinc. However, the New York State Department of Environmental Conservation (DEC), has set a public health protection limit of 2200 ppm in residential areas and 2480 ppm for ground-water[24].

Due to the high concentrations of zinc consistently observed in crumb rubber, zinc has been selected as one of the metals of concern, particularly in regards to the ingestion exposure pathway, as it is the most likely route for absorption.

While evaluating the bioavailability of metals in artificial turf, Zhang et al. also assessed zinc. For their assessment, Zhang only analyzed two samples of zinc from artificial turf fields. From these samples zinc concentrations were detected at 5710 and 9988 mg/kg, which far exceeds the DEC residential the soil standard of 2200ppm[14]. However, these results are consistent with other studies measuring zinc levels in vehicle tires (Bocca et al.). These high zinc concentrations are due to the use of zinc oxide in the vulcanization process when manufacturing tire rubber. Although Zhang detected high concentrations of zinc in crumb rubber, bioavailability was not determined from these samples. Therefore, further analysis of how much zinc would be released from the crumb rubber and absorbed through the GI tract is necessary in order to better understand the risk of oral exposure.

Leaching of zinc from crumb rubber into groundwater sources has been noted as a possible route for oral exposure. Much of the evaluation of leaching of chemical constituents from crumb rubber into water has focused primarily on the effects on ecological systems, few studies have addressed whether leaching may effect drinking water and therefore pose a risk to human health. The New York State Department of Environmental Conservation (DEC) conducted a study measuring both metals and semi-volatile organic compounds (SVOCs) in crumb rubber, surface water runoff, and groundwater collected in down-gradient wells in sandy soil areas by four existing artificial turf fields, with field ages ranging from less than 1 year to 7 years. The DEC first analyzed the potential for chemical release from crumb rubber, then conducted a water quality survey at existing fields sampling from surface water and groundwater sources. A laboratory leaching test was conducted to determine the potential of chemical release from crumb rubber. Results detected three metals above groundwater standard by utilizing a simulated precipitation leaching procedure (SPLP). Zinc was leached from every crumb rubber sample tested with an average concentration close to the DEC ground water standard (1947 μg/L and 1150 μg/L for the first and second SPLP respectively), revealing the potential of zinc to be released above groundwater standards[16]. For the surface water survey, runoff samples were collected from drainage pipes at existing turf fields during rainfall events, then the concentration of metals and organic compounds were measured. Results from the runoff samples revealed no organics were detected. However, for metals, zinc was detected at 58.5 μg/L which is below the surface water standard of 82.6 μg/L[16]. For the groundwater survey, thirty-two samples were collected. Test results from the groundwater samples were all below the limit of detection. Therefore, it was concluded that metals from crumb rubber infill are not likely to impact drinking water, and present a risk to humans.

Conclusion

Zinc has been shown to be present in crumb rubber in high concentrations, often exceeding DEC soil standards. Rain and field irrigation cause zinc to leach from the artificial turf allowing it to reach surface waters where it might then reach groundwater. However, surface water samples revealed zinc to be below the water standards, while concentrations in groundwater were below the limit of detection. Therefore, leaching of zinc from artificial turf is unlikely to effect the quality of drinking water. However, oral exposure to zinc from direct ingestion of crumb rubber (intentional or incidental) requires further investigation into the bioavailability of zinc when ingested as part of a crumb rubber matrix.

PAHs

Polycyclic aromatic hydrocarbons (PAHs) are a group of semi-volatile chemicals formed during the incomplete combustion of coal, oil, gas, wood, garbage, or other organic substances (i.e. food). Due to the nature of the formation of PAHs, these substances are found throughout the environment in the air, water, and soil. The primary route of exposure to PAHs is by inhalation of compounds in tobacco smoke, wood smoke, and ambient air, as well as the consumption of PAHs in foods[29]. There are more than 100 different PAHs, and they generally occur as complex mixtures rather than as single compounds. Therefore, it is typical for humans to be exposed to a mixture of PAHs rather than an individual PAH.

Although occurrence of PAHs is widespread, information is not available for every substance. Of the PAHs that have been studied, a small portion have been selected as representative PAHs due to their detection at higher concentrations, suspicion of their being more harmful than others, and that they exhibit harmful effects that are representative of PAHs[29]. These representative PAHs have been detected in the air at background levels reported to be 0.02-1.2 ng/m^3 in rural areas, and 0.15-19.3 ng/m^3 in urban areas[29]. In uncontaminated soil, background concentrations of up to 0.1 mg/kg of individual PAHs have been detected[30]. Due to the presence of PAHs in food, such as cereals, grains, flour, bread, vegetables, and fruits that have been grown in contaminated soil or air, and meat that has been cooked at high temperatures from grilling or charring, it has been estimated that the level of PAHs in the typical U.S. diet is less than 2 μg/kg[29].

Adverse health effects have been observed under certain circumstances from exposure to PAHs. Several PAHs have caused tumors in laboratory animals when exposed through oral, inhalation, and dermal routes[29]. The development of cancer has also been observed in human studies in which individuals have been exposed to mixtures containing PAHs for long periods. Based on the studies conducted in animals and in humans, the International Agency for Research on Cancer (IARC) has determined the classification of carcinogenicity of the representative PAHs (see **Table 4**).

Table 4: IARC Carcinogenicity Classification of PAHs[29]

Substance	Classification
Benzo[a]pyrene	Carcinogenic to humans
Benz[a]anthracene	Probably carcinogenic to humans
Benzo[b]fluoranthene	Probably carcinogenic to humans
Benzo[j]fluoranthene	Possibly carcinogenic to humans
Benzo[k]fluoranthene	Possibly carcinogenic to humans
Chrysene	Possibly carcinogenic to humans
Indeno[1,2,3-c,d]pyrene	Possibly carcinogenic to humans
Anthracene	Not classifiable as to their carcinogenicity to humans
Benzo[g,h,i]perylene	Not classifiable as to their carcinogenicity to humans
Benzo[e]pyrene	Not classifiable as to their carcinogenicity to humans
Fluoranthene	Not classifiable as to their carcinogenicity to humans
Fluorene	Not classifiable as to their carcinogenicity to humans
Phenanthrene	Not classifiable as to their carcinogenicity to humans
Pyrene	Not classifiable as to their carcinogenicity to humans

Benzo[a]pyrene, one of the representative PAHs, has been shown to caused reproductive effects in mice fed high levels of this substance during pregnancy[29]. The mice had difficulty reproducing as did their offspring. Birth defects and decreased body weight were also observed in the offspring of these pregnant mice. Animal studies have also shown that PAHs may cause harmful effects on skin, body fluids, and the body's immune system after short- and long-term exposure. These non-cancerous health effects have not been observed in humans, but similar effects may occur.

The U.S. EPA has set regulations to protect people from the possible adverse health effects associated with exposure to PAHs from oral ingestion, or inhalation routes. These EPA exposure limits are listed in **Table 5** for select individual PAHs, suggesting that exposure below these limits is not likely to cause any harmful health effects. The EPA has also set a maximum contaminant level (MCL) for PAHs in drinking water (see **Table 6**). There are currently no MCL standards established by the EPA for soil. However, the New York State DEC has set soil limits for individual PAHs in residential areas ranging from 0.33 to 100 ppm[24].

Table 5: EPA Exposure Limits for Individual PAHs[29]

Substance	Exposure Limit
Anthracene	0.3 mg/kg
Acenaphthene	0.06 mg/kg
Fluoranthene	0.04 mg/kg
Fluorene	0.04 mg/kg
Pyrene	0.03 mg/kg

Table 6: EPA Maximum Contaminant Level for PAH in Drinking Water[31]

Contaminant	Level
Benzo[a]anthracene	0.0001 mg/L
Benzo[a]pyrene, bezo[b]fluoranthene, benzo[k]fluoranthene, chrysene	0.0002 mg/L
Dibenz[a,h]anthracene	0.0003 mg/L
Idenol[1,2,3-c,d]pyrene	0.0004 mg/L

During the tire manufacturing process PAHs are detected as impurities in aromatic extender oils. As a result, many of the representative PAHs have been identified within crumb rubber. Since PAHs are semi-volatile compounds, the PAHs contained within crumb rubber are expected to evaporate into the atmosphere when ambient temperature is high, thereby reducing the concentration. Although concentrations have been shown to vary from field to field due to rapid decay of PAH content, determining the ability of PAHs to be absorbed through the digestive tract from ingestion of crumb rubber is necessary in determining risk of oral exposure.

During Zhang et. al.'s assessment of the bioavailability of hazardous chemicals in artificial turf, they also evaluated the bioaccessible fractions of PAHs. Zhang first analyzed the artificial turf field samples for chemical content of PAHs, determining the limit of detection within each extract. Their results concluded that crumb rubber in newer artificial turf fields contained PAH levels above DEC health-based soil standards for several individual PAHs (see **Table 7**), but that these levels would decline as the field aged[14]. All of the PAHs found to be above the DEC safety limits are known probably or possible human carcinogens according to IARC classification, which raises concern in regards to exposure for children and athletes utilizing artificial turf fields.

Table 7: Concentrations of PAH Samples Exceeding DEC Soil Limit[14]

Substance	DEC Soil Limit	Sample 1	Sample 2	Sample 5
Benzo[a]anthracene	1 ppm	1.23 ppm	1.26 ppm	NA
Benzo[a]pyrene	1 ppm	8.58 ppm	3.56 ppm	NA
Benzo[b]fluoranthene	1 ppm	3.39 ppm	2.19 ppm	1.08 ppm
Benzo[k]fluoranthene	1 ppm	7.29 ppm	1.78 ppm	NA

From their samples, Zhang used three synthetic digestive fluids to simulate bioaccessibility in the human digestive tract (saliva, gastric fluid, and intestinal fluid). The analysis indicated that PAHs contained within crumb rubber had zero bioavailability in the synthetic digestive fluids[14]. This finding was not a surprise as PAHs are non-polar organic compounds that have limited solubility in water-based digestive fluids. However, the primary limitation of Zhang's simulation method must be recognized, as the human digestive tract is far more complex, containing lipids that can enhance absorption of PAHs, as well as interaction of crumb rubber with foods that may increase PAHs bioavailability[14].

Conclusion

Several known potentially carcinogenic PAHs have been identified within crumb rubber at levels exceeding soil standards. It has also been observed that these concentrations decrease as the field ages due to off-gassing and leaching. However, since crumb rubber infill is often replaced as part of routine field maintenance there is continued potential for concentrations of PAHs to surpass soil limits. Although concentrations may remain above set limits, PAHs appear to have no bioavailability when digested within the crumb rubber matrix, and therefore do not pose a health risk to children or athletes through this pathway.

Conclusion on Oral studies

Studies evaluating oral exposure to crumb rubber infill indicate that there is a low risk to human health from zinc, and PAHs through this pathway. However, the high bioavailability of lead in particles less than 250 μm presents a cause for concern due to the potential for these smaller particles being ingested, especially among small children who are more susceptible to lead toxicity and have a greater frequency of hand-to-mouth activity.

Inhalation Exposure

Inhalation exposure may occur from off-gassing from the surfaces of artificial turf fields, as well as from particulate matter. The higher ventilation rate during active play enhances the potential for inhalation exposure, making it a primary pathway of concern.

VOCs

Volatile organic compounds (VOCs) are chemicals that evaporate easily into the air at normal atmospheric conditions of temperature and pressure[33]. The higher the volatility of a compound, the more likely it will be emitted from a product or surface into the air[33]. Therefore, VOCs can come from many different natural and manmade sources, and can enter the human body when we breath, eat or drink, or touch them. VOCs will not remain in the human body for a long time after a single exposure. However, repeated exposures to high levels may cause them to build up in the body[34]. When concentrations of VOCs are high enough, acute exposure may cause adverse health effects such as lung irritation. However, long-term (chronic) exposure to low concentrations of VOCs may also cause adverse health effects by damaging the liver or kidneys[34]. Since VOCs refer to a group of chemicals each substance has its own toxicity and potential for causing different health effects. **Table 8** lists some of the common symptoms of exposure to high levels of VOCs. As most health studies on VOCs have been conducted on single chemicals, less is known about the health effects of exposure to mixtures of chemicals such as are present in the off-gassing of VOCs from crumb rubber infill. Since the toxicity of VOCs varies for each individual chemical there is no state or federal health-based standard for VOCs as a group[35].

Table 8: Common Symptoms of VOC Exposure[35]

Acute/short term exposure (hours to days)	Chronic exposure (years to a lifetime)
Irritation of the eyes, nose and throat	Cancer
Headaches, dizziness	Liver and kidney damage
Nausea/vomiting	Damage to the central nervous system

Though many of the reactive substances used in the formation of tires are bound within the rubber matrix, studies have shown that after tires have been recycled into crumb rubber and reduced to smaller sizes, weathering, especially at high air and field temperatures, will release these substances from the matrix such that PAHs, phthalates, and other volatile organic compounds are able to reach the vapor phase and be inhaled by humans[17]. Therefore, inhalation is a primary route of exposure, and is expected to be the greatest under warm summertime conditions as the components may vaporize into the breathing zone of athletes.

In 2011, Ginsberg et. al, investigated five artificial turf fields (four outdoor, and one indoor) in Connecticut. Each field was investigated under sunny, warm, and low wind weather conditions in order to maximize the potential for detecting off-gassed rubber components. Volunteers played soccer for a 2-hour sampling event at each field, in which each player was equipped with a variety of personal sampling devices attached to the belt to determine what may be in the breathing zone of young children playing on the field. Stationary monitors were also utilized. Soccer was also played on a grass field to serve as a background data source for the personal monitors. Sampling and analysis tested for a wide range of VOC, and semi-volatile organic compounds (SVOCs). Analysis of personal monitoring and stationary samplers indicated that 10

VOCs were considered contaminants of potential concern (COPC) due to the high concentrations above background detections, with personal monitoring results giving the highest VOC detection levels[18]. Given the concentrations of VOCs detected, a risk characterization was conducted to estimate cancer and non-cancer risks due to exposure. Prorated time-weighted average exposures were calculated based on the highest measured analyte concentration, amount of play time, years of exposure, and exercise-induced breathing rate[18]. The assessment of human health risk revealed cancer and non-cancer risk levels were at or below minimal levels of concern (1 in a million) for all scenarios (child outdoor/indoor, adult outdoor/indoor), concluding there was no elevated health risk due to use of artificial turf fields via inhalation routes[18].

The 2006 Norwegian study in Oslo collected samples from three indoor artificial turf fields that use recycled tire crumb rubber. From their samples a total VOC concentration was found to be 716 $\mu g/m^3$ in the first sampling period, and 230 $\mu g/m^3$ for the second. Though the samples vary, both samples measured VOC values higher than are normally found at background levels[19]. Worse case scenarios were then prepared for risk characterization based on the data collected from each field in order to determine the uptake of total VOC by the lungs for each possible scenario (adults, juniors, older children, and children). In addition, VOC risk was determined for speciated VOCs with toxicity criteria for inhalation (toluene, benzene, benzoic acid, xylenes, styrene, formaldehyde, limonene, benzothiazole). Based on the exposures calculated in association with the use of indoor artificial turf fields with crumb rubber, they concluded there was no evidence to indicate use of artificial turf causes elevated health risk to children or adult athletes for short-term exposure (acute poisoning and irritation), since the estimated uptake of VOCs via the lungs was found to be on the order of 1-40 $\mu g/kg$ body weight/day, which is more than 1000 times lower than doses shown to lead to acute poisoning[19].

An air quality monitoring survey was conducted by the New York State Department of Environmental Conservation (NYSDEC) and Department of Health to determine if volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and particulate matter concentrations above the field surface were of public health concern. Samples were collected on summer days when temperatures were above 80 ˚F, and the VOC and SVOC releases would be expected to be higher due to off-gassing. The study was conducted on two synthetic turf fields with differing field age. Many of the analytes detected from the samples are commonly found in the urban environment, and in both fields there was no statistical difference in any VOC or SVOC concentrations from the background levels[16]. Cancer and non-cancer endpoints were evaluated, using hazard quotients. From their assessment it was determined that off-gassing from crumb rubber does not pose a health risk since the hazard quotients for all detected chemicals were significantly lower than 1.

Conclusion

Due to off-gassing from crumb rubber, VOCs have been detected at various concentrations above artificial turf fields within the breathing zone of athletes, revealing that there is potential for inhalation exposure. Although the concentrations range from low (similar to background levels), to high, further assessment of acute and chronic health outcomes due to exposure at the observed levels revealed that there was no elevated health risk due to inhalation of VOCs from crumb rubber, and therefore does not pose a health risk to children or athletes through this pathway.

Particulate Matter

Particulate matter (PM), is a term used to describe a mixture of solid particles and liquid droplets found in the air[36]. These particles include large substances, such as dust, dirt, soot or smoke that are visible, as well as small substances that can only be detected by special equipment. PM is a complex mixture of solid inorganic and semi-volatile organic chemicals, and aqueous materials and is found in a range of sizes[6]. The two size ranges of respirable concern are PM_{10} and $PM_{2.5}$. PM_{10} includes inhalable particles with diameters that are 10 micrometers (μm) and smaller, while $PM_{2.5}$ encompasses the fine inhalable particles with diameters that are 2.5 (μm) and smaller[36]. Due to the microscopic sizes of PM, the inhalation of these particles may cause serious health problems as they may deposit deep into the lungs. The U.S. EPA has established air quality standards for PM_{10} and $PM_{2.5}$ that are protective of human health, including sensitive populations such as asthmatics, children, and the elderly. The National air-quality standards for PM were first established in 1971, but have been revised multiple times throughout the years. Currently, the daily standard for PM_{10} and $PM_{2.5}$ is set at 150 $\mu g/m^3$ and 35 $\mu g/m^3$ respectively[37]. The annual standard for $PM_{2.5}$ is set at 12 $\mu g/m^3$, however the annual standard for PM_{10} was revoked in 2006 due to lack of evidence linking long-term exposure to PM_{10} to health problems[37].

Ambient particulate matter is generated in all indoor and outdoor environments from a variety of sources. The levels of particulate matter in the air in these environments will be influenced by the amount of air dispersion, ventilation, the rate of particle release, suspension as well as the physical configuration of the area[6]. Therefore, the inhalation of particulate matter from crumb rubber has been introduced as a potential concern as running may break down the crumb rubber, emitting particles into the air just above the field. However, two characteristics of crumb rubber limit the magnitude of fine particles or airborne dust that may be released. First, during waste tire recycling, fiber and dust is removed by air pollution control devices or other equipment[6]. Second, it is unlikely that foot traffic on an artificial athletic turf field will generate appreciable quantities of new particles since it would require a high amount of energy to generate small respirable particles[6]. However, it remains unknown to what degree coarse and fine particles are removed in the tire recycling process. Therefore, it is essential to assess the potential exposure of particulate matter during field use.

The air quality monitoring survey conducted by NYSDEC also measured particulate matter in ambient air in two athletic fields. Particulate matter concentrations were obtained for $PM_{2.5}$ and PM_{10}. Samples were collected during field use, and monitoring was conducted three feet from the ground. Air samples were collected in order to understand the size distribution of particles associated with crumb rubber infill. Particle analysis for the samples revealed a bi-modal distribution, such that both very large (mm size) and very small particles (micrometer size) were observed. The composition of the large particles consisted of rubber, grass, and cord material, while the very small particles were composed of primarily crustal minerals and biologicals (e.g. pollen or mold)[16]. Crumb rubber dust was not found in the respirable range from the air samples, thereby suggesting that particulate matter from ground rubber is unlikely to be respirable, and therefore does not pose as a health risk to children or athletes. However, this study only evaluated two fields and did not take into consideration contributing factors such as field age or the condition of the field. In addition, this study only characterized the size distribution of particulate matter in artificial turf fields, and therefore the data may not be representative.

The State of California also conducted a safety study on artificial turf measuring particulate matter above athletic fields with crumb rubber infill. Three outdoor athletic fields made of new generation turf containing crumb rubber infill were analyzed to determine if they release significant amounts of airborne $PM_{2.5}$. The air above these fields was sampled for three-hour intervals during periods of active field use (soccer games and practices). Ambient air upwind of the fields was analyzed as a background level comparison. For two of the fields, $PM_{2.5}$ was not detectable after 3 hours of sampling, while at the third field results from sampling revealed that $PM_{2.5}$ levels were consistent with nearby background concentrations (12 to 18 $\mu g/m^3$)[38]. These data indicate that crumb rubber infill is not a significant source of airborne $PM_{2.5}$.

Conclusion

The release of particulate matter from crumb rubber during use of athletic fields is unlikely to pose a human health risk based on the available data, as crumb rubber dust was not detected in the air samples, and the $PM_{2.5}$ that was detected was consistent with background levels. This may be attributed to the high ventilation of outdoor athletic fields, as well as the wash-off of particulate matter by precipitation or irrigation.

Conclusion on Inhalation Studies

Collectively, studies evaluating relevant endpoints for inhalation exposure for children and adult athletes indicate that there is low risk of adverse health affects associated with use of crumb rubber in artificial turf fields from inhalation exposure routes for both VOCs and particulate matter.

Dermal Exposure

Exposure to crumb rubber through dermal contact may occur through the use of crumb rubber in artificial turf fields from athletes sliding or running on the field. Concerns have arisen over the skin contact with artificial turf fields causing skin sensitization along with questions over whether absorption of constituents of crumb rubber through the skin is a potential mechanism of toxicity.

PAHs

As discussed previously, PAHs occur as complex mixtures rather than as single compounds. Therefore, humans are more likely to be exposed to a mixture of PAHs rather than an individual substance. Although there have been over 100 different PAHs identified, only a handful have been assessed and characterized for adverse health effects. Recently, there has been a growing awareness that the absorption of PAHs via the skin can be very substantial, and that dermal exposure may not only result in local effects but also systemic effects[8]. However, there are currently no regulations or exposure limits established for dermal exposure to PAHs. In addition, there have been no acute, intermediate, or chronic duration Minimal Risk Levels (MRLs) derived for PAHs due to the lack of appropriate methodology for the development of dermal MRLs[29].

In response to the growing concern of dermal exposure to PAHs and potential health effects, Van Rooij and Jongeneelen evaluated the uptake of PAH by soccer players after playing on artificial turf with crumb rubber infill. Urine of the athletes was collected over a three-day period; the day before, the day of, and the day after sporting. The urine samples were analyzed for 1-hydroxypyrene, a widely used quantitative biomarker (biological indicator of exposure) for PAHs that reflects both absorbed dose and body burden. After the 2.5-hour period of training and match on the field, urine samples did not reveal an increase in PAH, concluding that uptake of PAH for athletes on artificial turf with crumb rubber infill is minimal[8]. If there is any dermal exposure, then the uptake is very limited and within the range of uptake of PAHs from background sources (i.e. environment, and/or diet).

Conclusion

The absorption of PAHs through the skin is unlikely to result in any adverse health outcomes based on the available data. However, there have been very few studies conducted analyzing biomarkers of PAHs in the urine of athletes and children active on artificial turf fields. Therefore, results may not be substantiated.

Sensitization

Some of the chemicals used during the tire manufacturing process are believed to induce allergic contact dermatitis, as dermatitis has been demonstrated in employees working in tire manufacturing facilities[6]. Therefore, it is a reasonable assumption that there may be potential for allergenic response via dermal contact to crumb rubber in artificial turf for children and athletes.

A skin sensitization study was conducted by the California OEHHA. With guinea pigs as their test animal, three materials used in crumb rubber playground surfaces were tested: loose crumb rubber from recycled tires, tiles molded from tire shreds mixed with binder, and tiles molded from particles of the synthetic rubber EPDM mixed with a binder. Following the challenge exposure, the animals in the positive control group failed to exhibit skin sensitization reactions[20]. Also, no animals from the other groups showed a positive skin reaction following any of the three induction doses. Therefore, all animals were re-challenged seven days later. After the re-challenge exposure, five of ten animals in the positive control group showed positive skin reactions at 24 hours after re-challenge, with four of ten also exhibiting positive skin reactions at 48 hours[20]. However, none of the crumb rubber treatment groups contained any animal with a positive allergic response. The data therefore suggests that playground surfaces made of recycled tires are not a skin sensitization risk to children or athletes.

Conclusion

Dermal contact with crumb rubber is unlikely to induce skin sensitization in children or athletes based on the available data.

Conclusion on Dermal Studies

Results from dermal studies conclude that skin sensitization and chemical absorbing through the skin is unlikely to be of concern. This may be due to the unlikelihood of crumb rubber adhering to the skin, as prolonged contact is required for uptake to occur through the skin. Therefore, the skin provides a sufficient barrier to any hazardous chemicals present in crumb rubber.

Other Relevant Studies

Genotoxicity

Birkholz et. al. conducted a hazard assessment of the toxicological effects of crumb rubber choosing cancer as the outcome of greatest concern as it is associated with low-level exposures to the chemicals most likely to be released from crumb rubber. In order to determine whether ingestion of a small amount of crumb rubber poses a cancer hazard to small children with respect to low-level chemical exposure, Birkholz et. al. measured genotoxicity via relevant *in vitro* predictive assays. Exhaustive extraction of crumb rubber was performed with dichloromethane, omni solvent grade. The obtained extracts were then tested for acute lethality using genotoxicity testing with and without S9 (liver homogenate) activation in the following systems: *Salmonella typhimurium* mutagenicity fluctuation assay (TA98, TA100, TA1535, and TA1537), SOS chromotest, and Mutatox[12]. Results indicated that there was no DNA or chromosome-damaging chemicals present in the crumb rubber extract, suggesting ingestion of small amounts by children will not result in development of cancer. Furthermore, Birkholz et. al. concluded that there was little potential for an exposure sufficient to cause adverse health effects in children. Though Birkholz's study revealed crumb rubber poses minimal hazard to children in regards to genotoxic carcinogenicity, Birkholz failed to identify the chemical components of the extract obtained from their samples or test for non-genotoxic carcinogens.

In 2015, Dorsey et al. evaluated the mutagenic potential of crumb rubber from artificial turf at increased temperatures. Crumb rubber infill was collected directly from the surfaces of four artificial turf fields with varying ages (nine, four, two, and less than one). Leachates were then made from these samples at a range of temperatures in order to determine whether increase in field temperature may play a role in the release of mutagenic compounds from the infill. To mimic field conditions or rain or irrigation, leachates were made using distilled water. Samples were then assayed for mutagenic potential with fluctuation tests using *Salmonella typimurium* TA100 cells. Results from each of these fields indicated that leachates obtained in water 70 ˚C had significant mutagenic potential ($p \leq 0.001$)[32]. However, leachates obtained in water 40 ˚C showed no mutagenic potential. These results suggest that when the surface of artificial turf fields reaches high temperatures, crumb rubber is capable of releasing water soluble substances with mutagenic potential in bacteria. However, further investigation is required in order to determine if leachates obtained from crumb rubber at high temperatures has mutagenic potential in human cells.

Conclusion

Although leachates from crumb rubber infill do not have mutagenic/genotoxic potential when tested at low temperatures, at high temperatures there is a significant increase in mutagenic potential. Therefore, there may be greater potential for exposure to mutagenic substances when playing on an artificial turf field on a hot day. However, these mutagenic substances were only tested in leachates in a simulation of rain and irrigation runoff, not in relation to any human exposure pathway (ingestion, inhalation, dermal). Therefore, there is greater risk of exposure to aquatic environments, while data on human exposure remains unknown.

Conclusion

Based on available data, there is a low likelihood of adverse health effects for children and athletes exposed to crumb rubber infill in artificial turf fields. Studies on dermal exposure have shown absorption of PAHs through the skin is unlikely, as absorption would require prolonged skin contact, which does not occur during normal use of athletic fields. Dermal studies also revealed skin contact with crumb rubber will not induce skin sensitization and therefore is not a risk to children or athletes. Studies evaluating inhalation exposure to VOCs observed various concentrations of VOCs in the air above the field, with a few VOCs exceeding background level concentrations. Although some VOC concentrations were much higher on artificial turf fields, assessment of acute and chronic health outcomes for these concentrations revealed that there was no elevated risk. Therefore, inhalation exposure to VOCs while playing on artificial turf fields with crumb rubber infill does not pose a health risk. Inhalation studies assessing exposure to particulate matter during field use showed that crumb rubber did not produce respirable particles, and therefore does not contribute to airborne PM.

Bioavailability has been evaluated for several crumb rubber contaminants in order to determine oral exposure. Studies have shown that PAHs are not bioavailable when ingested, and therefore is not a health risk. Zinc has been detected at high levels often exceeding soil standard limits. However, bioavailability has not been determined for zinc in crumb rubber, therefore the potential health risk for direct ingestion of crumb rubber granules remains unknown. Studies on the bioavailability of lead in crumb rubber revealed that ingestion exposure increases as particle size decreases, and that even at very low concentrations the bioavailability of lead in crumb rubber ranges from 24.7 to 44.2%, and is therefore a potential health concern for children under the age of 6, who are more susceptible to the adverse effects of lead, and are more likely to display hand-to-mouth behavior. There also appears to be some potential for the release of mutagenic substances from crumb rubber during hot days. However, mutagenic potential has not been assessed in relation to a particular exposure pathway, therefore the feasibility of mutagenicity within humans remains unknown.

This review has assessed the most well documented and studied components of crumb rubber. Although the literature on the safety of crumb rubber use is thorough, addressing potential health concerns for every possible exposure pathway, there remains some uncertainty as toxicity and bioavailability data is not available for every substance detected in crumb rubber. Due to the large volume of chemicals associated with recycled tires, a complete toxicological profile for each substance is beyond the scope of this review.

Recommendation

If the Department of Recreation and Parks for Brooklyn Park determines that it is financially feasible and beneficial to upgrade their athletic fields, I recommend the use of artificial turf containing crumb rubber. This advice is based on the evaluation that there is a very low level of concern from exposure to substances found in crumb rubber infill, as the current literature does not provide a compelling reason to advise people against playing on artificial turf fields.

Appendix

Table A1: Hazardous Substances Detected in Crumb Rubber

Compound	CAS	Av. Concentration	Source
PAHs			
Naphthalene	91-20-3	1.93 $\mu g/g$	Llompart et al.
Acenaphthylene	208-96-8	1.37 $\mu g/g$	Llompart et al.
Acenaphthene	83-32-9	1.75 $\mu g/g$	Llompart et al.
Fluorene	86-73-7	3.98 $\mu g/g$	Llompart et al.
Phenanthrene	85-01-8	2.31 $\mu g/g$	Llompart et al.
Anthracene	120-12-7	1.80 $\mu g/g$	Llompart et al.
Fluoranthene	206-44-0	1.83 $\mu g/g$	Llompart et al.
Pyrene	129-00-0	7.73 $\mu g/g$	Llompart et al.
Benz[a]anthracene	56-55-3	0.95 $\mu g/g$	Llompart et al.
Chrysene	218-01-9	1.88 $\mu g/g$	Llompart et al.
Benzo[b]fluoranthene	205-99-2	2.82 $\mu g/g$	Llompart et al.
Benzo[k]fluoranthene	207-08-9	0.83 $\mu g/g$	Llompart et al.
Benzo[a]pyrene	50-32-8	2.23 $\mu g/g$	Llompart et al.
Indeno[1,2,3-cd]pyrene	193-39-5	1.37 $\mu g/g$	Llompart et al.
Dibenz[a,h]anthracene	53-70-3	0.97 $\mu g/g$	Llompart et al.
Benzo[ghi]perylene	191-24-2	4.94 $\mu g/g$	Llompart et al.
Vulcanisation additives, antioxidants and plasticizers			
Benzothiazole	95-16-9	9.60 $\mu g/g$	Llompart et al.
4-tert-butylphenol	98-54-4	0.43 $\mu g/g$	Llompart et al.
2-Mercaptobenzothiazole	149-30-4	195 $\mu g/g$	Llompart et al.
Butylated hydroxytoluene	128-37-0	7.08 $\mu g/g$	Llompart et al.
Diethyl phthalate	84-66-2	0.41 $\mu g/g$	Llompart et al.
Diisobutyl phthalate	84-69-5	0.97 $\mu g/g$	Llompart et al.
Dibutyl phthalate	84-74-2	0.59 $\mu g/g$	Llompart et al.
Di(2-ethylhexyl)phthalate	117-81-7	20.0 $\mu g/g$	Llompart et al.
Diisononyl phthalate	28553-12-0	5415 $\mu g/g$	Llompart et al.
Disodecyl phthalate	26761-40-0	1284 $\mu g/g$	Llompart et al.
Heavy Metals			
Aluminum		755 mg/kg	Bocca et al.
Arsenic		0.24 mg/kg	Bocca et al.
Barium		22 mg/kg	Bocca et al.
Berylliium		0.04 mg/kg	Bocca et al.
Cadmium		0.37 mg/kg	Bocca et al.
Cobalt		15 mg/kg	Bocca et al.
Chromium		6.2 mg/kg	Bocca et al.
Copper		12 mg/kg	Bocca et al.
Iron		305 mg/kg	Bocca et al.
Mercury		0.07 mg/kg	Bocca et al.
Lithium		1.5 mg/kg	Bocca et al.

Magnesium		456 mg/kg	Bocca et al.
Manganese		5.2 mg/kg	Bocca et al.
Molybdenum		0.2 mg/kg	Bocca et al.
Nickel		2.0 mg/kg	Bocca et al.
Lead		22 mg/kg	Bocca et al.
Rubidium		1.7 mg/kg	Bocca et al.
Antimony		1.1 mg/kg	Bocca et al.
Selenium		<0.3 mg/kg	Bocca et al.
Tin		1.2 mg/kg	Bocca et al.
Strontium		12 mg/kg	Bocca et al.
Thallium		0.06 mg/kg	Bocca et al.
Vanadium		2.2 mg/kg	Bocca et al.
Tungsten		0.13 mg/kg	Bocca et al.
Zinc		10,229 mg/kg	Bocca et al.

Glossary of Terms

Acute: occurring over a short time

Ambient: surrounding

Analyte: a substance whose chemical constituents are being identified and measured

Background Level: an average or expected amount of a substance in a specific environment, or typical amounts of substances that occur naturally in an environment

Bioavailability: the proportion of a substance that enters the circulation when introduced into the body and so is able to have an active effect

Biomarker: a measurable substance in an organism whose presence is indicative of some phenomenon such as environmental exposure

Chronic: occurring over a long time

Detection Limit: the lowest concentration of a chemical that can reliably be distinguished from a zero concentration

Genotoxicity: a destructive effect on a cell's genetic material (DNA, RNA) affecting its integrity

Hazard: something that can cause harm. A source of potential harm from past, current, or future exposures

Hazard Quotient: the ratio of the potential exposure to a substance and the level at which no adverse effects are expected. If the HQ is calculated to be less than 1, then no adverse health effects are expected as a result of exposure

LADD: lifetime average daily dose; a calculated value used to estimate potential lifetime exposure.

LADD = (contaminant concentration)(intake rate)(exposure duration)/(bodyweight)(average lifetime)

Leachate: water that has percolated through a solid and leached out of some of the constituents

Maximum Contaminant Level: standards that are set by the U.S. EPA for drinking water quality. An MCL is the legal threshold limit on the amount of a substance that is allowed in public water systems under the Safe Drinking Water Act

Minimal Risk Level: an ATSDR estimate of daily human exposure to a hazardous substance at or below which that substance is unlikely to pose a measurable risk of harmful (adverse), noncancerous effects. MRLs are calculated for a route of exposure (inhalation or oral) over a specified time period (acute, intermediate, or chronic). MRLs should not be used as predictors of harmful (adverse) health effects

Mutagen: a substance that causes mutations (genetic damage)

Reference Dose (RfD): an EPA estimate, with uncertainty or safety factors built in, of the daily lifetime dose of a substance that is unlikely to cause harm in humans

Respirable: the fraction of inhaled particles capable of passing beyond the larynx and ciliated airways during inhalation. Particles under 10 microns in diameter

Risk: the probability that any ***hazard*** will actually cause injury or harm

Route of Exposure: the way people come into contact with a hazardous substance. Three routes of exposure are breathing (inhalation), eating or drinking (ingestion) or contact with the skin (dermal contact)

Surface Water: water on the surface of the earth, such as in lakes, rivers, streams, ponds and springs

Systemic Effects: effecting the whole body, or at least multiple organ systems

Volatile Organic Compounds: organic compounds that evaporate readily into the air

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