Review of the Human Health & Ecological Safety of Exposure to Recycled Tire Rubber found at Playgrounds and Synthetic Turf Fields

Prepared for:
Rubber Manufacturers Association
Washington, DC

Prepared by:
Cardno ChemRisk
Pittsburgh, PA

August 1, 2013

Executive Summary

Increasingly, tires that reach the end of their serviceable life are processed for beneficial reuse in novel applications. Some of these include soil and surface amendments at athletic fields, playground and garden mulch, and bound surfaces at playgrounds and athletic facilities. These modern artificial surfaces reduce the likelihood of personal injury, provide uniform recreational playing surfaces, promote energy conservation, eliminate pesticide and fertilizer usage, and support waste recycling. Tires are manufactured with a variety of materials and additives to ensure optimum product safety, reliability and performance. Some tire ingredients are considered to be human health hazards at exposure levels several orders of magnitude greater than possible from contact with finished consumer products. Accordingly, athletes, parents and other stakeholders have expressed questions and concerns about the potential for adverse human health or ecological effects from the use of recycled tires in sport surface or playground materials.

The purpose of this report is to evaluate the health and ecological risks associated with the use of recycled tire rubber in consumer applications, particularly playgrounds and athletic fields. In doing so, a thorough review of available literature was conducted including studies from both advocates and opponents to the use of recycled tire materials.

An examination of the weight of evidence across all of the available studies was conducted to enable a comprehensive assessment of potential risk. As is true of all such studies, uncertainties and limitations to the health assessments that have been completed to date are recognized. However even recognizing such limitations, a review of available studies concludes that adverse health effects are not likely for children or athletes exposed to recycled tire materials found at playgrounds or athletic fields (Table 1). Similarly, no adverse ecological or environmental outcomes from field leachate are likely.

The reviewed studies considered the quantitative and qualitative aspects of exposure to classes of chemicals most likely to be inhaled, ingested or directly contacted during athletic or recreational use. While some of the ingredients used in tire manufacturing are considered potentially hazardous to human health at high doses, the potential for athlete or child exposure to these chemicals is very low. During tire manufacturing, tires are subjected to high temperature and pressure for a specified period. In this process the raw materials undergo multiple physical transformations and chemical reactions that change the initial mix from a plastic compound into an elastic rubber composite. The materials present in this composite are permanently linked, either chemically or physically. The process is designed so the release of chemicals into the environment is inhibited. Studies which assessed exposure from breathing in indoor sporting environments where tire materials are used did not find appreciable adverse health effects. The same conclusion is applicable to outdoor settings, where particulate and gaseous phase air concentrations are expected to be 10 to 100 times lower, due to air dispersion and turbulence.

Uncertainties in the existing literature have been cited as areas of concern, resulting in confusion regarding the safety of recycled tire products, especially for children or other sensitive individuals. While these uncertainties, such as the lack of a temperature-emission rate relationship for outdoor ground rubber field installations or the lack of an extensive peer

reviewed toxicology database for some compounds released from ground rubber from recycled tires, represent data gaps, the weight of the evidence indicates that these data gaps are not urgent or short term data needs. Although unique or significant health risks are unlikely from use of recycled tires in sports or playing fields, research to affirm the continued safety of these products is planned and ongoing.

Based on a review of the currently available data, there is one reasonable long term research goals: assessment of fine particulate exposure at indoor and outdoor fields. Completion of this goal is not considered to be a short term or urgent data need, but would be useful in enhancing the quality of risk communication regarding play surfaces that use recycled tires. Of the exposure pathways and chemicals reviewed in this report, inhalation of respirable fine particulates, particularly at indoor fields, was identified as a candidate for additional characterization. Although ground rubber used in playing fields are typically 1-mm or larger in diameter, they were identified in one study as an appreciable fraction of the respirable fine particulate matter ($PM_{2.5}$) using a tracer molecule. Fine particulate load is expected to be low for most applications due to the processing and washing of the product which occurs during recycling. However, since adverse health outcomes are associated with fine particles, further characterization of $PM_{2.5}$ in the raw material, as well as at indoor and outdoor fields, using a reliable tracer is recommended as a long term research objective. Although on-field outdoor $PM_{2.5}$ levels and composition are not likely to differ from local background levels or pose a health risk, as suggested by the preliminary studies by the NYDEC, additional assessment of these levels is important for risk communication given the scientific consensus on adverse health outcomes associated with fine particles. If indoor spaces adhere to building codes and best practices defined by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), no adverse health concern is expected due to $PM_{2.5}$ levels.

Concerns have been expressed about ecological toxicity from zinc and the possibility of natural rubber allergy. Zinc is ubiquitous in the urban environment, and zinc compounds leaching from artificial turf fields are not likely to pose unacceptable ecological risk. Surface water samples may easily be collected to address this issue if there are specific concerns about sensitive local species. Surface water sampling, effluent monitoring and lysimeter tests suggest that zinc in field leachate is unlikely to result in exceedance of aquatic toxicity criteria particularly when a sand or mineral underlayment system is used. The existing literature indicates that natural rubber sensitization or adverse allergic reactions are not likely from recycled tire materials, since liquid latex is not used in making tires. Tires are made from natural rubber in bale form, which does not contain the same level of active proteins which may trigger allergenic responses, as found in liquid latex.

In conclusion:

- The health and ecological risks associated with the use of ground rubber in consumer applications, particularly playgrounds and athletic fields, were evaluated through a thorough review of the literature;
- This review included studies from both advocates and opponents to the use of ground rubber;
- No adverse human health or ecological health effects are likely to result from these beneficial reuses of tire materials; and

- While these conclusions are supported by existing studies or screening risk assessments, additional research would provide useful supplemental and/or confirmatory data regarding the safety of recycled tire products and enhance the weight of evidence used in risk communication.

Table 1: Summary of Selected Human Health Assessments of Recycled Tire Rubber

Scenario	Classes of chemicals considered	Routes considered: Oral Ingestion or Hand-to-mouth transfer	Routes considered: Inhalation	Routes considered: Dermal	Study Conclusions	Study Year and Citation
Outdoor child playground usage	Metals, PAHs, VOCs, allergen	Literature data; simulated gastric digestion; wipe sampling of tile	--	Allergic skin sensitization based on standard guinea pig model	Acute ingestion of shreds unlikely to produce health effects; low chronic risk for hand-to-surface-to-mouth transfer; skin sensitization or reaction unlikely.	United States 2007[1]
Indoor professional athlete use of artificial turf	PAHs	Literature review	Literature Review	Leaching studies; urine biomarker	No significant health risk for professional athletes; sufficient indoor ventilation recommended to control fine dust.	Nether-lands 2007[2]
Artificial turf use	Nitrosamines	--	Air quality sampling and headspace analysis	--	Small quantities of nitrosamines emitted but not detectable in air; nitrosamine related health effects not likely.	Nether-lands 2007[3]
Indoor artificial turf installation and amateur/ professional athletic use	VOCs formaldehyde	--	Emission chamber test results paired with model small indoor gymnasium	--	Worst case indoor VOC and aldehyde concentrations do not pose a health concern for adult or child athletes; during field installation, an air exchange rate of at least 2 per hour is recommended for protection of worker health.	France 2007[4]
Indoor adult and child use of artificial turf	PAHs, PCBs, VOCs, phthalates, alkyl phenols	Ground rubber phthalate and alkyl phenol content	Indoor air quality sampling of gaseous and particulate phase compounds	Leaching studies	Chemical substances are released in very low quantities; based on worst case assumptions, use of artificial turf halls does not pose elevated risk; more information needed on natural rubber allergens.	Norway 2006[5]
Child use of public playgrounds	Organic extract of tire rubber	Genotoxicity testing			Extracts were not genotoxic and exposure potential in children deemed minimal; tire rubber at playgrounds does not pose a health hazard to children.	Canada 2003[6]
Outdoor use of artificial turf fields	VOCs, SVOCs, metals, PM	--	Measurement of VOCs and PM above field	--	Concentrations of VOCs and PM above field did not exceed background, even with high field temperatures; Not likely to pose risk from inhalation	United States, 2009, 2010 [7, 8]

1.0 INTRODUCTION

A portion of tires that have reached the end of their serviceable life are processed for beneficial reuse in athletic fields, playgrounds, and gardens. These include loose 1 to 3-mm particles used as soil and surface amendments, larger shreds for use as garden mulch, and bound surfaces at playgrounds and athletic fields. These modern artificial surfaces reduce the likelihood of personal injury, provide uniform recreational playing surfaces, promote energy conservation, eliminate pesticide and fertilizer usage and support waste recycling. Tires are manufactured with a variety of materials and additives to ensure optimum product safety, reliability and performance. Some tire ingredients are considered occupational hazards at high exposure levels. Accordingly, athletes, parents and other stakeholders have expressed questions and concerns about the potential for adverse human health or ecological effects from the use of recycled tires in sport surface or playground materials.

The purpose of this report is to evaluate the health and ecological risks associated with the use of ground rubber[1] from recycled tires in consumer applications, particularly playgrounds and athletic fields. In doing so, a thorough review of available literature was conducted including studies from both advocates and opponents to the use of recycled tire materials.

This report discusses the findings and limitations of key human health and ecological studies of ground rubber from recycled tires that have been completed to date. However even recognizing the limitations, the review of available studies concludes that adverse health effects are not likely for children or athletes exposed to recycled tire materials found at playgrounds or athletic fields (Table 1). Similarly, no adverse ecological or environmental outcomes from field leachate are likely.

The reviewed studies considered the quantitative and qualitative aspects of exposure to classes of chemicals most likely to be inhaled, ingested or directly contacted during athletic or recreational use. While some of the ingredients used in tire manufacturing are considered potentially hazardous to human health at high doses, the potential for athlete or child exposure to these chemicals is very low. Tires are heated during manufacturing to generate physical and chemical reactions which bind the individual chemicals together such that they are inhibited from release into the environment.

Various stakeholders have identified uncertainties in the existing literature as areas of concern, resulting in confusion regarding the safety of recycled tire products, especially for children or other sensitive individuals. While these uncertainties, such as the lack of a temperature-emission rate relationship for outdoor ground rubber field installations and the lack of an extensive peer reviewed toxicology database for some compounds from ground rubber from recycled tires represent data gaps, the weight of the evidence indicates that these data gaps are not urgent or short term data needs. Although unique or significant health risks are not likely from use of recycled tires in sports or playing fields, research to affirm the continued safety of these products is planned and ongoing, and may enable better communications on this topic.

---

[1] While synthetically produced ground rubber is available, for the purposes of this report, unless otherwise noted, reference to ground rubber implies ground rubber derived from recycled tires.

2.0 DISPOSAL AND RECYCLING OF TIRES

The focus of this report is the use of ground rubber from ground scrap tires in sports field, running track and playground applications.[9] A number of methods are used to dispose of the tires discarded in the United States each year including recycling approximately 75% of the total disposed into useful products such as tire derived fuel (TDF), tire derived aggregate for civil engineering applications, infill for artificial turfs and as a cushioning ground cover in playgrounds.[10-12] Landfilling and tire piles have been discouraged by state and federal agencies because landfill caps can be compromised by tires rising to the surface and tire piles pose pest and fire risks, potentially requiring costly cleanups.[12, 13] Many states have implemented incentives for useful applications of scrap tires including public reporting of waste tire fate in Arizona and a scrap tire recycling trust fund in Kentucky.[10, 14-16] The marketing of recycled ground rubber based products has been highly ranked in a list of environmental and economic preference for tire disposal, second only to using the tire for as long as possible before disposal.[9]

2.1 GROUND RUBBER PROCESSING

The recycling of used tires into ground rubber is a mature technology which requires complex machinery using either ambient - temperature or cryogenic processes. These multi-step processes result in a uniform product free of fiber or steel impurities.[9, 17, 18] For most applications, typical finished ground rubber diameters range from ½ to 10 mm.[9] Either process can be used to generate ground rubber for use as athletic field infill, with typical diameters between 1 to 3 mm.[19] In addition to inter-technology variation, there is likely to be variation in product characteristics within the same technology across various suppliers.[20]

In the ambient process, tire chips are ground by a sequence of consecutive granulators to produce ground rubber of varying size specifications with a yield of approximately 70% ground rubber and 30% steel and fiber.[9, 21] Steel and textiles are recovered using magnetic and vibration density separators. A spray or mist may be used for lubrication and to control particle generation rates. Respirable fine particles are generated during the mechanical shredding process, but are recovered to some degree in the latter stages by air pollution control devices such as cyclones or washing.[1, 17] In some applications, such as playground mats bound with polyurethane, roller mills are used to produce longer and rougher granulates which facilitate bonding.[22]

In cryogenic recycling, liquid nitrogen is used to cool whole tires or chips to a temperature below -112 °F.[9, 21] At this temperature, the rubber is brittle like glass and size reduction is accomplished by crushing or breaking. Cryogenic recycling has been historically considered to result in a cleaner, less porous, and more uniform end product in fewer steps than ambient grinding, but the expense of liquid nitrogen is a consideration when comparing the two processes. As with the ambient process, steel and fibrous byproducts are recovered in the process. Because smaller size particles are more cost effective to produce than larger particles sizes, ground rubber products from cryogenic technology may have smaller nominal sizes than ground rubber products from ambient technology.

2.2 USES OF GROUND RUBBER

Ground rubber from recycled tires has a variety of uses including: rubber modified asphalt, molded products, athletic surfaces such as fields and tracks, reuse in tires/automotive products, construction, landscaping, and playgrounds.[9, 10] The benefits of ground rubber use in these applications are cost savings, improved performance, and increased safety and durability.[10] Ground rubber does not promote microbial growth. When used as a surface cover in playgrounds, it was shown to be more protective in preventing serious brain injury compared to pea gravel, sand and wood chips, saving an estimated $6.6 billion per year in injury related costs.[10, 23-25] In landscaping uses, ground rubber resists compaction or decomposition over time when compared to wood mulch. Rubber modified asphalt is used on roads, highways, and bike, walking, and golf cart paths.[10]

Ground rubber is frequently used as infill for artificial turf athletic fields and the New York City Department of Parks and Recreation reports that artificial turf athletic fields are used 28% more often than a conventional sports field.[26] Although the cost to install artificial turf fields can be more than conventional fields, artificial fields are estimated to have lower maintenance costs than grass fields.[26] While frequency of injury does not differ between artificial and natural grass fields, the types of injuries that occur on each are very different. One study found that natural grass fields are associated with head and neural injuries, and ligament injuries whereas artificial turf fields were associated with noncontact injuries, surface and epidermal injuries, muscle trauma, and injuries at high temperature. Furthermore, natural grass field injuries generally require longer recovery times than do artificial turf field injuries.[27] A separate study evaluated rotational and translational traction in rubber in-filled artificial versus natural turf fields and determined that natural grass has an increased rotational traction (often associate with more serious ligament injuries) when compared to artificial turf fields.[25]

Some applications consist of ground rubber bound in a poured substrate, which is used at playground surfaces and running tracks.[9] As compared to loose rubber, it is easier to maintain and keep clean. The material is not moved or displaced during play but can have less shock absorbing potential than loose ground rubber.[24]

3.0 RECENT PUBLIC HEALTH STATEMENTS, QUESTIONS AND CONCERNS

While the use of ground rubber in its applications provides for the recycling of scrap tires and can provide appreciable benefits over conventional materials, recent attention has focused on the possibility that ground rubber may cause an environmental or human health risk through these uses. Specific concerns are that particles of ground rubber may be inhaled or ingested; that dermal exposure may result in natural rubber allergy; or that VOCs and other chemicals such as PAHs may be emitted from ground rubber, resulting in negative impacts on human health or the environment.[6, 26] National, state and local governments, in response to public questions, have addressed the issue of the use of ground rubber in commercial applications. The conclusions and recommendations of these governing bodies are summarized below.

New York State

In 2007, legislators in New York State proposed a six-month moratorium on the installation of new synthetic turf fields until the benefits and disadvantages could be more thoroughly investigated in terms of children's health and water quality. While this was not specific to the use of ground rubber as fill in artificial turf fields, some of the concerns raised from ground rubber usage have influenced this decision.[26] In July of 2008, the bill suggesting this moratorium was defeated. In 2009, New York State released an assessment of key issues related to the safety of ground-rubber infilled synthetic turf fields, specifically addressing chemical leaching into ground and surface waters and VOC and particulate releases into air. While some of the ground and surface water sampling campaigns have yet to be published their initial findings suggested that there was a low likelihood of risk to the environment or public health via drinking water from ground or surface water contamination. Further, the concentrations of VOCs and particulate matter detected above the surface of the fields did not exceed background levels, and thus do not suggest an increased risk from the installation of these fields[7].

New York City

New York City purchases the largest amount of synthetic turf compared to any other community in the United States.[26] To address consumer concerns about the potential hazards associated with the use of artificial turf fields, the New York City Department of Health and Mental Hygiene (NYC DOHMH) published a thorough review of the existing literature on the use of ground rubber in artificial turf fields, along with an accompanying fact sheet for consumers[28]. In addition to providing information about the benefits of using artificial turf fields in comparison to natural grass fields, they address concerns regarding chemicals detected in ground rubber (PAHs, metals, VOCs), and natural rubber. The Department recognizes that while chemicals are detected in ground rubber, they are unlikely to pose a health risk based on currently available information, and furthermore are ubiquitously found in the urban environment from alternative sources. Lastly, the DOHMH refers to ongoing research to identify gaps in current knowledge regarding the health effects associated with artificial turf. The key recommendations in the DOHMH report associated with identified data gaps were additional air sampling at synthetic turf fields (with appropriate comparison background samples) and better chemical characterization of ground rubber provided by suppliers. Despite the presence of these data gaps, the DOHMH continues to recommend the use of artificial turf fields to consumers.[29]

New Jersey

The New Jersey Department of Environmental Protection released a white paper in 2008 reviewing the toxicity associated with the use of ground rubber from recycled tires in playgrounds and artificial turf fields. They concluded that there is “no obvious toxicological concern” associated with the intended uses of ground rubber in outdoor settings[30], while reserving conclusions about the potential for allergic reaction and natural rubber sensitization. An investigation by the New Jersey Department of Health and Human Services (2008) found elevated lead levels in fibers and dust at three fields[31]. This result was attributed exclusively to lead contained in certain nylon fibers and was not associated with the rubber infill.

California

In 2007, the California Office of Environmental Health Hazard Assessment (OEHHA) released a risk assessment of the use of recycled scrap tires in playgrounds and tracks with a specific focus on children as a susceptible population. This study included a thorough review of the literature related to chemical leaching from tire material and other relevant studies; an analysis of exposure and risk associated with oral ingestion of ground rubber; an analysis of exposure via hand-to-mouth activity; an analysis of the potential for skin sensitization through dermal contact; ecotoxicity associated with recycled tire uses; and evaluation of head injuries related to different playground surfaces. The conclusions of this study indicate that there is little risk associated with exposure to recycled tire materials used in playgrounds or tracks[1]. A follow-up research plan to assess inhalation of particulates and volatile chemicals was completed in October 2010 [32]. The results of this study indicated that VOC and particulate levels above outdoor fields were very low and often not detectable, indicating there was a low likelihood of adverse health risk from inhalation of either particulate or VOCs above outdoor athletic fields with ground rubber infill.

Connecticut

The Connecticut Department of Public Health (DPH) released a fact sheet in 2007 addressing common questions regarding the health issues associated with artificial turf fields. In this fact sheet, the Department addresses chemical releases from infill material and routes of exposure. The Department suggests that, with respect to VOC emissions from turf fields, wind and temperature gradients should result in rapid dilution such that concentrations in the athlete’s breathing zone are below levels of concern. Furthermore, they state that many of the chemicals emitted from the tire material are commonly found in urban and suburban environments from car exhausts, furnaces, consumer products, and foods. In conclusion, the fact sheet states that, based on current evidence, which is not without uncertainty, there is little risk to public health.[33] The DPH published a risk assessment in July, 2010 using data collected by other agencies or organizations in the state [34]. The data considered in the risk assessment included laboratory leaching and volatilization studies, air samples collected under stationary and field-use conditions and stormwater sampling. From this assessment, they concluded that the use of outdoor and indoor artificial turf fields is not associated with elevated health risks.

Concord, Massachusetts

The town of Concord Massachusetts hired an environmental engineering firm and a human health risk assessment expert to evaluate the potential human health risks associated with ground rubber in artificial turf fields. The expert reviewed literature and wrote a brief memorandum to the director of the Public Works Department in Concord. Much of the focus of the assessment was on PAHs, and the conclusions of the assessment were that there is little exposure to and thus little risk from PAHs or other chemicals associated with ground rubber used in artificial turf fields to the human population.[35]

EPA Region 8

In 2006 and in response to Executive Order 13045, which instructs the EPA to investigate environmental or safety risks that may disproportionately affect children, and likely prompted by questions from consumers, regulators in Region 8 identified potential health hazards to children from playing on surfaces such as athletic fields that employ ground tire rubber.[15, 36, 37] EPA Region 8 representatives suggest that based on limited data and existing data gaps, the risk from the use of tire rubber at playgrounds and athletic fields is unknown with respect to pulmonary toxicity from particulate and fibers, systemic toxicity from inhalation of volatile organic compounds (VOCs) and heavy metals, and pulmonary sensitization to natural rubber. Furthermore, it is recommended that the EPA conduct a comprehensive risk assessment to include these endpoints, and initiate research to fill existing data gaps that may aid in this assessment.[37]

U.S. EPA

In September 2009 and in response to the Region 8 request, the EPA had completed an internal literature review and a limited methods evaluation.[38] In December of 2009, the results of their review and methods evaluation were made public. Based on their review of the available literature on the health effects related to the use of ground rubber in athletic fields and playgrounds, they collected additional monitoring data at recreational surfaces employing ground rubber applications to verify the applicability of current monitoring practices for measuring environmental concentrations of crumb rubber constituents. In doing so, they also generated a dataset, albeit limited, on environmental levels of VOCs and particulate (including particulate metal concentration and morphology) at these locations. In addition to concluding that current monitoring methods are reliable for ground rubber, they concluded that the concentrations of the monitored components were below levels of concern.[39]

EHHI

In response to government issued statements regarding the safety of ground rubber used in consumer applications, Environment and Human Health, Inc. (EHHI), a Connecticut non-profit organization that conducts human health and environmental policy analysis, recently issued a report recommending a moratorium on the installation of fields or playgrounds that use ground-up rubber tires.[40] These conclusions were based on limited testing which showed that low levels of metals or organic compounds are leachable from tire rubber, extrapolation from occupational studies, and critique of relevant quantitative studies.

The concerns of EPA Region 8 and those publicized by EHHI are addressed in the literature review presented in Section 5.0 and discussion presented in Section 6.0.

4.0 OVERVIEW OF CHEMICALS USED IN TIRE MANUFACTURING

In order to understand the potential chemical risks associated with the use of ground rubber from recycled tires, it is necessary to review the tire manufacturing process, the type of chemicals used, and their potential for release from a tire during or after use as well as the toxicities associated with these chemicals. A tire consists of five primary components, namely: tread, sidewall, steel belts, body plies, and beads.[41] Tires are manufactured from many different materials, including natural and synthetic rubber, reinforcing fillers, chemicals, textile and steel. Depending on the specific function and performance of a tire, and the role of the different tire components, formulations based on different polymers, fillers and low molecular weight ingredients are needed.[42] Chemically reactive and unreactive materials used in rubber formulation are listed in Table 2.

Table 2. Chemicals used in Tire Manufacturing

Unreactive materials	Reactive materials
Polymer	Silane (coupling agent)[45]
Carbon black (filler)[43]	Reactive resins (adhesion, reinforcement)
Silica (filler)[44]	Accelerators (cross linking)[46]
Oil (plasticizer)[42]	Sulfur (cross linking) [46]
Resins (uncured adhesion)	Stearic acid (activator) [46]
Wax (protection)	Zinc oxide (activator)[46]
Fatty acids, esters, glycol derivatives (processability)[42]	Retarders (cross linking) [46]
	Antioxidants and antiozonants (protection)[47]

The tire production process includes the following steps: rubber compounding and mixing, tire components preparation (extrusion, textile and metallic composites), tire assembly and tire curing (vulcanization). Throughout the different stages of the manufacturing process, mainly during mixing and curing, many of the reactive materials are either consumed or transformed into less reactive chemicals, while others are chemically bound into the elastomeric matrix. Because of the chemical and physical transformations undergone during manufacturing, the amount of reactive chemicals found in the final finished tire is very small; therefore, very low detection limit analytical techniques are required to detect the presence of these chemicals in the tire, if possible at all.

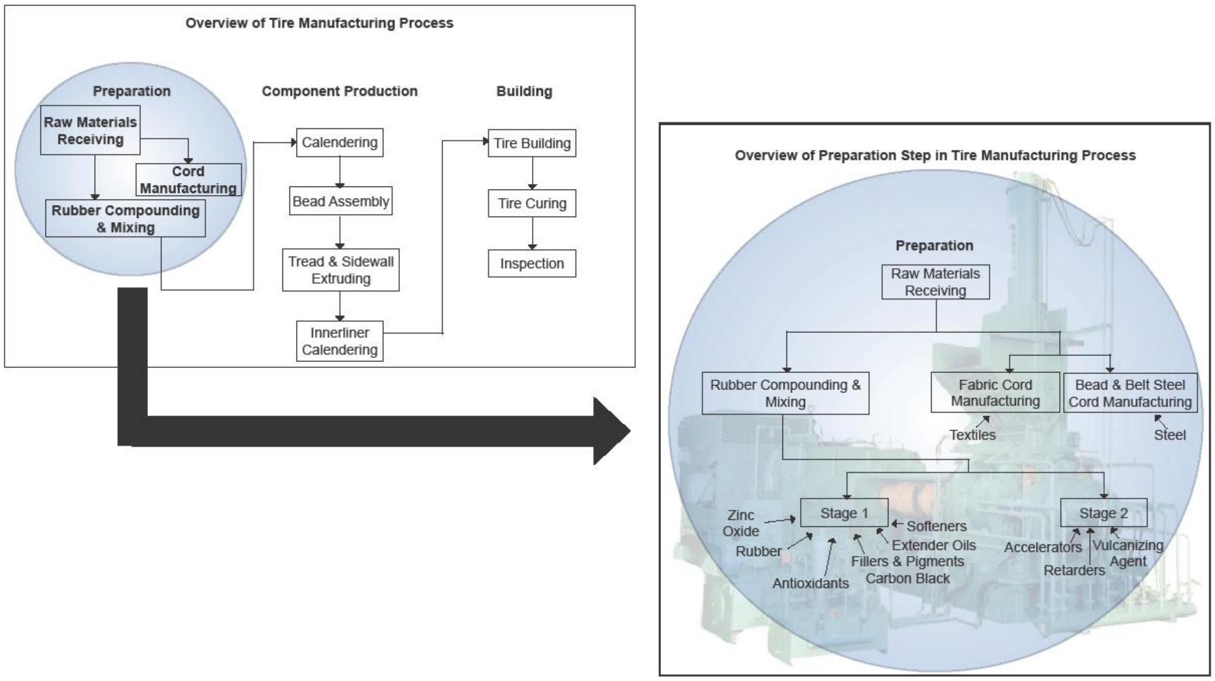


Figure 1: Overview of the Tire Manufacturing Process

4.1 HAZARD IDENTIFICATION IN TIRES

Even while reactive chemicals may not be available for release from end-product tires, the identification of chemicals used in tire manufacturing as mutagens, carcinogens, or reproductive toxicants has resulted in a significant amount of attention on safety from the use of recycled tires in applications such as playground surfaces and artificial turf athletic fields, particularly in light of the fact that one of the exposure populations is children. Much of the focus of this research has been on polynuclear aromatic hydrocarbons (PAHs), phthalates, and metals. A brief summary of the classes of chemicals used in tire manufacturing that were the focus of rubber crumb investigators is presented below.

4.1.1 Antioxidants

Antioxidants are added to the rubber compounding mixture to inhibit oxidative aging of the end-product rubber. Antioxidants are not consumed during vulcanization, but are consumed during product use. Common families of compounds used as antioxidants in tire manufacturing include quinolines, phenolic stabilizers and phenylenediamines. Antioxidants migrate within the vulcanized rubber, but have been infrequently detected in leachate studies from scrap tires or in highway runoff, indicating the likelihood of exposure to antioxidants from the use of recycled tire rubber in playgrounds and artificial turf fields is low.[48-50] The authors of two studies that have reported detectable phenylenediamine compounds or derivatives in water contacting rubber infill concluded that there was a low likelihood of adverse environmental effects, but that long term field studies are needed [51, 52].

4.1.2 Vulcanizing Agents

Accelerators, activators and retarders are reactive chemicals used to control and promote the rate of the vulcanization (sulfur crosslinking) process during tire curing. As reactive chemicals, they are transformed during the curing process and they are not expected to be present in the end products as the original raw materials. Furthermore, individually these chemicals represent only a small component of the rubber compounding mixture, as they are added to the rubber compounding mixture up to 1% by weight.[48, 49] Consequently, exposure to these chemicals from the use of recycled tire rubber in playgrounds and artificial turf fields is likely to be negligible. Transformation products, such as aniline, benzothiazole, and zinc sulfide are formed during curing. Representative water soluble transformation products are routinely included in studies evaluating the chemical composition of leachate from rubber infill used in artificial turf fields. [51, 52]

4.1.3 PAHs

Polynuclear aromatic hydrocarbons (PAHs) are found as impurities in aromatic extender oils which are used as plasticizers to provide elasticity and hardness to the finished tire. Therefore, recycled tires may contain PAHs,[53] although recent legislation in the European Union which restricts the use of aromatic oils in tire manufacturing will result in fewer recycled tires that contain PAHs in the future.[54] Some PAHs are recognized carcinogens by the International Agency for Research on Cancer (IARC), and several other regulatory bodies.[55, 56] As such, PAHs are often heavily regulated in terms of industrial emissions and clean-up levels.[57] The predominant source of PAHs in the environment is fuel combustion, and on roadways, it is primarily associated with diesel fuel.[58] Because of the perceived risk associated with PAHs, nearly all of the risk assessments evaluating the safety of ground rubber used in artificial turf fields and playgrounds have evaluated PAH exposures as an endpoint.[1, 4, 5, 53] PAHs, as a family, are also highly toxic to aquatic organisms.

4.1.4 Phthalates

Phthalates are plasticizers used at some tire manufacturing facilities to control elasticity of the end-product rubber.[5] One phthalate that has received significant attention related to environmental health is di(2-ethylhexyl) phthalate (DEHP). While it may be used as a plasticizer in both synthetic and natural rubber products, it's most common use is in PVC plastics. DEHP is considered a probable human carcinogen by the U.S. EPA, although IARC concludes that the carcinogenicity of DEHP cannot be classified because the mechanism of carcinogenicity as demonstrated in rats and mice may not be relevant to humans. DEHP has also been identified as a suspected endocrine disrupter, as high acute exposures to DEHP can induce alterations in sperm formation and fertility in both mice and rats. However, no reproductive effects have been observed at low level environmental exposures. Because of the perceived risk associated with DEHP, the detection of phthalates in ground rubber has drawn attention in relationship to the use of ground rubber in playgrounds and artificial turf fields.[59]

4.1.5 Metals

Zinc, in the form of zinc oxide, is the only metal present in rubber compounds. Together with stearic acid, it activates the vulcanization reaction with sulfur. At the end of the vulcanization process, the zinc is present in the tire as a zinc sulfide salt. The solubility of zinc sulfide in water is practically negligible.[48, 49, 60] Zinc is an essential element to human health and is not typically regarded as a health hazard, although excessive zinc intake can result in electrolyte imbalance via interference with copper homeostasis.[61, 62] Zinc, like many other metals, has a low threshold for toxicity in aquatic species,[63] and is therefore often the focus of leaching studies evaluating the potential for aquatic toxicity from the use of recycled tires in playground and artificial turf fields.[64] While there are other metals found in whole tires, primarily in the steel belting of the tire, the ground rubber manufacturing process isolates and recovers these metals and therefore the recycled rubber is not a source of those metals in the environment.[1, 17]

4.1.6 Other

Because petroleum based oils containing volatile organic compounds (VOCs) are used during tire manufacturing, some VOCs may be present in end-product tires and ground rubber from recycled tires. It is expected that VOCs should off-gas from the tire after only a short time, due to high volatility, but these compounds have received significant focus in exposure and risk assessments of ground rubber uses, likely due to the toxicity associated with many VOCs (i.e. benzene and formaldehyde).[1, 4, 5, 65, 66]

Certain proteins found in natural rubber are also detectable in small quantities in tires.[67] Sensitization to these natural rubber proteins (i.e., natural rubber latex (NRL) proteins) through skin contact or inhalation can result in significant health hazards, such as severe allergy or asthma. Several groups have identified allergy as an endpoint of concern, based on limited information regarding natural rubber allergen concentrations in air as a result of the use of ground rubber in athletic fields and playgrounds.[1, 5]

5.0 SUMMARY OF HUMAN AND ECOLOGICAL RISK STUDIES OF RECYCLED TIRE PRODUCTS

This section provides a review of the literature associated with human health and ecological studies of useful applications of recycled tires. While the use of ground rubber is most pertinent here, findings associated with other recycled tire products (i.e. tire shreds) may also be relevant and are also discussed briefly.

5.1 IMPACTS ON HUMAN HEALTH

5.1.1 Oral Exposure to Ground rubber

Oral exposure to ground rubber or associated chemicals may occur through multiple means: ingestion of ground rubber (intentional or incidental); hand-to-mouth activity; and intake of drinking water contaminated by chemical leaching from ground rubber. The existing literature evaluating oral exposure to components of ground rubber addresses each of these issues.

5.1.1.1 Oral Ingestion of Ground rubber

Oral ingestion of ground rubber, either intentional or incidental, is unlikely to represent a major exposure pathway. However, consideration of this pathway is necessary, especially in the case of children who may consume ground rubber or pieces of poured rubber at playgrounds. The California OEHHA assessed the potential risk to children from this pathway.[1] In the OEHHA analysis, the toxicity assessment was conducted using data from published literature of leachate from tire shreds as well as a human bioavailability study. In the first analysis using the leachate data from the literature, OEHHA conservatively assumed that the highest concentration of each chemical detected in the leachate would be available for ingestion. Additionally, a single dose estimate of individual chemical constituents from ingestion of 10g of ground rubber (in a 15 kg child) was determined based on the leaching concentrations and risk quantified using a hazard index (acute screening value/dose estimate). This approach is consistent with U.S. EPA guidance which recommends assessment of acute exposure for a pica child using an ingestion rate of 10g per day. Where no acute screening value was available, a subchronic or chronic screening value was used for comparison. Where the dose was lower than a subchronic or chronic screening level, it was assumed that acute health effects were unlikely. This is a reasonable approach, as acute effects most frequently require much higher doses than do chronic effects. Of those chemicals identified to leach from tire materials, 17 were unable to be characterized in terms of risk due to either absence of a screening criteria or insufficient available information to calculate dose. Hazard indices were calculated for 24 chemicals, but only zinc exceeded a hazard index of 1.0. The hazard index for zinc was 5.167 based on an average daily intake of 1.55 mg/kg. Zinc, however, is an essential element to the diet, and has a tolerable upper intake level of 7 mg/kg for a 3-year old child.[61] Furthermore, the leaching value used to estimate dose for zinc (2.3 mg/g tread) was 2.6-2,300-fold higher than results from other studies. Therefore, OEHHA concluded that the risk associated with zinc leaching is overestimated.

In addition to acute health risk, long term risk for developing cancer was estimated for those chemicals in the leachate that were considered carcinogens by the State of California. Those substances that were evaluated for carcinogenic risk included arsenic, cadmium, lead,[2] benzene, trichloroethylene, aniline, and naphthalene. Dose estimates were calculated using the same exposure assumptions as defined above (10 g single exposure) but averaged over a 70 year lifespan. Considerations were made for the increased susceptibility of children to mutagenic carcinogens by multiplying cancer risk by 3, as recommended by the U.S. EPA.[68] Total cancer risk from ingestion of ground rubber based on available leaching studies in the literature was 1.2×10^{-7}, well below the acceptable limit of 1×10^{-6}.

In order to more accurately predict leaching from ingestion by humans, OEHHA conducted a simulated stomach leaching study, wherein 40 grams of ground rubber were leached using a simulated gastric fluid, in order to replicate the environment of the stomach. The simulated gastric fluid was subsequently analyzed for chemical constituents. The non-cancer acute hazard indices and cancer risks were then recalculated using these leachate concentrations and the previous exposure assumptions. The non-cancer hazard index for all leachable chemicals was below 1.0, with the exception of aniline (1.062). Leaching of zinc into the gastric juices yielded a concentration of zinc nearly 1/18th that of the estimate used for determination of risk from the tire shred leaching studies, indicating this value is an overestimate, and thus risk from zinc is likely to be very low. Of the chemicals detected in the simulated gastric leachate, five were considered carcinogens by the State of California (arsenic, cadmium, cobalt, lead, aniline) and therefore theoretical excess cancer risk estimates were made. None presented an increased risk for cancer based on the dose estimate, and the cumulative cancer risk was 3.7×10^{-8}. This is well below the acceptable risk level of 1×10^{-6}, as determined by the EPA, and is one-third of the estimate based on tire shred leaching values obtained from the literature.

In estimating non-cancer and cancer risk based on literature studies and the gastric leaching experiment, the OEHHA used a conservative approach in determining bioavailability of the chemical following leaching. They assumed that 100 percent of all of the chemicals were available for uptake into the systemic circulation. Therefore, it is likely that cumulative risk estimates, while low, are actually overestimates of risk associated with ingestion of ground rubber.

In a similar study, Zhang, et al. evaluated the potential for specific chemicals (PAHs and metals) detected in ground rubber used in artificial turf fields to be bioaccessible by using a sequential extraction that is intended to mimic the digestive tract. [69] In this study, the authors measured PAH and metallic content of the ground rubber prior to subjecting the rubber to extraction in three synthetic digestive fluids: synthetic saliva, gastric fluid, and intestinal fluid. Although PAHs were detected in the ground rubber, they did not leach into the synthetic digestive fluids at appreciable concentrations. Approximately 3% of available benzo(a)pyrene and 1% of available benzo(g,h,i)perylene were extracted into synthetic

---

[2] Arsenic, cadmium, and lead are not expected to be present in native tire tread based on composition, but may become entrained in the tread rubber upon contact with the road surface and are thus detectable in ground rubber from used tires.

gastric fluid (but not saliva or intestinal fluid). There is some uncertainty that accompanies these values, however, as the authors caution that the human digestive tract contains lipids that may enhance the absorption of lipophilic PAHs; hence a need to distinguish between bioaccessibility and bioavailability. Additional biological factors (such as metabolism, limits on absorption, etc.) may further decrease the transport of PAHs from the digestive tract (bioaccessible fraction) into the systemic circulation (bioavailable fraction). Of the metals detected in the ground rubber samples, only chromium and lead were bioaccessible at 23.3% and 44.2%, respectively. However, the concentrations of these metals in ground rubber were low (averages of 0.81 ppm Cr and 3.8 ppm Pb), such that it is unlikely that the threshold of toxicity will be met once bioavailability and dilution in the systemic circulation are considered. Further, the authors concluded that compared to house dust, the fraction that is bioaccessible is lower. Pavilonis, et al. (2013) reached similar conclusions on the bioacessibility of rubber chemicals from ground rubber based on simulated gastric leaching (along with leaching into simulated lung fluid or sweat).[70]

The Danish Ministry of the Environment (2008) assessed potential health effects resulting from oral ingestion of rubber infill based on the maximum results of leaching studies conducted using either pure water or calcium chloride solution. Worst case scenarios for football players using artificial turf pitches were developed, however it is uncertain the degree to which the leaching studies adequately characterized the bioaccessible fraction. The uncertainty in the bioaccessible fraction is partially balanced by the assumed worst case ingestion rate, which corresponds to 93.4 mg/kg-day or an ingestion rate of approximately 6 g of rubber infill per day for a 65 kg junior player exposed for 6 months. Based on the calculated margin of safety for the four compounds considered (i.e. benzothiazole, dicyclohexylamine, cyclohexanamine and dibutylphthalate), it was concluded that adverse health effects were unlikely as a result of oral ingestion. [52]

These studies suggest that there is not likely to be appreciable risk to human health from the ingestion of ground rubber. However, the OEHHA study, while the most comprehensive available study for investigating the risk associated with ingestion of ground rubber, has been criticized by EHHI.[40] Because some chemicals lacked criteria values for comparison, EHHI suggests the risk may actually be higher as it was not possible to assess risk from those chemicals. Furthermore, they criticize the use of an acute exposure estimate to estimate lifetime cancer risk. Recommendations for estimating soil intake in children (which is assumed to be similar to intake of rubber) suggest that children may ingest up to 10g of soil one or two days per year, a behavior expected to discontinue as the child ages.[71] Supplemental chronic risk estimates based on a child's typical incidental ingestion rate of 100 mg/day, as prescribed by the U.S. EPA's Child-Specific Exposure Factors Handbook, indicate that regular exposure (e.g., regular play on ground rubber filled athletic fields) to ground rubber for the length of one's childhood does not increase risk of cancer above levels considered by the state of California to be *de minimus* (i.e. a lifetime excess cancer risk of 1×10^{-6}) or pose a likelihood of non-cancer effects (i.e. hazard index less than 1).[71] Consideration of additional exposure through adulthood (based on total child through adult-hood upper bound residential tenure of 30 years), indicates that chronic adverse health effects are unlikely under any scenario. (See Attachment II for risk calculations).

Incidental ingestion following inhalation of non-respirable particulate also represents a possible exposure pathway. However, as this exposure scenario is likely to result in very little ingestion relative to the intentional ingestion scenario as described above, the associated risks would be appreciably lower. In addition to the detailed California assessment based on acute intake, the Norwegian health assessment concluded that chronic incidental ingestion of 0.5 to 1 g/match ground rubber containing phthalates and alkyl phenols does not pose an elevated health risk.[5] Therefore, the California evaluation of acute exposures was reasonably health protective for this exposure scenario.

5.1.1.2 Hand-to-Mouth Activity

In order to estimate exposure to chemicals from ground rubber via hand-to-mouth activity, a wipe sampling study was initiated by the California OEHHA. In this study, the OEHHA used rubber tiles made from recycled tire material (often ground rubber in a poured substrate). A steel weight was placed atop a wipe and dragged across the rubber tile three times along the same 12 foot path. The wipe samples were then evaluated for chemical constituents. Five chemicals were detected at levels above background: zinc, and four PAHs (chrysene, fluoranthene, phenanthrene, and pyrene). In order to estimate oral exposure via hand-to-mouth activity, several factors need to be considered: surface area of body in contact with playground surface; frequency of hand-to-playground contact; frequency of hand-to-mouth activity; efficiency of chemical transfer from hand to mouth; and frequency of playground use. Using previously established values for these variables[71-79], estimations of oral exposure via hand-to-mouth activity were derived for those five chemicals detected above background levels and risk assessed. For non-cancer effects, screening criteria values were several fold higher than ingested dose estimates, indicating a low risk from oral exposure via hand-to-mouth activity. Estimation of carcinogenic risk for those chemicals identified as carcinogens (chrysene only) resulted in a cancer risk of 2.9×10^{-6}. As a note, chrysene was only detected in the wipe survey from a playground that used a bottom layer of recycled tire and top layers of EPDM rubber (ethylene propylene diene monomer rubber). Chrysene was not found in the wipe survey of a playground surface that only used recycled tire material. Therefore, any increased risk associated with exposure to chrysene via hand-to-mouth activity at playgrounds is not attributable to the use of ground rubber from recycled tires in poured rubber applications.

5.1.1.3 Leaching into Drinking Water

While most studies evaluating the leaching of chemical constituents into water sources have focused on impact on ecological systems, a few have addressed the issue of whether leaching of recycled tire material may impact drinking water, and thus present a human health risk. Of these studies, most focus on civil engineering applications of tire material, such as use in soil absorption systems or roadside leaching fields. While the physical characteristics of the shreds used in these applications are very different from that of ground rubber, the ability of chemicals to be extracted by water is likely to remain similar, as the compositions of ground rubber and shreds are similar. Only the National Institute for Public Health and the Environment (RIVM) in the Netherlands and the New York State Department of

Environmental Conservation have evaluated the potential for leaching from artificial turf fields using ground rubber infill to impact drinking water.

The RIVM study, which focused on zinc loading into water and soil from the use of ground rubber in artificial turfs, suggested that the risk to human health from zinc leaching will be negligible as concentrations of zinc in groundwater should fall well below drinking water standards for zinc.[64] The study conducted in New York State measured both metals and SVOCs in groundwater collected in downgradient wells in sandy soil areas at existing four synthetic turf fields <1 to 7 years old [7]. Based on preliminary laboratory leaching studies, they focused their analysis on zinc, aniline, phenol, and benzothiazole, each of which exceeded drinking water screening criteria in laboratory studies designed to predict groundwater impacts of ground rubber used in artificial turf fields. For all SVOCs, including aniline, phenol and benzothiazole, and all metals, including zinc, results were below the limits of detection for all groundwater samples analyzed, indicating that under real-world conditions, these chemicals are not likely to impact drinking water and present a risk to humans. Although groundwater downgradient of only a limited number of fields was sampled, supplemental laboratory leaching results and environmental models were used to predict groundwater concentrations of metals and SVOCs. The predicted concentrations, when considering dilution and attenuation in the environment, were less than groundwater standards and guidance values, affiriming the groundwater sampling results.

In addition to these studies which suggest that ground rubber is unlikely to impact drinking water from use in artificial turf fields, other studies evaluating the impact of other applications of rubber in the environment from various civil engineering applications draw similar conclusions. Analyses of the impact of the use of tire shreds in civil engineering applications on groundwater concentrations of metals and other contaminants have conflicting conclusions. In field studies performed by the Minnesota Department of Transportation, drinking water standards were exceeded for barium, cadmium, chromium, lead, and PAHs, where as a similar study from the Wisconsin Department of Transportation only found exceedances for lead and barium.[80, 81] However, these studies have been criticized for not maintaining proper controls.[82] A well controlled study from the University of Maine indicated that primary drinking water standards (health protective) for metals were not exceeded due to the use of tire shreds, while secondary standards for iron and manganese (based on aesthetics) were exceeded.[83] Humphrey et al. were unable to detect VOCs and SVOCs in groundwater below tire shred applications, and thus concluded that tire shreds have a negligible impact on groundwater quality at neutral pH.[84] Based on these studies, it is unlikely that leaching of recycled tire material will represent a health risk for humans from ingestion of drinking water due to use in athletic fields, civil engineering applications, or other applications.

5.1.1.4 Other potentially Relevant Studies

A study conducted by the Danish Ministry of the Environment assessed health risks associated with play in sandpits lined with used tires.[53] Migration studies were performed to determine what chemicals moved from the tire rubber into the sand, and thus were available for intake through ingestion of sand by children. Several PAHs and phenylenediamines (used as antioxidants in tires) were detected in the sand, although it was noted that the PAH profile was not identical to that in the tires and was considered to originate from atmospheric deposition from alternative sources of PAHs. Nonetheless, a risk assessment using a margin of safety approach was conducted based on ingestion of 10g of sand, five times a week for half a year. It was assumed that 100% of the substances in the sand were able to be absorbed into the body upon ingestion. Margins of safety for ingestion from chemicals detected in the sand (fluoranthene; 6PPD; IPPD; pyrene; benzo(a)pyrene;) ranged from 10,000 to greater than 1,000,000, indicating there is a very low likelihood of risk to children from ingestion of sand in tire-lined sand boxes. While this study evaluates the health risk associated with whole tires used in playground applications, it is not without relevance when understanding the risks associated with ground rubber from recycled tires used in playground applications. When normalized by surface area, both whole tires and ground rubber will contain similar chemical profiles, and thus migration of these chemicals from the rubber matrix into sand or other surrounding media (e.g., soil) would be similar.

5.1.1.5 Conclusions about Oral Studies

Collectively, studies evaluating endpoints in both children and adults indicate that there is low risk associated with the use of recycled tires in playgrounds or athletic fields to human health from oral exposure pathways. Such pathways include incidental or intentional ingestion of ground rubber, hand-to-mouth activity in children following contact with rubberized surfaces, and drinking of contaminated water. Other relevant studies evaluating safety associated with alternative tire uses in playgrounds supports this conclusion.

5.1.2 Inhalation Exposure to Ground rubber

Another potential pathway for exposure to ground rubber is inhalation, including chemicals off-gassing from the surfaces (playground, artificial turf fields, etc.) and inhalation of particulate matter (and subsequent chemical exposure via interaction in lung) entrained in the ground rubber product.

5.1.2.1 VOCs

As suggested by EHHI, one of the primary concerns associated with the use of ground rubber is the potential for volatile organic compounds (VOCs), and possibly semi-volatile organic compounds (SVOCs) to off-gas, especially with the high temperatures that rubber-containing surfaces can achieve in outdoor environments.[40] Llompart, et al. (2013) evaluated headspace of rubber mulch used in playgrounds, finding PAHs and phthalates among other chemicals.[85] Additionally, a study conducted by the Connecticut Agricultural Experimental Station evaluated the chemical composition of the head space above 0.25g of ground rubber in a 2 mL bottle heated to 60 ºC.[65] Analysis identified four chemicals in the headspace: benzothiazole, butylated hydroxyanisole, n-hexadecane, and 4-t-octyl-phenol.

The study conducted by the Connecticut agency lacks a defined relationship between the findings and exposure to a human receptor population. In defining risk from inhalation (or any other exposure pathway), it is necessary to base risk estimates on likely air concentrations in an exposure scenario (such as at a playground or athletic field that uses ground rubber). Several organizations including The Environmental French Agency (ADEME), the Norwegian Institute of Public Health and the Radium Hospital ("Norwegian study") and the New York State Department of Environmental Conservation have measured air concentrations of VOCs under real-world conditions in order to more accurately predict inhalation risk from VOCs in ground rubber used in artificial turf fields. [4, 5, 7]

In the ADEME study, miniaturized artificial turf fields were built and maintained at a constant temperature (23 ± 2 ºC).[4] Samples were collected in the airspace at day 0, day 1, day 3, and day 28 and analyzed for VOCs and aldehyde emissions (including formaldehyde). Total VOCs at day 0 were approximately 1600 $\mu g/m^3$, but decreased to 134 $\mu g/m^3$ by day 28, indicating an appreciable decrease in total VOCs over time. This data was subsequently used in an exposure assessment which modeled exposure during field installation or athletic activity on the indoor field. Of the 112 substances identified in the samples, quantitative exposure estimates and health risks were calculated for 16 (based on available toxicity criteria). Four population groups were identified (workers installing surfaces; professional athletes/coaches; amateur athletes; spectators at sporting events) and both acute and chronic exposure scenarios considered. The authors concluded that based on these exposure scenarios, VOC and aldehyde emissions from artificial turf floorings do not pose a health risk in any of the exposure groups, with the exception of workers installing artificial surfaces in small and poorly ventilated areas.

In the Norwegian study, air samples were collected at three indoor artificial turf fields, two of which (Manglerudden and Valhall) used recycled tire rubber and SBR rubber, respectively, for infill.[5] In Manglerudden, 234 chemical compounds were detected, of which 29 were able to be identified. Total VOC concentration was 716 $\mu g/m^3$. During a second sampling period, total VOC concentrations were 230 $\mu g/m^3$. In Valhall, mean total VOC concentrations were 234 $\mu g/m^3$. In estimating risk, VOC concentrations from Valhall were used in order to establish a worst-case scenario, as chemical concentrations at this location were consistently two to three times higher when compared to the other locations. Exposure estimates and risk were calculated for four exposure scenarios: adults, juniors, older children, and children using the facility for training. Risk from acute exposure was determined to be negligible. While risk cannot be estimated based on total VOCs, risk can be determined for speciated VOCs with toxicity criteria for inhalation (toluene; benzene; benzoic acid; xylenes; styrene; formaldehyde; limonene; benzothiazole). Margins of safety based on non-cancer NOAELs for all of these chemicals, with the exception of formaldehyde, exceed 100, and in most cases are greater than 10,000 for all exposure scenarios. Only benzene was considered for carcinogenic risk, although that too was within the range of acceptable risk.

Total VOC levels detected in these two studies fall within the range of other indoor air spaces. In a study investigating VOC concentrations in 750 homes in the United States, Wallace et al. detected total VOC levels exceeding 1000 $\mu g/m^3$ in more than half of the homes.[86] Similar findings were reported in a study measuring total VOCs in newly manufactured and site-built homes in the U.S.[87] A similar study of home environments in Germany detected a geometric mean total VOC concentration of 584 $\mu g/m^3$.[88] However, in the Norwegian study, it was concluded that rubber granulate was an important contributor to the total VOCs in the hall.[5] Therefore, while the total VOC levels in these buildings may be comparable to other indoor environments, the chemical makeup of the VOC mixture is likely to be different. Furthermore, sports arenas, such as those evaluated in this study, are subject to more demanding requirements for ventilation than are homes, and comparisons to homes or other indoor air spaces may not be appropriate.

While the authors from both of these studies consider the indoor scenario a "worst case" scenario, neither of these studies considered temperature variation in the field. In fact, in the ADEME study, a temperature-controlled scenario was employed. Volatilization of chemicals is a temperature-dependent process, and surface temperatures at outdoor fields may reach as high as 160 ^{o}F. However, surface temperatures of this magnitude are not particularly remarkable as asphalt, which is another common surface used for recreational purposes such as basketball courts, also achieves similar maximum temperatures.[89]

The question of temperature effects on VOC emissions from outdoor fields was addressed in the study conducted by New York State. In this study, researchers evaluated both off-gassing from heated samples of ground rubber and air samples collected at two synthetic turf fields at heights between 0.5 to 6 feet. The samples were analyzed for selected VOCs and SVOCs in order to understand what potential risks result from off-gassing of chemicals from ground rubber infill used in the field.[7] The results of the laboratory off-gassing study were difficult to interpret, according to the authors, based on the absorptive nature of the rubber samples for VOCs. However, five analytes were selected for inclusion in the ambient air sampling study, based on these results. These included aniline, 1,2,3-trimethylbenzene, 1-methylnaphthalene, benzothiazole, and tert-butylamine. The initial goal of the field sampling study was to collect samples during days when the temperatures were above 80 degrees F, in order to address issues about volatilization upon heating of the fields. Background samples were also collected in areas adjacent to the fields. At both fields, there was no statistical difference in any VOC or SVOC concentrations from background levels of the analytes. Despite this, those chemicals that were detected in the field samples or the off-gassing study were compared to health benchmarks in order to understand the potential for health risks from play on artificial turf fields. Cancer and non-cancer endpoints were evaluated, and it was determined that off-gassing from ground rubber in artificial turf fields does not represent a health risk, as hazard quotients for all chemicals were typically well below 1, and calculated cancer risks did not differ from cancer risks from background concentrations of the chemicals of interest.

While the NYDEC study represents one of the best available studies to characterize VOC concentrations at outdoor fields, it is not without limitations. In addition to a small sample size (sampling from two fields does not allow for thorough understanding of emissions related to age or condition of field), this study was limited to evaluating VOCs at approximately one ambient temperature and field surface temperature during the sampling was not reported. In an effort to improve upon the available data, the State of California initiated a sampling campaign for VOCs at outdoor fields as well. They analyzed for VOCs at eight different fields on hot summer days (temperatures ranged from 63 to 98 ^{o}F over the sampling periods, with the lowest maximum daily temperature equal to 84 ^{o}F). [8] Results of the air sampling were compared to that of samples taken at nearby natural grass fields. Although few VOCs were detected above the detection limit in any of the samples (only 10 of 94 VOCs were detected in at least one sample), all detected VOCs were taken through a human health risk assessment to determine if exposure would result in adverse health effects. Results of the risk assessment indicated that for these fields, there was no increased health risk from VOC emissions from the turf fields.

In addition to evaluating VOCs in the ambient air above the fields, the State of California study was designed to evaluate changes in VOC concentrations as a result of changing field surface temperatures. When conducting the air sampling, these researchers also measured field surface temperatures in an effort to understand if there was a correlation between surface temperature and level of VOCs above the field. Surface temperatures were measured up to 137 ^{o}F, but no correlation with VOC concentrations was found. [8]

Although chemical emission rates increase with temperature, the increase in volatile organic emissions from rubber is much less than that implied by theoretical vapor pressure relationships. The reason for the discrepancy is that as the ground rubber surface is depleted of VOCs, subsequent emissions are limited by the slow rate of chemical diffusion to the surface of the rubber. This process is much less dependent upon temperature than solid to vapor phase partitioning equilibrium. For example, over a temperature range of 67 to 160 °F, the vapor pressure of benzothiazole increases by a factor of almost 40.[90] However, based on a study of a synthetic rubber athletic track, total VOC emissions are estimated to increase by a factor of only 2 over the same range.[91]

Chang et al. measured emissions of VOCs at breathing height from athletic tracks made of synthetic rubber, and evaluated impact of temperature and aging on VOC emissions.[91] Hexanal, 2-methyl furan, toluene + octane, and methyl isobutyl ketone (MIBK) were the dominant compounds emitted from the synthetic rubber track. MIBK was unique to the synthetic rubber track, in comparison to those tracks using polyurethane based surfaces. With aging of the track, VOC emissions decreased. Emissions did not vary substantially by temperature, especially in comparison to track age. While the rubberized surface in this study is not ground rubber (although it may be made of poured ground rubber), this is the study corroborates the low emissions of VOCs found in the New York State study. No exposure estimates or risk calculations were determined based on results from this study. However, total VOC concentration at breathing height above the track was 0.39 μg/m^3. This is several orders of magnitude lower than detected in the indoor scenario, which based on the exposure scenarios used in the ADEME and Norwegian studies, did not pose any risk to human health.

The Norwegian and ADEME indoor studies are clearly representative of worst case inhalation exposure concentrations, as the increased dilution outdoors is expected to be many times more important than the increase in emission rates with temperature, as is indicated by the above referenced studies. At one of the Norwegian fields, it was specifically noted that natural ventilation (i.e. open windows and hatches) was employed. Had mechanical ventilation been employed, it is likely exposure concentrations would have been lower. Another important observation is that outdoor emission rates are expected to decrease appreciably with age of the field due to surface depletion of the volatile chemicals, as shown in the synthetic rubber track and ADEME studies. Two additional studies addressed specific VOCs or SVOCs in air samples above artificial turf fields. Milone & Macbroom, Inc. (MMI) collected air samples above two artificial turf fields in Connecticut and analyzed for benzothiazole, 4-tert-octyl-phenol, and volatile nitrosamines.[92] Only benzothiazole was detected in the air above the fields (only at one of two fields) at levels exceeding background levels, although concentrations of benzothiazole were still very low (0.39 $\mu g/m^3$) and below the reference concentration of 18 $\mu g/m^3$ derived from reference dose in the New York State synthetic turf evaluation. J.C. Broderick and Associates, Inc. collected air samples above two artificial turf fields in New York State and analyzed for PAHs.[93, 94] All PAHs were below the limit of detection of 6 $\mu g/m^3$. Schiliro, et al. (2013) measured PAHs and BTX (benzene, toluene, and xylene) at artificial turf fields and urban areas and found no differences in the concentration of either at the fields, when compared to the urban background.[95] The U.S. EPA also conducted a limited research study to verify the reliability of current monitoring techniques for detecting VOCs associated with ground rubber fields and playgrounds. This study found that measured VOC levels above these fields or playgrounds were generally very low (did not exceed 1 ppb by air volume for any analyte).[39]

In summary, VOC emissions from rubberized surfaces in athletic fields or playgrounds are unlikely to pose a human health risk based on the available data. The authors of the Norwegian study note that absence of toxicity criteria for some of the chemicals detected does not mean these chemicals cannot constitute a health risk, but that rather, based on currently available data, no cause for concern based on VOC emissions exists.

5.1.2.2 Particulate

Ambient particulate matter (PM), including airborne dust, is generated in all indoor and outdoor environments from a variety of sources such as agriculture, power plants, industrial facilities, on-road and off-road vehicles and forest fires.[96] PM is a complex mixture of solid inorganic and semivolatile organic chemicals and aqueous materials and is found in a range of sizes described by an aerodynamic diameter. Examples of particulate matter are soot, smoke, elemental and organic carbon, nitrates, sulfates, acids, bacteria, fungi, spores, pollen, dust, and tire wear materials. Fine particles (i.e., < 1 to 3 μm in diameter) generally originate from combustion sources or precursor gases whereas larger coarse particles are considered primary particles emitted directly from specific sources.[96] Generally, fine rubber particles cannot not be derived from rubber crumb due to the amount of physical energy that would be required to break apart the crumb pieces.

In any environment, the levels of PM are influenced by the amount of air dispersion or ventilation, the rate of particle release or suspension and the physical configuration of the space or area. With regard to potential human health risk, scientists assess both the bulk physical characteristics of the particles (i.e. total mass, surface roughness and geometry of inhaled particulate) as well as the particulate phase chemical composition (i.e. concentrations of individual chemicals).

Although validated relationships between specific sources of particulate matter and health outcomes are not available, long term exposure to fine and coarse particulate matter is associated with mortality in older adults with cardiopulmonary disease.[96-98] There is not scientific consensus regarding the mechanisms relating the characteristics of ambient PM to specific health effects, however, research suggests that chemical composition may be a minor contributor to PM toxicity because similar dose-response relationships are observed across the world despite a wide range of particulate compositions.[99] Proposed fine particle respiratory damage mechanisms include penetration and accumulation in the interstitial spaces of the lungs, tissue damage by aggressive chemicals such as acids and catalytic effects and oxidant formation attributable to trace metals within the lungs.[100, 101] Consistent with this research, systemic toxicity attributed to trace inorganic or organic compounds found within particulate matter is expected to be low. In outdoor settings, the U.S. EPA generally considers evaluations of the soil direct contact pathway to be protective of fugitive dust inhalation exposures, as soil screening levels are typically several orders of magnitude lower (i.e. more stringent) for the oral route versus the inhalation rate.[102] With the exception of hexavalent chromium, routine evaluation of residential or commercial/industrial fugitive dust exposure is not recommended unless unusual heavy truck traffic or annual average wind speeds well above national averages are expected. Therefore, individual chemical risks attributable to airborne ground rubber are expected to be low. With respect to ground rubber recreational field installations, limited airborne particulate data are available, but upper bound total mass and individual chemical particulate exposures can be assessed using data collected at indoor Norwegian artificial turf fields (addressed below).[5]

<u>*5.1.2.2.1 Total Respirable Airborne Particulate Exposure*</u>

Two characteristics of ground rubber are likely to limit the magnitude of fine particle or airborne dust release and subsequent exposure. First, during rubber recycling, fiber and dust removal is typically accomplished using air classifiers or other equipment.[9, 17, 18] Second, foot traffic is unlikely to generate appreciable quantities of new particulates during field use due to the high amount of energy that would be required to generate small respirable particles.[15] However, it is unknown the degree to which coarse and fine particles created or entrained are removed in processing of recycled rubber. In two ambient scrap-tire shredding facilities located in France and Taiwan, ambient levels of respirable dust were 230 to 1250 $\mu g/m^3$ indicating the potential for particle generation during processing.[17] In a study conducted by the New York State Department of Environmental Conservation, microvacuum samples were taken at two fields in an attempt to understand the size distribution of particles associated with the ground rubber infill. The size distribution was bimodal, with both very large (millimeter sized) and very small (micrometer sized) particles observed. The large fraction appeared to contain rubber, grass, and cord material, while the small particles originated from crustal minerals and plant material. This data suggests that the rubber containing portion of particulate from ground rubber is unlikely to be respirable. However, this data is the only available characterization of the size distribution from particulate in artificial turf fields and the authors state that its representativeness is unknown.

Regardless of the underlying particulate content of the ground rubber, turbulent air dispersion in outdoor settings and precipitation wash-off are expected to appreciably attenuate on-field particulate concentrations relative to indoor settings. For settled dust, the two primary resuspension processes in air are abrasion of surfaces by applied mechanical force by foot traffic, wheels or other implements and dust particle entrainment by turbulent air currents at high wind speeds (i.e. greater than 12 mph).[103] Based on a review of the literature and a simple screening calculation, the primary resuspension process for ground rubber particles used in fields or playgrounds appears to be surface disturbance by foot traffic.[5, 103]

In air, total suspended particulate matter (PM) is defined as aggregated molecules or particles which typically range in aerodynamic diameter from 0.01 to 100 μm (one micrometer is 1 millionth of a meter). For health assessment, the operational definition (i.e. indicator) of particulate matter is typically based on the cut-point of 50% collection efficiency for a sampler that contains a size fractionator. The common metrics include PM_{10} based on an aerodynamic diameter cutpoint of 10 μm, $PM_{2.5}$ based on an aerodynamic cutpoint diameter of 2.5 μm and $PM_{10\text{-}2.5}$ representing the difference between the two size fractions.

Particles are considered to be thoracic if they penetrate anywhere within the lung airways or gas exchange region, whereas particles are considered to be respirable if they deposit exclusively in the gas-exchange or pulmonary region of the deep lung. Particles greater than 100 μm are too large to remain suspended in air, whereas particles larger than 10 μm are not considered to be respirable, as they are not deposited on the non-ciliated portion of the lungs. Particles less than 10 μm are characterized by slow gravitational settling velocities which in the presence of air turbulence impede the rate of settling back to the ground after initial release. Therefore, pulmonary risk is primarily attributed to particles with characteristic aerodynamic diameters less than 10 μm. Particles with diameters between 2.5 and 10 μm accumulate in the lung and are considered coarse particles and regulated in the United States based on acute risk.[104] Particles with diameters less than 2.5 μm, or $PM_{2.5}$, are considered fine particles, and considered to pose greater health risk than PM_{10} due to their ability to penetrate deeper into the lung and are regulated based on both chronic and acute health risk.[104] Epidemiological studies have shown associations between ambient particulate concentrations and adverse health indicators such as increased mortality and chronic respiratory disease or secondary cardiovascular effects.[96-98]

For open sources, such as dirt roads or playing fields, fugitive dust is generated when mechanical disturbances suspend granular material exposed to the atmosphere.[103] Data regarding outdoor emission rates of particulate from ground rubber playing surfaces was not identified in the literature. However, the New York State Department of Environmental Conservation recently monitored $PM_{2.5}$ and PM_{10} concentrations at two fields. Using a simple "unlimited reservoir" model which assumes that wind erosion suspends an unlimited reservoir of erodible particles from an unobstructed open field or playing surface with a nominal grain diameter of 3-mm (Attachment 1), the estimated PM_{10} and $PM_{2.5}$ concentrations from wind erosion are unlikely to exceed 0.1 $\mu g/m^3$.[102, 105]

In contrast to the low particulate levels estimated in the NYDEC study, the authors of a study of three indoor Norwegian turf halls concluded that fine particulate associated with ground rubber with a nominal diameter of approximately 3 to 4 mm may be readily suspended by regular field use.[5] The study assessed two fields constructed with ground rubber infill derived from recycled tires including a newly installed field and a field approximately one year old. The source of the airborne particulate is likely to have been resuspension of existing fine and coarse particles by the mechanical force generated by use and maintenance of the field. In contrast to outdoor settings, air dispersion and dilution in indoor settings is limited by mechanical ventilation rates or natural ventilation induced by infiltration or open doors and windows. Additionally, particle washoff by precipitation is likely to reduce outdoor particle levels on the field over time. Therefore, particulate levels of ground rubber caused by disturbance of the field are likely be on average at least an order of magnitude lower in outdoor settings.

Measured air concentrations of PM_{10} in the indoor fields containing recycled tire crumb rubber ranged from 30 to 40 $\mu g/m^3$ and $PM_{2.5}$ concentrations ranged from 17 to 18 $\mu g/m^3$. The total indoor PM_{10} and $PM_{2.5}$ concentrations were similar to levels measured in other urban indoor settings.[106] [107] Based on the use of N-cyclohexyl-2-benzothiazolamine (NCBA) as a marker for rubber, the Norwegian researchers calculated that the rubber portion of PM_{10} in the indoor fields was approximately 9 $\mu g/m^3$, or 23 to 30% of total PM_{10}. For the $PM_{2.5}$ fraction, the concentration attributable to ground rubber was 7 to 9 $\mu g/m^3$ or 35 to 50% of total $PM_{2.5}$. It should be noted that a more specific and reliable marker for tire tread based on pyrolysis products of rubber has recently been published and it is recommended that any further research regarding airborne particles from crumb rubber employ this marker.[108]

The U.S. EPA has established standards for PM_{10} and $PM_{2.5}$ which are protective of human health including sensitive subpopulations such as children.[109] With regard to assessing indoor air quality, the American Society of Heating Refrigeration and Air-Conditioning Engineers standards (ASHRAE 62.1-2007) adopt the U.S. EPA's National Ambient Air Quality Standards as one of the appropriate evaluation metrics, including the PM_{10} and $PM_{2.5}$ standards. The PM_{10} standard is a 24-hour average of 150 $\mu g/m^3$and the corresponding 24-hour $PM_{2.5}$ standard is 35 $\mu g/m^3$. In addition, an annual average $PM_{2.5}$ standard of 15 $\mu g/m^3$ has been established (3-year average of weighted annual mean). The total particulate levels measured at the indoor fields are specific to the ventilation conditions and pre-existing fine particle content of the ground rubber. Although detailed information regarding ventilation was not provided, the authors indicated that ventilation was induced by opening 8 roof hatches and 16 windows at one of the fields. Based on the observed maximum ground rubber PM_{10} and $PM_{2.5}$ concentrations of 9 $\mu g/m^3$, indoor installations of ground rubber are unlikely to result in exceedances of the 24-hour EPA standard for $PM_{2.5}$ and PM_{10} when fields are ventilated in accordance with recommended design standards and background outdoor ambient particulate concentrations comply with the standard.

For short term exposure such as athletic field usage, the 24-hour $PM_{2.5}$ standard is the best metric by which to assess potential health effects. However, in order to also qualitatively evaluate the chronic $PM_{2.5}$ exposure, an annual average $PM_{2.5}$ exposure concentration was calculated based on the maximum portion of indoor $PM_{2.5}$ attributable to ground rubber of 9 $\mu g/m^3$ and adjustments to account for less than 24 hour exposure time and higher inhalation rate during vigorous activity. The exposure time adjustment is based on worst case assumption of indoor field use for 2 hours per day, 5 days per week for 25 weeks per year or (2 hours x 5 days/week x 25 weeks/year) / (24 hours x 7 days/week x 50 weeks/year) =

0.028. The inhalation rate adjustment factor accounts for higher inhalation rate during field usage and was set equal to the heavy activity adult short term inhalation rate of 3.2 m^3/hour divided by the average male and female long term inhalation rate of 0.55 m^3/hour, equal to 5.8. Therefore, the worst case adjusted annual average $PM_{2.5}$ concentration attributable to field use would be 9 $\mu g/m^3$ x 0.028 annual field hours/total annual hours x 5.8 vigorous activity inhalation rate/long term inhalation rate, or 1.5 $\mu g/m^3$, or 10% of the chronic U.S. $PM_{2.5}$ standard. Accordingly, indoor field containing ground rubber are unlikely to result in personal exposure exceedances of the annual average $PM_{2.5}$ standard when fields are ventilated in accordance with recommended design standards and background outdoor ambient particulate concentrations comply with the standard. Particulate exposure to ground rubber at outdoor fields is expected to be at least an order of magnitude lower than indoor settings.

In a study conducted by New York State, PM_{10} and $PM_{2.5}$ air sampling was conducted above two artificial turf fields that contain ground rubber infill.[7] The field particulate levels were compared to background particulate levels. There was no meaningful increase in PM_{10} or $PM_{2.5}$ on the fields; however, the study only evaluated two fields and did not consider factors such as field age or condition. Further the results for one location were judged inadequate for reliable direct comparison of upwind and downwind measurements because of potential synchronization problems and perturbations of the instruments. The State of California measured $PM_{2.5}$ levels above three outdoor artificial turf fields, comparing results to particulate levels above nearby natural grass fields[8]. For two fields, the PM2.5 was not detectable after 3 hours of sampling; at the third field, $PM_{2.5}$ levels were consistent with nearby background (both up and downwind of the field). The U.S. EPA also measured levels of PM_{10} above athletic fields and playgrounds in their effort to validate the reliability of current sampling methods for these applications. As with the findings of New York State, the levels of PM_{10} at athletic fields were equivalent to ambient particulate levels measured at upwind background sites.[39] At the one playground sampled, the PM_{10} levels exceeded background by 15 $\mu g/m^3$. Although morphological analysis of the particulate in these samples indicated that no tire particles were present on the samples via SEM, this data was judged to be insufficient based the variability in compositional and morphological characteristics of the rubber particles associated with crumb rubber material. The concentration PM_{10} at all sites ranged from 24 to 33 $\mu g/m^3$, below the short-term PM_{10} standard (150 $\mu g/m^3$) established by the U.S. EPA.[39, 109] Schiliro, et al. (2013) had similar findings regarding low particulate levels (PM_{10} and $PM_{2.5}$) at fields, particularly in comparison to urban background.[95] Although these studies suggest that levels of fine and course particulate generated at ground rubber fields and playgrounds is not likely to pose a health concern, they are limited (by number of sampling sites, total number of samples collected, uncertainty regarding variability in material, etc.). More study may be required to evaluate outdoor fields and to assess variability in particulate generation rates between indoor and outdoor fields. Given that $PM_{2.5}$ and PM_{10} are ubiquitous in the atmosphere, the characterization of background levels and use of rubber tracer molecules to assess the fraction of particulate matter generated from the field are key considerations for future studies. Additionally, for fields situated near high density traffic areas, an important consideration is the rubber contribution from tire wear particles versus ground rubber from the field.

5.1.2.2.2 Particulate Phase Chemical Exposure

For ambient conditions, particulate phase chemical exposures are typically low, with potential human risk several orders of magnitude lower than potential incidental oral ingestion or dermal risk.[102] The authors of the Norwegian artificial field study assessed several particulate exposure scenarios including adults, juniors and children. Dose was calculated based on concentration in the rubber granulate and the PM_{10} concentration (PCBs, PAHs, phthalates, alkyl phenols) and based on the measured air concentration (PAHs and phthalates). As expected based on past experience, daily chemical uptakes were low. For example, a worst case daily phthalate uptake of 47,000 pg/kg resulted in child and adult scenario margins of safety of 23,000 to 80,000. For all chemical classes assessed, it was concluded that the chemical compounds present did not pose an elevated health risk.

5.1.2.2.3 Natural Rubber Allergy and Asthma from Particulate Inhalation

One of the concerns with regard to exposure to rubber-containing particulate is the risk for the development of natural rubber allergy[3] and associated asthma. Natural rubber contains proteins thought to induce allergy or hypersensitivity to natural rubber-containing products.[110, 111] Therefore, there is a concern due to the severity of natural rubber allergies that exposure to recycled tire material may lead to natural rubber allergy, and in the case of inhaled natural rubber-containing particles, asthma. While a recent publication indicates that exposure to particles in ambient air (from traffic sources) does not pose an asthma risk from exposure to natural rubber associated proteins from tire tread [112], this question has not been formally addressed with respect to the use of ground rubber from whole tires. Approximately 20% of tire treads produced contain natural rubber (primarily in the truck market)[110], and natural rubber is a constituent of both passenger and truck tire casings.[113]

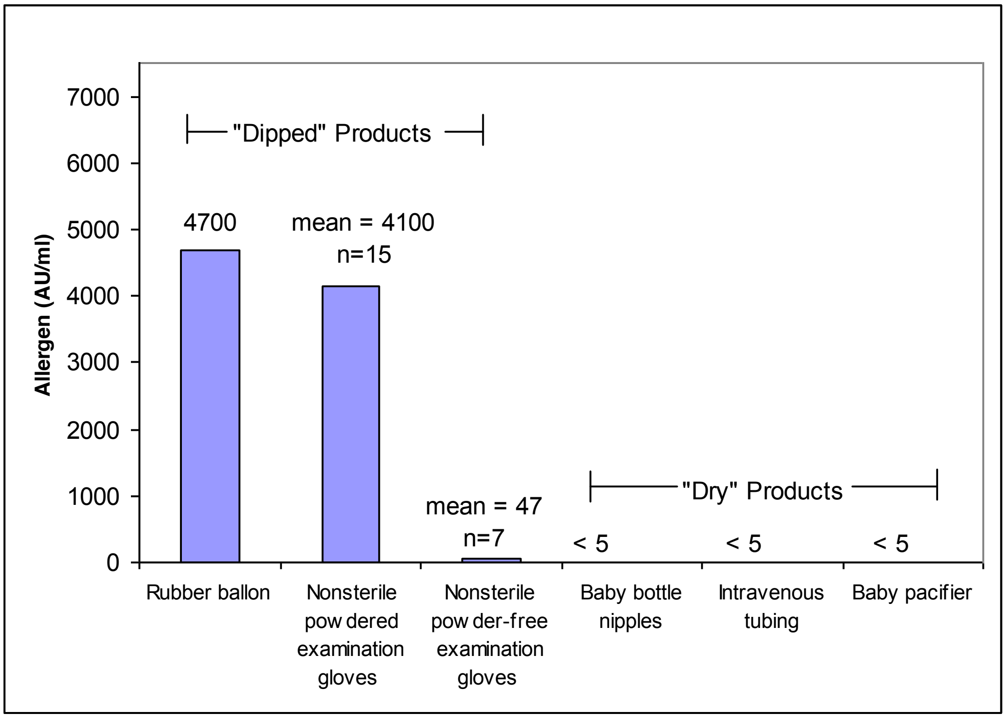
For natural rubber products, the induction of Type I (immediate hypersensitivity) allergic response is mediated by the human IgE antibody. The potential to induce allergy in sensitized and non-sensitized populations is dependent on the level of natural rubber protein antigens in a product, typically assessed using an *in vitro* IgE binding assay or *in vivo* skin prick test. With regard to the Type I allergic responses associated with the specific proteins in natural rubber,[112] it is important to evaluate the two main types of natural rubber products used in the manufacture of products. Products based on solid natural rubber, such as tires or footwear are processed differently than more elastic products based on untreated natural rubber latex (NRL), such as surgical gloves or balloons. The production of treated solid, or bale natural rubber, requires intensive heating which decreases the levels of proteins by several orders of magnitude and the chemical additives used further decrease the bioavailability of the remaining protein. In contrast, dipped products are based on raw natural rubber latex with little pre-treatment, retaining many of the antigenic proteins from

---

[3] The term natural rubber allergy is used here to clarify the difference in protein activity between dipped latex products such as surgical gloves and products based on the solid bale form of natural rubber such as tires. As noted in the text, the activity and levels of natural rubber latex (NRL) protein in the solid form of processed natural rubber used in tires is appreciably lower than that found in products based on untreated dipped latex.

the raw material when sufficient washing or chlorination treatments are not applied. For example, dry rubber and dipped rubber extracts tested using the *in vitro* IgE binding assay demonstrate that the levels of allergen were up to 1000 times lower in dry versus dipped products (Figure 2). As expected, dry rubber products do not elicit skin reactions when tested and are generally considered free of the protein allergy problems reported for dipped products.[112]

Figure 2: Relative Quantity of Extractable Allergens in Various Rubber Products[114]



There is no evidence based on occupational exposures to dry rubber products to support the hypothesis that this form of rubber is a potent allergen. First, if the level of allergen in tire products were above a clinically relevant threshold, it would be reasonable to expect a high incidence of natural rubber allergy in the tire industry, especially in tire retreading or recycling where buffing and grinding leads to airborne tire dust particulate. However, no such case reports or studies have been published in the literature.[110] Additionally, a natural rubber IgE reaction has not been found in a survey of 208 workers from 9 different rubber manufacturing companies in the Netherlands.[110]

Tire tread particle extracts have been assessed for binding with serum IgE from latex-sensitive patients. Miguel et al. measured the natural rubber latex (NLR) allergens in radial tires, truck tires, and recap waste treads from truck tires at levels of 3.48, 1.31 and 0.6 µg protein/g tire tread respectively.[67] Based on this data and a No-Adverse Effect Level of 55 to 100 ng/m^3 determined from a controlled study in latex-sensitive population,[115] Finley et al. concluded that the weight of evidence indicates that natural rubber in tire particulates are not a significant contributor to asthma.[112]

Of note is a recent EPA action under the Toxic Substances Control Act (TCSA), which denied a petition to prohibit use and distribution of natural rubber latex adhesives with a total protein content greater than 200 μg/g dry weight based on ASTM D-1076-06[116]. In it's denial of the petition, EPA stated that a regulation requiring reduced protein content would be unlikely to reduce natural rubber allergy in the general population. The EPA also cited the governmental evaluation, including a June 2004 Consumer Product Safety Commission assessment that found the while many consumer products contain natural rubber, there are few documented cases of reaction to these products. Of the case reports showing an association, most were associated with medical products. EPA concluded that the CPSC evaluation suggests that risks associated with natural rubber are "relatively insubstantial".

Exposure to allergens from the use of ground rubber in CRM asphalt is also unlikely. As suggested by Liu et al, any allergens that may be present in ground rubber are likely to remain in the pavement matrix.[11] The conclusion that ground rubber and other recycled tire uses do not pose a threat to the development of natural rubber-associated allergies or respiratory disease, despite the presence natural rubber in tire compositions, is further supported by an absence of occupational natural rubber allergies in the tire industry.[110]

5.1.3 Dermal Exposure to Ground rubber

Exposure to ground rubber through dermal contact may occur through the use of ground rubber in playground applications and athletic fields. In addition to the concern of natural rubber allergy from the presence of natural rubber protein in some tire formulations, some of the chemicals used in tire manufacturing are thought to induce allergic contact dermatitis.[117] Furthermore, allergic contact dermatitis has been demonstrated in employees working in rubber manufacturing facilities.[118] As such, some argue that there is a potential for allergenic response via dermal contact to ground rubber.[119]

The California OEHHA conducted a skin sensitization test to evaluate the potential for allergic response due to dermal contact with rubberized playground surfaces.[1] In this study elicitation of an allergenic response in the guinea pig, (a standard model for identifying human contact skin sensitizers) from exposure to materials (including ground rubber) used in playground surfaces was evaluated.[120] Test samples were applied to the animal's skin during three six-hour induction exposures each separated by one week. Following the induction exposure regimen, the animals were challenged with the test samples for six hours and evaluated 24 and 48 hours later for signs of erythema. A second challenge was initiated one week later. None of the rubber containing material, including the ground rubber, initiated an allergic response or indicated sensitization.[1] While this study was intended to evaluate the potential for development of allergy in response to the use of recycled tires in playground surfaces, it too is applicable to dermal contact with ground rubber used in athletic fields as both are similar products in terms of chemical composition and contact surface area (not particle surface area) would determine toxicity.

In addition to contact allergy, Environment and Human Health, Inc. (EHHI) has raised concerns related to chemical leaching through skin from dermal contact with ground rubber as a potential mechanism of toxicity.[40] However, because the ground rubber is unlikely to adhere, the prolonged contact required for uptake through the skin, which provides a reasonable barrier to many chemicals, is not likely. As such, uptake of chemicals is unlikely to result in systemic toxicity from dermal contact with ground rubber. This is supported by work performed by the Norwegian Institute of Public Health that evaluated the potential for dermal uptake of PCBs, PAHs, phthalates, and alkyl phenols from skin contact with rubber particles from artificial turf fields.[5] In this analysis, 100g of rubber were leached in 1L of water over 48 hours in order to determine what is extractable from the rubber matrix. From this experiment, they determined that the leaching potential for PCBs, PAHs, phthalates, and alkyl phenols are 0.8×10^{-6} %, 1×10^{-6} %, 30×10^{-6} %, and 5×10^{-6} %, respectively. Using the leaching potential and assuming 100% uptake through skin absorption, the exposure estimates from dermal exposure to rubber granulate for adults, juniors, and children using athletic fields employing ground rubber is very low (for all chronic exposure scenarios, daily intake is less than 100 parts per trillion (ppt). These concentrations, while exceedingly low, assume 100% of the chemical that can leach from the particle into aqueous solution is able to be absorbed by the skin. Because the skin provides a natural barrier to absorption of chemical toxicants, 100% bioavailability is unlikely in intact skin.[121] In the case of phthalates it is known that only 5% of the compound will be absorbed into the systemic circulation.[5] In fact, based on a biomarker study in soccer players exposed to "intensive skin contact" with rubber infill, detection of biomarkers for PAHs was not increased over background, indicating that bioavailability of these compounds is low via the dermal pathway.[2]

A similar study evaluating the potential for chemicals (PAHs and phenylenediamines) in sand originating from tire barriers (as used in sandpits) to migrate through the skin was conducted by the Danish Ministry for the Environment.[53] Four compounds (fluoranthene, pyrene, 6PPD, and IPPD) were able to migrate into artificial sweat from the sand. Based on these results, a risk assessment for exposure via this pathway was completed based on 200 cm^2 of exposed skin (child's thighs) and daily one hour exposure. Margins of safety for all chemicals evaluated ranged from 10,000 to greater than 1,000,000, indicating negligible risk from this exposure scenario.

The Danish Ministry of the Environment (2008) assessed potential health effects resulting from skin contact with rubber infill based on the maximum results of leaching studies conducted using either pure water or calcium chloride solution.[52] The worst case scenarios for football players using artificial turf pitches included an exposed skin surface of 6,600 cm^2 and 7 exposure episodes per week for approximately 6 months. Based on the calculated margin of safety for the four compounds considered (i.e. benzothiazole, dicyclohexylamine, cyclohexanamine and dibutylphthalate), it was concluded that adverse health effects were unlikely as a result of skin absorption of rubber infill related compounds. The authors noted that for sensitive individuals, there could be a potential risk for sensitization for benzothiazole or the amine compounds for sensitive sub-populations. However, the anticipated low concentrations of these compounds at the surface and results of the California OEHHA skin sensitization test indicate that sensitization is unlikely to be a concern.

In summary, the results from these studies of dermal exposure indicate that the dermal pathway represents a low health risk from the use of recycled rubber products in playgrounds or artificial turf fields.

5.1.4 Other Toxicity Studies Regarding Ground rubber

In addition to the assessments described above, there are a few studies in the literature that investigate the impact of ground rubber on other endpoints of toxicity. Multiple researchers have investigated the potential for extracts from rubber materials to induce genetic changes in *in vitro* systems. Birkholz et al. performed an extraction of tire rubber with dichloromethane and evaluated mutagenicity of the pooled extract in *Salmonella typhimurium* with and without metabolic activation with human S9 (pooled liver enzyme fractions). This assay is regularly used as a screening level genotoxicity test, and has become a standard component of mutagenicity testing battery.[122] In none of the tests was the extract genotoxic to *Salmonella*.[6] Gualtieri et al. evaluated DNA damage to A549 cells, a human lung cell line, in response to tire debris organic extract (TDOE) using the Comet assay and detected a dose dependent increase in damage to the DNA.[123] However, the Comet assay as used is a non-specific DNA damage assay that is difficult to replicate, sensitive to physical changes in the environment, and does not provide specific information regarding the mutagenic potential of the extract itself.

In both of these studies, extracts were performed using dichloromethane, but the Gualtieri study utilized particulate ranging from 10 to 80 μm, as this study was intended to evaluate the potential for lung damage in response to inhalation of tire particulate. Therefore, while the composition of the rubber products in each study (tire debris in Gualtieri and ground rubber in Birkholz) may be similar, the total surface area for extraction is much higher in the Gualtieri study allowing for greater quantity of the chemicals to be extracted. However, Schiliro, et al. (2013) also found negative mutagenicity results when testing extracts of PM10 and PM2.5 collected above artificial turf fields containing ground rubber infill.[95] Therefore, even if mutagenic chemicals can be extracted from ground rubber, as indicated in Gualtieri, et al. (2005), the exposure is unlikely to be high enough to elicit this response from inhalation. As a note, organic extraction does not represent a reasonable extraction method for mimicking lung exposure to humans. Rather, organic extraction allows for a worst case scenario in terms of exposure to organic constituents. Although several of the rubber compounding materials may be extractable using harsh solvents such as dichloromethane, few organic compounds can be extracted using water. Thus, genotoxicity screens using organic extracts must be viewed with caution, as relevance to human exposure scenarios is unclear and overestimation of genotoxic potential from organic constituents is likely. While the results from these two studies appear to be contradictory, the dissimilarities in study approach and endpoints of interest make comparison between the studies difficult. Further research may be required to fully characterize the mutagenic potential associated with exposure to ground rubber.

In a study of occupational exposures in scrap-tire shredding facilities, airborne particulate collected in two scrap-tire shredding plants was subject to a mutagenicity screen in *Salmonella*.[17] The particulate was extracted using acetone, the extract analyzed for chemical composition and tested for mutagenicity with and without S9. The extracted chemicals did not exhibit mutagenic activity in any of the strains tested in the absence of S9. The addition of S9 increased frame-shift mutations, but not base-pair substitution mutations. Based on chemical structure and known mutagenic activity of compounds used in rubber manufacturing, vulcanization stabilizers (and degradation products such as N-nitrosamines) and PAHs may contribute to the mutagenic potential of the particulate matter generated during scrap-tire shredding. The authors caution that without understanding the quantities of particulate generated and the ability of the body to absorb chemicals through the particulate, conclusions regarding the mutagenicity of these particles *in vivo* are premature. As suggested earlier, methodology utilizing organic extraction is not the best model for anticipating mutagenic effects in the human lung. In fact, organic extraction is likely to exaggerate the mutagenic potential of organic constituents, and therefore the findings from this study may not be relevant to human exposure scenarios.

In response to a concern that artificial turf fields may increase *Staphylococcus aureus* infections, a comparison study was initiated at Penn State University to evaluate microbial populations in rubber-infilled artificial turf fields versus natural grass fields. Total microbial numbers were *lower* in synthetic turf systems when compared to natural grass fields. *Staphylococcus aureus* was not found on any of the playing surfaces. One explanation offered is that the surface temperatures associated with rubber-infilled artificial turf fields, which are much higher than natural grass fields, are not conducive to the growth of many infectious microbes, including *S. aureus*.[25] This finding is somewhat contradictory to studies suggesting that play on artificial turf surfaces may be a risk factor for the *S. aureus* infections.[124-126] However, artificial turf fields are more abrasive than natural grass fields, and as a result, athletes are more prone to epidermal injuries such as cuts or abrasions.[27] Therefore, transmission of microbes through locker room activities (towel or equipment sharing, for example) could result in a higher likelihood of skin penetration and subsequent infection.

5.2 IMPACTS ON THE ENVIRONMENT

In considering the hazards associated with the use of ground rubber in commercial applications, such as playgrounds or athletic fields, ecological endpoints are a necessary consideration. A standard aquatic toxicity battery as recommended by the EPA includes evaluating lethality or growth inhibition in algae, invertebrates (often *Daphnia magna* or *Ceriodaphnia dubia*), and fish, although the approach for estimating aquatic toxicity of solids is not straightforward.[127] Other international regulatory bodies (OECD, Health Canada) employ similar recommendations, but sometimes use different test species. The method used in much of the existing literature addressing the toxicity of tire shreds, ground rubber, or other tire-related material (wear particles, etc.) includes using a leachate of the rubber product and treating the test species.

Birkholz et al. leached 250g of both fresh and aged ground rubber from tires in 1L of water and treated bacteria (*Vibrio fisheri*), algae, microcrustaceans (*Daphnia magna)*, and fish (*Pimphales promelas*) with the resulting leachate.[6] While leachates from the fresh ground rubber were toxic to all species investigated, aging of the ground rubber resulted in a nearly

60% reduction in toxicity. Further reduction in toxicity occurred with the addition of nutrients, sewage seed, and five days of aeration. They conclude that while undiluted leachate from fresh tire rubber may pose a moderate threat to aquatic toxicity, environmental aging will attenuate this toxicity such that the risk is not appreciable. Further, they state that surface runoff from playgrounds or athletic fields containing ground rubber is likely to be diluted by larger bodies of water (in which the aquatic species dwell), which should eliminate the possibility that even fresh ground rubber is an ecologic hazard.[6]

Sheehan et al. evaluated the toxicity of samples (and serial dilutions thereof) collected from the aforementioned field study in Maine to *Ceriodaphnia dubia* and *Pimphales promelas*.[128] It was noted, however, that the shreds used in the field study contained exposed steel belts at the cut edges of the shreds. Metallic material from steel belts is removed from ground rubber during production. Survival and reproductive capacity of *C. dubia* was negatively impacted by tire shreds placed below the water table over control, but not from that placed above the water table. Furthermore, it was expected that *C.dubia* toxicity would be reduced to that equivalent to background upon a 2- to 4-fold dilution of leachate. It was suggested that the demonstrated toxicity was related to the concentration of iron (and possibly other metals), which are likely attributable to the presence of steel belting in the shreds. Aquatic toxicity studies using tire derived aggregate (TDA) produced similar results: a small amount of dilution (~10-25%) would eliminate adverse effects on *C. dubia* from TDA placed below the groundwater table [129]. In the same study, *w*ater collected from TDA-filled trenches had no toxic impacts on fathead minnows.

ADEME, in coordination with ALIAPUR and Fieldturf Tarkett (a manufacturer of artificial turf field surfaces), assessed the environmental impact of the use of ground rubber in outdoor artificial turf fields.[4] In this study, ground rubber infilled artificial turf fields were built atop a lysimeter and water collection system and treated with simulated rain (one year of rainfall). Percolates were collected weekly, combined, and analyzed at 1, 2, 3, 6, 9, and 11 months. The percolates were then used to treat *Daphnia magna* and *Pseudokirchneriella subcapitata* (soft water algae). Results from this study indicate that these species were not affected by the percolates from the rubber-infilled artificial turf fields.

Milone and MacBroom, Inc. (MMI) treated *Daphnia pulex* with stormwater collected from a drainage system at an artificial turf field to predict aquatic toxicity from field runoff.[92] After 24 and 48 hours of treatment, there was no lethality in the aquatic species, indicating that the field runoff is not acutely toxic in *Daphnia pulex*. As this study only predicts acute aquatic toxicity, they also analyzed the drainage water for metals to determine if any constituents exceeded the lowest aquatic life criterion established by the Connecticut Department of Environmental Protection. Of the metals analyzed for, only zinc was detected (in 3 of 5 samples). However, zinc concentrations did not exceed the lowest aquatic toxicity screening criteria for zinc of 0.065 mg/L in any of the samples.

The Laboratory of Ecological Risk Assessment in the Netherlands (RIVM) assessed leaching of zinc from rubber infilled artificial turf fields.[64] They estimated zinc loads in soil, groundwater and surface water based on leaching results from both laboratory and field experiments utilizing both fresh and aged ground rubber. Based on these studies, they conclude that zinc leaching (and thus load) increases with aging. The predicted zinc loads to each compartment were compared to environmental risk criteria for soil, groundwater and surface water and found to exceed these criteria in all three environmental compartments, indicating that, based on this study, the use of rubber-infilled artificial turf fields presents an ecological risk. To address the uncertainties in this analysis, RIVM recommends a series of studies to: investigate the impact of aging of rubber in constituent releases to the environment; monitor drainage water from artificial turf fields utilizing rubber as an infill component; perform bioassays with drainage water; and to construct a miniaturized artificial turf field with a lysimeter to provide insight on emission and mobility of zinc under actual field conditions. The results of the above studies can provide useful information to improve the modeling and more accurately estimate risk to the environment.

Between 2006 and 2007, a literature review and limited experimental investigation was completed in the Netherlands by INTRON to study the potential environmental impact of use of rubber infill from recycled tires in artificial turf systems.[130] Detailed results from the study are not available, but the authors concluded based on a comparison of data to the Dutch Building Materials Decree that the leaching of zinc was the primary concern. Based on this conclusion, follow-up studies of the potential local impacts of zinc leaching from rubber infill were conducted between 2008 and 2009 by INTRON in association with TNO Quality Services.[131, 132] A laboratory-based lysimeter installed in a climate chamber was used to perform weathering tests with rubber obtained from passenger tires. Data from aged particles from the lysimeter percolate and column studies was used to estimate that the criteria specified in the Dutch Decree on soil quality would not be exceeded for 60 to 100 years when the entire field system is considered (i.e. rubber infill derived from passenger tires, lava underlay and sand drainage zone). It was also concluded that the standard for added dissolved zinc in surface water would not be exceeded for 50 to 95 years. Truck tires were also analyzed with the conclusion that the standards would be exceeded a few years earlier than for passenger tires.

In the original INTRON follow-up study conducted in 2008, the transport time through the sand layer was estimated based on an assumed partitioning coefficient. Based on questions regarding the validity of this assumption, adsorption coefficients for various types of lava and sand were determined at pH 6.5 and 7.5 with the conclusion that the actual zinc breakthrough time is likely longer than previously assumed, or 230 to 1800 years.[132] The technical lifetime of the rubber infill and artificial blades is 15 years. The authors recommend that the structural integrity and adsorptive capacity of the underlay materials be confirmed every 15 and 30 years, respectively.

Separate field tests completed by INTRON have confirmed the results of the laboratory studies. Field tests in 2007 from five fields aged 5 to 6 years showed that the drainage water concentration averaging 16 ppb was less than the average influent rainwater concentration of 33 ppb.[131] Data from the same fields collected in 2008 showed that the average zinc concentration in drainage water did not increase but that the concentration in rainwater decreased slightly.[132] Therefore, it can be concluded based on both field data and laboratory studies that for the fields considered by INTRON, zinc is not likely to penetrate the underlay materials over the time period spanning the technical lifetime of the rubber infill and artificial blade system.

The Norwegian Institute for Water Research, based on a leaching study conducted previously that collected run-off from artificial turf fields, modeled local concentrations of metals, PAHs, phthalates and other rubber-affiliated chemicals in surface water and sediment to estimate PEC/PNEC ratios, a measure of ecologic risk.[133] The risk assessment performed in this study was specific for local environments (i.e. surface runoff from artificial turfs in nearby streams). The PEC/PNEC ratio exceeded 1.0 (indicating a potential for ecologic risk in local environments) for octylphenol (2.9), total PAHs (1.13), and zinc (40) in surface water. In sediment, only octylphenol and zinc result in PEC/PNEC ratios greater than one. However, the leachate studies that provide the environmental concentrations for this study were determined based on a laboratory leaching study (recycled ground rubber placed in water), and were not collected based on a field study (or under simulated field conditions). The authors suggest that, while the results indicate an ecological risk, further work is required in order to more definitively characterize risk in a more realistic setting. In addition, they state that the ecological effects are likely to elicit an impact locally only, and that over the course of the year, the limited runoff is not expected to be an important source of pollution when compared to other potential sources.

In 2008, the Danish Ministry of the Environment reviewed the existing literature and conducted rubber infill and artificial turf laboratory leaching studies to supplement the available information.[52] A liquid to solid ratio of 10: 1 was with an extraction time of 24 hours on a shaker table. Potential chemicals of interest were determined by DCM extraction of the rubber infill. In addition to pure water, these studies included leaching by sodium chloride (pH 4.7) and calcium chloride (pH 11) due to the use of these salts to de-ice fields in Denmark. The scenario evaluated with the leaching data was overflow of drainage water to a nearby watercourse. For rubber infill derived from recycled tires (study infill no. 1, 2, 3 and 16), maximum PEC/PNEC ratios for surface water exceeded 1.0 for dicyclohexylamine (728), degradation products of 6-PPD (470), zinc (10), diisobutylphthalate (10) and dibutylphthalate (1.7). A PNEC for aniline was not derived, but using the $PNEC_{aqua}$ of 1.5 ppb presented in the aniline EU RAR and a dilution factor of 10, the maximum PEC/PNEC ratio would be 1.1.[134] The authors concluded that the potential for leaching of some classes of chemicals from rubber infill exists, but that the concentrations determined based on the laboratory study likely significantly overestimate natural leaching conditions. Among the factors affecting PECs under real conditions are liquid to solid contact efficiencies and decreasing leachate concentration over time. Taking into account these factors, the authors concluded that the results of the study are consistent with other studies that concluded that use of recycled rubber infill from car tires does not pose an unacceptable environmental risk.[3, 4, 51, 64, 130] However, field measurements were recommended to accurately assess potential risk.

Between 2005 and 2007, the Swiss Federal Authority of Sports (BASPO) performed field tests of simulated artificial turf surfaces using lysimeters originally designed for agricultural research.[51] The purpose of the testing was to study the substances that leach from synthetic sports surfaces under natural rainwater conditions over a period of one year. Of four artificial turf surfaces considered, one consisted of truck tire infill with quartz sand underlay, two used EPDM infill and one did not contain infill material. The surface area exposed was 1 m^2 and approximately 1.1 m (43 inches) of precipitation occurred during the test period.[51] Organic chemical detection limits were approximately 0.2 ppb (0.02 ppb for PAHs). Parameters monitored included total DOC, total dissolved organic nitrogen, inorganic nitrogen compounds, aniline, alkylated phenylenediamines, benzothiazole, PAHs, and zinc. The results of the tests indicated that zinc and PAH concentrations were not elevated when compared to the blank sample containing only gravel (Müller 2008). These results are attributable to zinc retention by absorption in the underlayment layer and low amounts of leachable PAHs in the rubber compounds. Aromatic amine and benzothiazole compounds were initially detected in the range of 10 to 300 ppb, but typically rapidly decreased to below the detection limit by the end of the testing period.[51, 52] The conclusion of the study was that organic substances similar to that observed in roadway runoff are leached off by rainwater over a relatively short time period, but that state of the art synthetic sports surfaces are unlikely to have adverse surface water or groundwater effects.[51] However, the need for longer term (i.e. multi-year) studies was noted to improve the understanding of the temporal effect of environmental stresses including light, ozone, oxygen and heat on rubber particles. Based on the results of this testing, BASPO Guideline 112 - Recommendations on Environmental Compatibility was developed.

Bocca, et al. collected samples of ground rubber from existing turf fields (at various locations on the fields).[135] These samples were subject to microwave acidic digestion to characterize composition; extraction with acetic acid; and extraction in water; and metals analysis. For metals detected in the ground rubber (via digestion), all were below the soil screening criteria, with the exception of cobalt, tin, and zinc. Zinc concentration in ground rubber was approximately 10,000 ppm, which is consistent with common formulations of tires that use approximately 1.0% zinc oxide as an activator of vulcanization. However, while the content of zinc was high in the rubber granualate, very little was able to leach into aqueous solution. When the ground rubber was mixed with water, less than 1% of the zinc leached into the water. The authors suggest that, if a risk to ecosystems results from the use of ground rubber in artificial turf fields exists, zinc contributes the greatest amount to this risk. However, they report a wide variability in both metallic composition and variability in leaching in this study, and state that local conditions and drainage may contribute to reduce or increase potential ecological risk. Sampling water at artificial turf fields may provide information that best predicts the risk to the environment from the use of ground rubber as infill.

The New York State Department of Environmental Conservation conducted a series of leaching studies on ground rubber, coupled with sampling of surface water at artificial turf fields which employed ground rubber as the infill.[7] Their initial study, a simulated precipitation leaching procedure (SPLP) conducted according to EPA SW-846 Method 1312, was used to evaluate the leaching potential of four ground rubber samples. The ground rubber (100 g) was mixed with 2 L of simulated rain water (pH = 4.2) and analyzed for SVOCs and metals. Zinc, iron, and copper were identified in the leachate in exceedance of the standard. Fifteen SVOCs were identified in the leachate, with aniline found at the highest concentration. Aniline and phenol were detected above the groundwater standard. Because this study design is expected to overestimate chemical releases, additional studies were conducted. First, a column study, simulating the conditions of the field, was conducted. Simulated rainfall was eluted intermittently, to replicate realistic leaching conditions. The concentrations of the analytes of interest were determined after 12, 24, 36, and 48 inches of rain. All analyte concentrations were lower than in the SPLP test, although aniline and phenol still exceeded the groundwater standard. Lastly, surface and groundwater sampling was conducted at two fields. Groundwater sampling results were present with potential risk related to impacted drinking water (see Section 5.1.1.3). Results for the surface water sampling indicated that all organics were below the limits of detection (and the surface water standard); zinc, although detected at 59.5 ug/L, was also below the surface water standard, as were all other metals detected. This suggests that leaching from artificial turf fields into surface water is unlikely to impact aquatic life. However, the results of this study are based on a single sampling event, and therefore, while they suggest that chemicals of interest do not leach into surface waters off of artificial turf fields at appreciable concentrations, they are not conclusive.

In addition to studies evaluating the potential for rubber products in artificial turf fields and playgrounds to leach chemicals and/or induce toxicity in aquatic species, research has been conducted to evaluate potential toxicity from ground tread particles. [136-138] These studies must be viewed with caution when considering aquatic toxicity in the natural environment as they do not account for particle aging, biodegradation of leached chemicals, or dilution in bodies of water, all important considerations when understanding the environmental relevance of the findings, as suggested by Birkholz, et al. (2003). In addition, in some instances, harsh organic solvents are used to extract the rubber material. The importance of selecting an appropriate solvent for extraction or leaching was demonstrated by Kanematsu, et al. (2009). They evaluated arylhydrocarbon receptor (AhR) response to extracts of rubber mulch in 100% water, 50:50 methanol:water, and 100% methanol. AhR responds to, among other ligands, PAHs. Although the methanol extract of rubber mulch induced an AhR response, the water extraction produced no response. [139] Additional research has recently been conducted to evaluate particles from tire tread, with studies focused on understanding toxicity of these particles under more relevant environmental conditions; these studies indicate that under typical environmental conditions, particles from tire tread are not toxic to aquatic species.[140]

Additional studies evaluating the impact of other tire-related material (whole tires, scrap tire fill, etc.) were also performed by several researchers. The Minnesota Pollution Control Agency conducted a general roadside vegetation survey on roads containing or lacking scrap tire fill that indicated no difference between the two road types, suggesting that leaching from the pavement into road runoff did not affect plant survival or growth.[81] Anecdotal evidence regarding the impact of tires used as energy absorbing bumpers on fresh water lake docks indicated that the tires have little effect on the water, fish, or plant life in the lake. [11] However, the Canadian Water Research Institute prepared contaminated water by submerging whole passenger tires in natural groundwater with continuous aeration. The contaminated water was used to treat fish (rainbow trout and fathead minnows) and cladoceran (*Daphnia magna*). The leachate was 100% lethal within 48 hours to the rainbow trout, but no toxicity was demonstrated in fathead minnows or *D. magna*. Zinc was identified as the toxic constituent for rainbow trout.[141] This study, however, is intended to understand toxicity from submerged whole tires as used in artificial reefs rather than rubber material contacting rainwater, as would occur with ground rubber used in turf fields or artificial playgrounds. It has been well established that zinc can leach from rubber material upon contact with water. However, water renewal (as with a rain event), dilution in water bodies, and the presence of sediment and soil (where zinc preferentially partitions) would attenuate the toxicity of the leached zinc to aquatic species.

Collectively, these ecological toxicity studies indicate that, although some laboratory based-research suggests that leachates or extracts of tire material can result in decreased survival of some species, [136-138, 141] evidence from scenarios relevant to the use of ground rubber in playgrounds and artificial turf fields (e.g. from field sampling, from anecdotal reports of real-world uses of tires, under conditions that promote biodegradation or allow for dilution) suggests that this toxicity is not likely to occur under real-world conditions. This conclusion is supported by analysis of artificial turf field run-off, which does not contain leached chemical constituents in levels exceeding aquatic toxicity thresholds.[7, 132] Therefore, the use of ground rubber in athletic fields and playgrounds is unlikely to represent an ecological risk.

5.3 CONCLUSIONS FROM LITERATURE REVIEW

The literature surrounding the safety of ground rubber in uses such as playgrounds or artificial turf fields is, collectively, quite thorough in addressing potential concerns from the consumer standpoint. Each likely exposure pathway has been investigated, and in many cases deemed to be an unlikely risk to either human or ecological receptors. In many cases, authors focused on children as a susceptible subpopulation, and yet risks remained low. The current literature does not provide a compelling argument for discontinuation of the use of ground rubber products in playgrounds or athletic fields from the standpoint of either human or ecological risk. Furthermore, there are significant benefits associated with the use of ground rubber in these applications. Many of the criticisms that remain focus on the absence of toxicity information relating to some of the chemicals associated with ground rubber. However, due to the shear volume of chemicals (both natural and synthetic) that are found in consumer products, a complete toxicity profile for all chemicals for which humans are exposed is a goal requiring many decades of future study. The vast number of synthetic and natural chemicals has motivated health scientists to develop tiered and hierarchical approaches to safety assessment. The following section details the approaches used for chemical safety assessments of whole products, citing examples from both natural and synthetic products.

6.0 SCIENTIFIC APPROACH TO CHEMICAL, SITE AND PRODUCT SAFETY ASSESSMENT

The U.S. Environmental Protection Agency has established an overall framework for assessing the nature and extent of site-specific health risks as part of the National Oil and Hazardous Substances Pollution Contingency Plan (NCP).[142] A comprehensive evaluation of human health risk involves several key components. The first step is the collection and evaluation of data relative to human heath and the identification of substances for risk characterization. An exposure assessment is then performed to assess the magnitude, frequency and duration of exposure, typically with a characterization of typical and reasonable maximum exposure. As part of an exposure assessment, the pathways of exposure (e.g. oral, dermal, inhalation), exposure concentrations and characteristics of the exposed population are used to calculate intake.

In parallel to the exposure assessment, a toxicity assessment is completed to describe the types of adverse health effects and dose-response relationship which describes the relationship between magnitude of exposure and adverse effects. The process of characterizing the nature and extent of strength of evidence of causation, as well as determining whether the agent can cause a specific adverse health effect is termed hazard identification. The quantitative use of toxicity information to relate the administered dose to incidence of adverse outcomes in humans at different exposure levels is termed dose-response evaluation. Although most natural and anthropogenic settings are characterized by complex mixtures of inorganic and organic chemicals, many of which are not fully studied, site risk assessments are primarily based on currently existing toxicity information developed for specific chemicals.

The outcome of the exposure and toxicity assessment is summarized in the risk characterization. One of the important features of a risk characterization is that both qualitative and quantitative statements regarding potential for noncancer or cancer risks are developed. Another purpose of the risk characterization is to evaluate uncertainties and to address the need for further characterization.

High quality general human health and ecological evaluations of recycled tire rubber products which conform to the U.S. EPA risk assessment framework have been completed, and these assessments have concluded that these products present a low likelihood of adverse health effects.[1, 4, 5] Recently, the Bainbridge Island School District located in Washington State requested an initial site-specific assessment of potential human health risks associated with the installation of a synthetic turf field based on recycled tire rubber.[143] This assessment was consistent with the U.S. EPA risk assessment framework and considered exposure concentration, route of chemical exposure, duration of exposure and chemical potency. The assessment identifies the important distinction between the composition of a product and the potential environmental exposure. For many consumer products, the component chemicals are not accessible to humans (e.g. the lead used inside cathode ray tube computer monitor) while in other instances the chemicals are accessible but absorbed by the body at different rates (e.g. the age dependent internal uptake of lead in paint chips). Analytical methods which monitor unventilated headspace or total chemical composition dissolved in strong acid are useful for hazard identification but unusable for assessment of exposure, which is a critical step in the risk assessment process. Exposure scenarios representative of upper bound Pacific Northwest exposures were assessed in a child sport play scenario and teenager sport play scenario. The risk and exposure assessments were based on key chemical compounds determined based on a review of the literature and paired with conservative (i.e. likely to overestimate risk) assumptions of 261 days/year exposure frequency, high exertion breathing rates for 3 hours per day and use of indoor concentrations as a surrogate for outdoor concentrations. The assessment was consistent with other generic evaluations of recycled tire rubber and concluded some chemicals leach or volatilize from the recycled product in small amounts, but the weight of evidence indicated that the carcinogenic and noncarcinogenic risk for inhalation, dermal adherence and incidental ingestion pathways were minimal.

Although comprehensive health assessments of ground rubber based fields have been completed which are consistent with the EPA risk assessment framework, there are additional considerations when evaluating the chemical composition of a discrete consumer product. Chemicals in the environment are derived from natural sources such as plant or animal metabolism, forest fires or weather or from synthetic sources during chemical manufacture. There have been over 39 million organic and inorganic compounds identified from synthetic or natural sources in the scientific literature since 1957 with each of these compounds assigned a unique identifier by the American Chemical Society termed a CAS number.[144] In the quantitative assessment of potential human health risk, the current state of knowledge precludes individual assessment of each of these compounds. For example, as of September, 2009, there were only 548 substances with peer reviewed quantitative toxicity factors listed in the U.S. EPA Integrated Risk Information System (IRIS) database, or 0.001% of the total substances identified since 1957.[145] Similarly, U.S. EPA Regions III, VI and IX maintain a database of toxicity values which includes additional provisional data but currently includes only 670 compounds.[146]

The absence of toxicity factors for each possible compound does not imply that a framework to rigorously assess human safety of complex products does not exist. In contrast, there are a variety of tools health scientists use to assess product safety, many of which rely on hierarchical approaches, human epidemiology and evaluation of indicator compounds for which toxicity is well characterized. One example of such an approach is the U.S. EPA's Voluntary Children's Chemical Evaluation program, which identified 23 compounds for detailed assessment based on data which showed exposure had occurred based on human blood, breast milk or exhaled breath.[147] For these compounds, sponsoring companies were asked to identify all of the sources of exposure that contributed to the observed body burdens. In this program, a tiered approach was used to assess data needs for both potential hazard and exposure. Another example is in the assessment of disinfection byproducts created during drinking water treatment, where U.S. EPA has identified and cataloged more than 600 halogenated and other byproduct chemicals.[148] Based on a peer review, 252 of these compounds were detected in drinking water in various studies. Of the chemicals detected in drinking water, only 30 were considered to have sufficient toxicity data and 209 were evaluated for cancer potential using theoretical structural activity relationships. Compounds that show high potential for toxicity were considered for further animal or other testing. Many of the compounds were considered to be of low priority for further study due to the low likelihood of adverse health effects. The qualitative hierarchal treatment of potential chemical risk is an essential and key step in the assessment of real world consumer products, including food, many of which are comprised of complex mixtures.

Although exposures to complex mixtures are frequently associated with synthetic, or human made chemicals, there are many examples of natural products for which individual chemical assessment is not plausible. For example, a detailed chemical analysis of natural products such as roasted coffee reveals an extensive list of over 1,000 compounds, the majority of which traditional quantitative risk assessment is not possible.[149] Of the 30 compounds tested for rodent carcinogenicity, 21 were positive, resulting in approximately10 mg of rodent carcinogen per cup of coffee. One of the compounds detected, the carcinogenic PAH benzo(a)pyrene, is a common byproduct of cooking. However, most people generally consider coffee to be an extremely safe product when consumed in moderation based on the characteristics of the product. Coffee is not necessarily a risk factor in human cancer. Rather, this example shows that natural compounds that are carcinogens in high dose rodent tests are ubiquitous in the human diet, at levels often far exceeding synthetic chemical exposure.

The most abundant semi-volatile organic compound identified in ground rubber head space analyzed by the Connecticut Agricultural Experiment Station was benzothiazole. EHHI specifically noted the lack of information regarding benzothiazole was a severe limitation of the existing research on recycled tire rubber exposure. This substance, however, has been evaluated by the Joint FAO/WHO Expert Committee on Food Additives (JECFA), who considers benzothiazole to be a safe food additive when ingested as a flavoring agent and is considered to be generally recognized as safe (GRAS) by the Flavor and Extract Manufacturers Association (FEMA).[150] Further, there are many natural dietary sources of this compound such as fresh apple, sour cherry, butter, wine, tea and cooked scented rice.[151] This example illustrates the ubiquity of chemicals in our diet as well as the importance of comprehensive evaluation of health hazards.

The University of California – Berkley maintains a Carcinogenic Potency Database (CPDB), which catalogs 6,500 chronic, long-term animal studies on approximately 1,500 chemicals. This research group, including the creator of the Ames test, a mutagenic biological assay screening method, has identified several key points regarding synthetic versus natural chemical exposure which are essential for reliable assessment of product health effects, costs and benefits. Natural chemical exposure is far broader and much greater in magnitude than synthetic chemical exposure, yet exposure to natural chemicals has not been systematically evaluated. For example, 99.99% of dietary pesticides (upwards of 10,000 compounds) are estimated to be naturally produced by plants for protection against fungi, insects or animal predators.[149] Accordingly, public and regulatory perception of carcinogenic hazards, which emphasize synthetic chemicals, is not properly aligned with true human exposure. Given the level of these natural pesticides, dietary human exposure to known rodent carcinogens is frequent and high in magnitude. Assessment of the potential health risk of exposure to natural compounds should not reduce the level of study of synthetic chemicals. However, knowledge of the ubiquitous presence of natural and synthetic compounds (many of which are carcinogenic in rodent studies at high doses) is useful in understanding the tiered and hierarchical scientific process which must be used by heath scientists to assess food and consumer product safety.

In food or consumer products, many inorganic, volatile and semi-volatile compounds will be detected for which detailed toxicity assessments have not been completed. In these instances, three types of assessments are performed. First, whole product safety is assessed using animal data. For example, in the assessment of white spirits solvent (mineral spirits), guinea pigs were the most sensitive of five species based on continuous inhalation exposure for 90 days.[152] Mineral spirits are complex products derived from crude oil of variable raw composition and whole product testing is essential in understanding human health risk. Next, key individual chemicals of known toxicity are evaluated. In the case of mineral spirits, scientific consensus dictates that an individual exposure or risk assessment be performed for trace aromatic compounds such as 1,2,4-trimethylbenzene and benzene. Finally, human epidemiological information is considered, typically from controlled studies or occupational exposure assessments which report short and long term neurological, target organ specific, irritation and other effects. In some instances, reliable human epidemiological data may not be available due to the difficulty in controlling for confounding exposures or lack of knowledge regarding historical dose or non-occupational dose. However, even in these instances, qualitative case reports regarding respiratory irritation or dermal sensitivity may be available.

In 2007, EHHI issued a report recommending a moratorium on the installation of fields or playgrounds that use recycled rubber crumb based on limited testing which showed that low levels of metals or organic compounds are leachable from tire rubber, extrapolation from occupational studies, and critique of relevant quantitative studies. While the creation of a long term research program for recycled tire rubber products may be appropriate, the weight of evidence and range of studies that have been performed to date does not support EHHI's conclusion that use of existing fields should be limited or that planned fields should not be installed. EHHI's criticisms of existing studies fail to acknowledge the spectrum of valid qualitative and quantitative methodologies which have been traditionally employed to evaluate many of the useful, but chemically complex, consumer products where human contact occurs on a daily basis. Specific examples of EHHI criticisms that could generically be applied to other common products include surface temperature (comparable to upper bound outdoor asphalt basketball court temperatures of 160 °F), leachable organic chemicals lacking toxicity factors (comparable to several hundred semivolatile and volatile compounds found in roasted coffee) or the potential for unacceptable levels of zinc in the rubber tire mulch leachate (comparable to zinc leached from galvanized residential cistern rainwater collection systems).[40] The concerns publicized by EHHI represent a viewpoint that is unsupported by the current scientific consensus, or weight of evidence, as well as the views of the majority of governmental agencies.

As can be seen from these examples, criticisms of ground rubber which question the safety of the product based solely on the absence of comprehensive peer reviewed toxicity database for every possible detected organic compound are quite misleading. Scientific health and safety assessment of natural and processed food and food additives, as well as consumer products is necessarily based on a holistic and hierarchical approach which synthesizes a number of different types of information to inform an assessment of product safety. Such assessments ensure that beneficial products are available to the public, and that use of these products will not result in unacceptable adverse human or ecological effects.

7.0 CONCLUSIONS

Based on a review of the available studies, there is a low likelihood of adverse health effects for children or athletes exposed to recycled tires found at playgrounds or athletic fields (Table 1). There were no short-term or urgent research needs identified upon consideration of the weight of evidence presented in the current literature. However, additional research could be useful in better defining and communicating potential risks. One such area is assessment of fine particulate exposure at ground rubber installations and assessment of outdoor airborne concentrations of volatile organic compounds as a function of temperature. Based on the range of questions and concerns among various stakeholders, another area of potential inquiry could be site-specific assessment of zinc concentrations in local ecosystems. Although some studies have suggested that more information is needed regarding the potential for natural rubber allergy after contact with recycled tire products, no evidence was found to support the hypothesis that tires, which are made from natural rubber in bale form, are likely to cause adverse allergic reactions.

Attachment 1: Calculation of outdoor airborne ground rubber concentration from wind dispersion as PM-10.

EPA 2002. Equation E-4[102]			
Area of site	8,094	m^2	Large 2-acre field.
Area of site	2.0	acres	Unit conversion.
A (default)	16.2302	unitless	EPA 2002.[102] Equation E-4.
B (default)	18.7762	unitless	EPA 2002. Equation E-4.
C (default)	216.108	unitless	EPA 2002. Equation E-4.
Q/C_{Wind}	73.69941495	g/m^2-s per kg/m^3	EPA 2002. Equation E-4.
V (no vegetation)	0	%	EPA 2002. Equation 4-5.
U_m (default)	4.69	m/s	EPA 2002. Equation 4-5.
zo (plowed field)	1	cm	Hayes et al. (eds) 1996.[105] Figure C-3-3.
u* (3-mm diameter mode)	1	m/s	Hayes et al. (eds) 1996. Figure C-3-1.
u_t (threshold velocity)	16.38	m/s	Hayes et al. (eds) 1996. Equation C-3.
x	3.09		Hayes et al. (eds) 1996. Equation C-4.
F(x)	0.0034		Hayes et al. (eds) 1996. Figure C-3-2.
C_{wind} = 1/PEF	1.1E-11	kg/m^3	EPA 2002. Equation 4-5.
C_{wind} = 1/PEF	0.01	ug/m^3	Unit conversion.

Attachment II: Gastrric digestion supplmental childhood chronic ingestion assessment: cancer risk and non-cancer hazard quotient

Cancer Risk - Screening Assessment

Chemical	Age range considered	Exposure duration (years)	Gastric Digestion Concentration (μg/g)	Slope Factor (mg/kg-day)$^{-1}$	Slope Factor Source	Excess Lifetime Cancer Risk [a]
Arsenic	3 to 70	Child (16 years) + Adult (14 years) = 30 years total	0.031	9.45	OEHHA	2E-07
Cadmium			0.014	0.38	OEHHA	4E-09
Lead			0.71	0.0085	OEHHA	5E-09
Aniline			33.5	0.0057	OEHHA	1E-07
					Total	4E-07

Hazard Quotient - Screening Assessment

Chemical	Age range considered	Exposure duration (years)	Gastric Digestion Concentration (μg/g)	Ordal RfF (mg/kg-day)	RfD Source	Maximum Hazard Quotient
Antimony	3 to 70	Child (16 years) + Adult (14 years) = 30 years total	0.55	0.0004	IRIS	0.002
Arsenic			0.031	0.0003	IRIS	0.0002
Barium			0.44	0.2	IRIS	0.000003
Cadmium			0.014	0.001	IRIS (food)	0.00002
Chromium			0.285	0.003	IRIS	0.0002
Cobalt			0.25	0.02	NCEA P	0.00002
Copper			8	0.04	HEAST	0.0003
Lead			0.71	0.00067	OEHHA	0.002
Molybdenum			0.09	0.005	IRIS	0.00003
Nickel			0.135	0.02	IRIS	0.00001
Selenium			0.09	0.005	IRIS	0.00003
Vandium			0.048	0.001	IRIS	0.0001
Zinc			130	0.3	IRIS	0.0007
Aniline			33.5	0.007	NCEA P	0.008
Captan			2.5	0.13	NCEA P	0.00003
					Total	0.013

a An age-dependant adjustment factor of 3 for ages 3 to 15 was used to estimate risk, as was done in the initial risk assessment performed by OEHHA. However, this adjustment factor is recommended by the U.S. EPA ***only*** in cases where the mode of action of the chemical is definitively mutagenic. While this may not be the case for all chemicals considered here, the risk calculation here was modeled after the initial OEHHA risk assessment.

Sample Calculation: Cancer

Risk = CS x IR x EF x ED x FI / (AT x BW) x (SF x ADAF)

Chemical	Age range	Concentration (mg/g)[a]	Ingestion rate (g/day)[b]	Exposure Frequency (day/year)[c]	Exposure duration (years)	Fraction Ingested from Sourced	Averaging Time	Average Body Weight (kg)[d]	Slope Factor $(mg/kg\text{-}day)^{-1}$[e]	Age-Dependant Adjustment Factor[f]	Risk
		CS	IR	EF	ED	FI	AT	BW	SF	ADAF	R
Arsenic	3 to 5	0.000031	0.1	129	3	100%	25550	17.5	9.45	3	8E-08
	6 to 10	0.000031	0.1	129	5	100%	25550	27.5	9.45	3	8E-08
	11 to 15	0.000031	0.1	129	5	100%	25550	47.5	9.45	3	5E-08
	16 to 18	0.000031	0.1	129	3	100%	25550	65	9.45	1	7E-09
	19 to 70	0.000031	0.05	129	14	100%	25550	70	9.45	1	1E-08
				Total	30						2E-07

Notes:

a Based on results from gastric ingestion study by OEHHA

b Based on EPA recommendation for soil ingestion rate (100 mg/d)

c Exposure frequency is 5 days per week x 4.3 weeks per month x 6 months per year equal to 129 days per year. This frequency is based on EPA recommendations for outdoor recreational activity and is also used in RIVM and Norwegian oral ingestion risk assessments for ground rubber.

d EPA Children's Exposure Factor Handbook

e California Integrated Waste Mangagement Board, 2007

f An age-dependant adjustment factor of 3 for ages 3 to 15 was used to estimate risk, as was done in the initial risk assessment performed by OEHHA. However, this adjustment factor is recommended by the U.S. EPA in their Supplemental Guidance for Assessing Susceptibility from Early-Life Exposure to Carcinogens (2005) only in cases where the mode of action of the chemical is definitively mutagenic. While this may not be the case for all chemicals considered here, the risk calculation here was modeled after the initial OEHHA risk assessment.

Sample Calculation: Non-Cancer

HQ = CS x IR x EF x ED x FI / (AT x BW) / (RfD)

Chemical	Age range	Concentration (mg/g)[a]	Ingestion rate (g/day)[b]	Exposure Frequency (day/year)[c]	Exposure duration (years)	Fraction Ingested from Sourced	Averaging Time	Average Body Weight (kg)[d]	Oral Refrence Dose (mg/kg-day)	RdD Source	Hazard Quotient
		CS	IR	EF	ED	FI	AT	BW	RfD	--	HQ
Antimony	3 to 5	0.00055	0.1	129	3	100%	1395	17.5	4.00E-04	IRIS	0.002
	6 to 10	0.00055	0.1	129	5	100%	2325	27.5	4.00E-04	IRIS	0.001
	11 to 15	0.00055	0.1	129	5	100%	2325	47.5	4.00E-04	IRIS	0.001
	16 to 18	0.00055	0.1	129	3	100%	1395	65	4.00E-04	IRIS	0.001
	19 to 70	0.00055	0.05	129	14	100%	6510	70	4.00E-04	IRIS	0.0003
										Maximum	0.002

Notes:

a Based on results from gastric ingestion study by OEHHA

b Based on EPA recommendation for soil ingestion rate (100 mg/d)

c Exposure frequency is 5 days per week x 4.3 weeks per month x 6 months per year equal to 129 days per year. This frequency is based on EPA recommendations for outdoor recreational activity and is also used in RIVM and Norwegian oral ingestion risk assessments for ground rubber.

d EPA Children's Exposure Factor Handbook

REFERENCES

1. California Integrated Waste Management Board, *Evaluation of Health Effects of Recycled Waste Tires in Playground and Track Products*. 2007, Integrated Waste Management Board: Sacramento, CA.
2. Hofstra, U., *Environmental and Health Risks of Rubber Infill: Rubber crumb from car tyres as infill on artificial turf*. 2007, INTRON.
3. van Bruggen, M., E.M. van Putten, and P.C.J.M. Janssen, *Nitrosamines released from rubber crumb* 2007, RIVM: Bilthoven, the Netherlands.
4. Moretto, R., *Environmental and health assessment of the use of elastomer granules (virgin and from used tyres) as filling in third-generation artificial turf*. 2007, ADEME/ALIAPUR/FIELDTURF TARKETT. p. 1-27.
5. Norwegian Institute of Public Health and the Radium Hospital, *Artificial turf pitches – an assessment of the health risks for football players*. 2006, Norwegian Institute of Public Health and the Radium Hospital: Oslo. p. 1-34.
6. Birkholz, D.A., K.L. Belton, and T.L. Guidotti, *Toxicological evaluation for the hazard assessment of tire crumb for use in public playgrounds*. J Air Waste Manag Assoc, 2003. **53**(7): p. 903-7.
7. Lim, L. and R. Walker, *An Assessment of Chemical Leaching, Releases to Air and Temperature at Crumb-Rubber Infilled Synthetic Turf Fields*, New York State Department of Environmental Conservation and Department of Health, Editor. 2009.
8. Office of Environmental Health and Hazard Assessment, *Safety Study of Artificial Turf Containing Crumb Rubber Infill Made from Recycled Tires: Measurements of Chemicals and Particulates in the Air, Bacteria in the Turf, and Skin Abrasions Caused by Contact with the Surface*, Department of Resources Recycling and Recovery, Editor. 2010, State of California.
9. Reschner, K. *Scrap Tire Recycling- A Summary of Prevalent Scrap Tire Recycling Methods*. 2006; Available from: http://www.energymanagertraining.com/tyre/pdf/ScrapTireRecycling.pdf.
10. Stutz, J., et al., *Recycled rubber products in landscaping applications*. 2003, Tellus Institute Resource and Environmental Strategies: Boston, MA. p. 1-19.
11. Liu, H.S., J.L. Mead, and R.G. Stacer, *Environmental effects of recycled rubber in light-fill applications*. Rubber Chem & Tech, 2000. **73**(3): p. 551.
12. U.S. EPA. *Management of Scrap Tires*. 2008; Available from: http://www.epa.gov/garbage/tires/basic.htm.
13. Rubber Manufacturers Association. *RMA Briefing Sheet: The use of scrap tire as playground material*. 2008 4/21]; Available from: http://www.rma.org/scrap_tires/scrap_tire_markets/.
14. U.S. EPA. *Tire Fires*. 2007; Available from: http://www.epa.gov/garbage/tires/fires.htm.
15. Anderson, M.E., et al., *A case study of tire crumb use on playgrounds: Risk analysis and communication when major clinical knowledge gaps exist*. Environ Health Perspect, 2006. **114**(1): p. 1-3.
16. Arizona Department of Environmental Quality, *Waste Tire Report*. 2002, Arizona Department of Environmental Quality: Phoenix, AZ. p. 1-9.

17. Chien, Y.C., et al., *Assessment of occupational health hazards in scrap-tire shredding facilities*. Sci Total Environ, 2003. **309**(1-3): p. 35-46.
18. Texas Natural Resources Conservation Commission (TNRCC). *TNRCC Information: The Many Uses of Rubber*. 2008; Available from: http://www.tceq.state.tx.us/assets/public/permitting/registration/tires/crumb.pdf
19. Recipneu. *Memo: Cryogenic rubber infill for artificial grass sports fields: Comprehensive description of its superior technical features*. 2006 [cited 2008 4/28]; Available from: http://www.tufsd.org/documents/budget/turffields/MEMO%20-%20Criogenic%20rubber%20infill%20for%20Artificial%20Grass%20%204%20Sept.pdf.
20. Sportexe. *Ambient vs. cryogenic: Do rubber processing methods affect synthetic turf system quality?* 2008 [cited 2008 4/28]; Available from: http://www.sportexe.com/PDF/101/TT_Rubber.pdf.
21. Clean Washington Center (CWC). *Best Practices in Scrap Tires & Rubber Recycling: Ambient versus Cryogenic Grinding*. 1998; Available from: www.cwc.org/tire_bp/t_bp_pdf/2-03-04.pdf
22. Weibold, R. *Rubber granulates for the purpose of infilling artificial turf. eximlink Ltd*. 2005; Available from: http://eximlink.com/wp-content/uploads/2007/10/eximreport_on_artificial_turf_infill.pdf.
23. Amme, R.C., et al., *Scrap tires in full swing: a recent study demonstrates the benefits of playground surfaces covered with recycled crumb rubber*. Resource Recycling, 2003: p. 1-2.
24. Spencer, A.-M., *What lies beneath: learn the pros and cons of a variety of surfacing solutions*, in *Parks & Recreation*. 2005.
25. McNitt, A.S. *Evaluation of Playing Surface Characteristics of Various In-Filled Systems*. April 9, 2008; Available from: http://cropsoil.psu.edu/mcnitt/infill.cfm.
26. Claudio, L., *Synthetic turf: health debate takes root*. Environ Health Perspect, 2008. **116**(3): p. A116-22.
27. Meyers, M.C. and B.S. Barnhill, *Incidence, causes and severity of high school football injuries on FieldTurf versus natural grass*. Am J Sports Medicine, 2004. **32**(7): p. 1626-1638.
28. Denly, E., K. Rutkowski, and K. Vetrano, *A Review of the Potential Health and Safety Risks from Synthetic Turf Fields Containing Crumb Rubber Infill*. 2008, New York City Department of Health and Mental Hygiene.
29. New York City Department of Health and Mental Hygiene. *Artificial Turf Fact Sheet*. 2008 April 15, 2008]; Available from: http://www.nyc.gov/html/doh/html/eode/eode-turf.shtml.
30. Ledoux, T., *Preliminary Assessment of the Toxicity from Exposure to Crumb Rubber: its use in Playgrounds and Artificial Turf Playing Fields*. 2007, New Jersey Department of Environmental Protection, Division of Science, Research and Technology: Trenton, NJ. p. 1-2.
31. Consumer and Environmental Health Services, *Update: New Jersey Investigation of Artificial Turf and Human Health Concerns*. 2008, New Jersey Department of Health and Senior Services.

32. California Integrated Waste Management Board, *Five-Year Plan for the Waste Tire Recycling Management Program*. 2009: Sacramento, CA.
33. Connecticut Department of Public Health, *Fact Sheet Artificial Turf Fields: Health Questions*, Environmental & Occupational Health Assessment Program, Editor. 2007: Hartford, CT. p. 1.
34. Connecticut Department of Public Health, *Human Health Risk Assessment of Artificial Turf Fields Based upon Results from Five Fields in Connecticut*. 2010, Program in Environmental and Occupational Health Assessment.
35. Lamie, P. *Memorandum to: Richard Reine, Director Concord Publc Works*. *Rubber Crumb Health Risk Evaluation*. *April 24*. 2007 [cited 2008 4/28]; Available from: http://www.concordma.gov/pages/ConcordMA_publicworks/rubber.pdf.
36. Executive Order #13045, *Protection of Children From Environmental Health Risks and Safety Risks*. 1997.
37. U.S. EPA Region 8, *Region 8 Crumb Rubber Research and Recommendation*. 2008.
38. Wachter, E.E., *Freedom of Information Act Request Number HQ-RIN-01586-09*, J. Reed, Editor. 2009, U.S. Environmental Protection Agency: Washington, D.C.
39. U.S. EPA, *A Scoping-Level Field Monitoring Study of Synthetic Turf Fields and Playgrounds*. 2009, United States Environmental Protection Agency: Office of Research and Development, National Exposure Research Laboratory.
40. Brown, D.R., *Artificial Turf - Exposures To Ground-Up Rubber Tires - Athletic Fields - Playgrounds - Gardening Mulch*, N. Alderman and S. Addiss, Editors. 2007, Environment & Human Health, Inc.: North Haven, CT. p. 1-40.
41. Kovac, F.J. and M.B. Rodgers, *Tire Engineering*, in *Science and Technology of Rubber*, J.E. Mark, B. Erman, and F.R. Eirich, Editors. 1994, Academic Press.
42. Morton, M., ed. *Rubber Technology*. Vol. 3rd edition. 1995, Chapman and Hall.
43. Donnet, B.J., *Carbon Black: Physics, chemistry and elastomer reinforcement*. 1993, New York: Decker.
44. Hewitt, N., ed. *Compounding Precipitated Silica in Elastomers: Theory and Practice*. 2007, William Andrew.
45. Plueddemann, E.P., ed. *Silane Coupling Agents*. Vol. 2nd edition. 1991, Springer.
46. Hepburn, C., *Rubber Compounding Ingredients - Need, Theory and Innovation, Part 1: Vulcanising Systems, Anti-Degradants and Particulate Fillers for General Purpose Rubbers*. 1994, Shrewsbury: Rapra Technology Limited.
47. Bender, H., *Manual for the Rubber Industry*. 1993: Bayer AG Rubber Business Group.
48. Lawrence Livermore National Laboratory, *Effect of waste tires, waste tire facilities and waste tire projects on the environment*, Department of Energy, Editor. 1996.
49. U.S. EPA, *AP-42 Section 4.12, Manufacture of Rubber Products*, United States Environmental Protection Agency (U.S. EPA), Editor. 1997.
50. Japanese Automobile Tyre Manufacturers Association, *JATMA Report No. 15-8A-0098*. 1998.
51. Müller, E., *Results of a Field Study on Environmental Compatibility of Synthetic Sports Surfaces*. 2007, Swiss Federal Authority of Sports (BASPO).
52. Nilsson, N.H., B. Malmgren-Hansen, and U.S. Thomsen, *Mapping, emissions and environmental and health assessment of chemical substances in artificial turf*. 2008, Danish Ministry of the Environment.

53. Nilsson, N.H., A. Feilberg, and K. Pommer, *Emissions and evaluation of health effects of PAH's and aromatic mines from tyres*. 2005, Danish Ministry of the Environment.
54. European Commission, *Directive 2005/69/EEC (OJ L323, 9/12/2005, p. 51)*. 2005.
55. International Agency for Research on Cancer, *Some non-heterocyclic polycyclic aromatic hydrocarbons and some related exposures*. 2005, IARC Monographs on the Evaluation of Carcinogenic Risk to Humans.
56. National Toxicology Program, *Report on Carcinogens, Eleventh Edition*, Department of Health and Human Services, Editor. 2005.
57. Agency for Toxic Substances and Disease Registry, *Public Health Statement for Polycyclic Aromatic Hydrocarbons (PAHs)*. 1995.
58. Takada, H., T. Onda, and N. Ogura, *Determination of polycyclic aromatic hydrocarbons in urban street dusts and their source materials by capillary gas chromatography*. Environ Sci Technol, 1990. **24**: p. 1179.
59. Agency for Toxic Substances and Human Services, *Toxicological profile for di(2-ethylhexyl)phthalate*, Department of Health and Human Services, Editor. 2002.
60. Clever, H.L.D., M.E.; Johnson, S.A., *The solubility of some sparingly soluble salts of zinc and cadmium in water and aqueous electrolyte solutions*. Journal of Physical Chemical Reference Data, 1992. **21**(5): p. 943.
61. The National Academies, *Dietary Reference Intakes for Vitamin A, Vitamin K, Arsenic, Boron, Chromium, Copper, Iodine, Iron, Manganese, Molybdenum, Nickel, Vanadium, and Zinc*. 2001, Washington, D.C.: National Academies Press.
62. U.S. EPA, *Zinc and compounds*, Integrated Risk Information System, Editor. 1992, National Center for Environmental Assessment.
63. Smolders, E. and F. Degryse, *Fate and effect of zinc from tire debris in soil*. Environ Sci Technol, 2002. **36**(17): p. 3706-10.
64. Verschoor, A.J., *Leaching of zinc from rubber infill on artificial turf (football pitches)*. 2007, RIVM: Bilthoven, the Netherlands.
65. Mattina, M.I., et al., *Examination of crumb rubber produced from recycled tires*. 2007, The Connecticut Agricultural Experiment Station. Department of Analytical Chemistry. .
66. The Swedish Chemicals Inspectorate (Kemi), *Synthetic turf from a chemical perspective - a status report*. 2006, KEMIKALIENIMSPEKTIONEN Sundbyberg. p. 1-31.
67. Miguel, A.G., et al., *Latex allergens in tire dust and airborne particles*. Environ Health Perspect, 1996. **104**(11): p. 1180-6.
68. U.S. EPA, *Supplemental guidance for assessing cancer susceptibility from early-life exposures to carcinogens, External Review Draft*. 2003.
69. Zhang, J.J., et al., *Hazardous chemicals in synthetic turf materials and their bioaccessibility in digestive fluids*. J Expo Sci Environ Epidemiol, 2008. **18**(6): p. 600-7.
70. Pavilonis, B.T., et al., *Bioaccessibility and Risk of Exposure to Metals and SVOCs in Artificial Turf Field Fill Materials and Fibers*. Risk Anal, 2013.
71. U.S. EPA, *Child-Specific Exposure Factors Handbook, Interim Report*. 2002.

72. U.S. EPA, *Memorandum: Acephate-sensitivity analysis for turf risk assessment [Case #819371, PC Code 103301, DP Barcode D276433]*, Office of Prevention Pesticides and Toxic Substances, Editor. 2001.
73. U.S. EPA, *A probabilistic exposure assessment for children who contact CCA-treated playsets and decks*. 2005.
74. Freeman, N., et al., *Characterizing indoor-outdoor activity patterns of young children*, in *Annual Meeting of the International Society of Exposure Analysis*. 2005: Tucson, AZ.
75. Freeman, N.C.G., et al., *Quantitative analysis of children's microactivity patterns: The Minnesota Children's Pesticide Exposure Study*. J Exposure Anal Environ Epidemiol, 2001. **11**: p. 501-509.
76. Beamer, P., et al., *Analysis of a child's mobility on their micro-level activity pattern*, in *Annual Meeting of the International Society of Exposure Analysis*. 2004: Philadelphia, PA.
77. Black, K., et al., *Children's mouthing and food-handling behavior in an agricultural community on the US/Mexico border*. J Expo Anal Environ Epidemiol, 2004. **15**: p. 244-251.
78. AuYeung, W., et al., *Young children's hand contact activities*, in *Annual Meeting of the International Society for Environmental Epidemiology*. 2004: Johannesburg, South Africa.
79. AuYeung, W., et al., *Young children's mouthing behavior: an observational study via videotaping in a primarily outdoor residential setting*. J Children's Health, 2004. **2**: p. 1-25.
80. Edil, T.B., J.K. Park, and J.Y. Kim, *Effectiveness of Scrap Tire Chips as Sorptive Drainage Material*. J. Envir. Engrg, 2004. **130**(7): p. 824-831.
81. Twin City Testing Corporation and A. Ronchak, *Waste tires in sub-grade road beds*, in *Environmental Study of the Use of Shredded Waste Tires For Roadway Sub-grade Support*. 1990, Minnesota Pollution Control Agency: St Paul, MN. p. 1-44.
82. Sengupta, S. and H. Miller, *An Evaluation of Recycled Tire Shreds as a Substitute for Gravel in Residential Soil Absorption Systems*, in *Civil Engineering Practice*. 2004. p. 33-52.
83. Downs, L., et al., *Water quality effects of using tire chips below the groundwater table*, in *Department of Civil and Environmental Engineering*. 1996, University of Maine: Orono, ME.
84. Humphrey, D.N. and E.K. Lynn, *Five Year Study of the Water Quality Effects of Tire Shreds Placed Above the Water Table*. 2000, Transportation Research Board: Washington DC.
85. Llompart, M., et al., *Hazardous organic chemicals in rubber recycled tire playgrounds and pavers*. Chemosphere, 2013. **90**(2): p. 423-31.
86. Wallace, L., E. Pellizarri, and C. Wendel, *Total volatile organic concentrations in 2700 personal, indoor, and outdoor air samples collected in the US EPA Team studies*. Indoor Air, 1991. **1**: p. 465-477.
87. Hodgson, A.T., et al., *Volatile organic compound concentrations and emission rates in new manufactured and site-built houses*. Indoor Air, 2000. **10**: p. 178-192.

88. Hoffman, K., et al., *The German environmental survey 1990/92 (GerES II): Sources of personal exposure to volatile organic compounds*. Journal of Exposure Analysis and Environmental Epidemiology, 2000. **10**: p. 115-125.
89. Diefenderfer, B., I. Al-Qadi, and S. Diefenderfer, *Model to predict pavement temperature profile: development and validation*. Journal of Transportation Engineering, 2006. **132**(2): p. 162-167.
90. Steele, W., et al., *The thermodynamic properties of benzothiazole and benzoxazole*. 1991, Bartlesville, Oklahoma: National Institute for Petroleum and Energy Research.
91. Chang, F.H., et al., *Emission characteristics of VOCs from athletic tracks*. J Hazard Mater, 1999. **70**(1-2): p. 1-20.
92. Bristol, S.G. and V.C. McDermott, *Evaluation of the Environmental Effects of Synthetic Turf Athletic Fields*. 2008, Milone and MacBroom, Inc (MMI).
93. Broderick, J.C., *Re: Ambient Air Sampling for PAH's, Comsewogue High School Football Field (565 Bicycle Path, Port Jeff Station, NY 11776; Sampling Date: October 16, 2007)*, M. Granger, Editor. 2007, J.C. Broderick & Associates: Port Jefferson Station, NY.
94. Broderick, J.C., *Re: Ambient Air Sampling for PAH's, Schreiber High School Football Field (101 Campus Dr., Port Washington, NY 11050; Sampling Date: October 17, 2007)*, E. Vonderhorst, Editor. 2007, J.C. Broderick & Associates, Inc.: Port Washington, NY.
95. Schiliro, T., et al., *Artificial turf football fields: environmental and mutagenicity assessment*. Arch Environ Contam Toxicol, 2013. **64**(1): p. 1-11.
96. U.S. EPA, *Review of the National Ambient Air Quality Standards for Particulate Matter: Policy Assessment of Scientific and Technical Information*. *EPA-452/R-05-005a*. 2005, Washington D.C.: Office of Air Quality Planning and Standards (OAQPS).
97. Dockery, D., et al., *An association between air pollution and mortality in six US cities*. New England Journal of Medicine, 1993. **329**(24): p. 1753-1759.
98. Pope III, C., et al., *Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults*. American Journal of Respiratory Critical Care and Medicine, 1995. **151**(3): p. 669-674.
99. Harrison, R. and J. Yin, *Particulate matter in the atmosphere which particle properties are important for its effects on health?* Sci Total Environ, 2000. **249**(1): p. 85-101.
100. Mauderly, J., L. Neas, and R. Schlesinger. *PM monitoring needs related to health effects*. in *Atmospheric observations: helping build the scientific basis for decisions related to airborne particulate matter*. *Report of the PM Measurements Research Workshop Chapel Hill, NC, July 22-23*. 1998. Cambridge, MA: Health Effects Institute.
101. Oberdorster, G., et al., *Association of particulate air pollution and acute mortality: Involvement of ultrafine particles?* Inhalation Toxicology, 1995. **7**(1): p. 111-124.
102. U.S. EPA, *Supplemental guidance for developing soil screening levels for superfund sites*. *OSWER 9355.4-24*. 2002, Washington D.C.: Office of Solid Waste and Emergency Response.
103. U.S. EPA, *AP 42, Fifth Edition, Volume I, Chapter 13: Miscellaneous Sources*. 1995, Washington D.C.: Office of Air Quality Planning and Standards (OAQPS).

104. Trimbach, J. *Oil in the rubber - new oils for an old product*. in *German Rubber Conference*. 2006. Nuremberg, Germany.
105. Hayes, T.D., et al., eds. *Gas Research Institute: Management of Manufactured Gas Plant Sites.Vol I, II*. 1996, Amherst Scientific Publishers: Amherst, MA.
106. Suh, H., P. Koutrakis, and S. Ebelt, *Detailed characterization of indoor personal particulate matter concentrations*. *Prepared for California Air Resources Board. Final Report Contract No. 00-302*. 2004, Boston, MA: Harvard School of Public Health.
107. Ligman, B., et al., *Airborne particulate matter within school environments in the United States*. Proceedings of Indoor Air, 1999. **IV**: p. 255-261.
108. Unice, K.M., M.L. Kreider, and J.M. Panko, *Use of a deuterated internal standard with pyrolysis-GC/MS dimeric marker analysis to quantify tire tread particles in the environment*. Int J Env Res Pub Health, 2012. **9**: p. 4033-4055
109. U.S. EPA. *Particulate Matter: PM Standards*. 2007; Available from: http://epa.gov/particles/standards.html.
110. Vermeulen, R., G. Doekes, and H. Kromhout, *Latex allergy risk among the general population due to traffic-related airborne dust?* Epidemiology, 2000. **11**(1): p. 92.
111. Turjanmaa, K., *Allergy to natural rubber latex: A growing problem*. Ann Med, 1994. **26**: p. 297-300.
112. Finley, B.L., D.R. Ownby, and S.M. Hays, *Airborne Tire Particles in the Environment: A Possible Asthma Risk from Latex Proteins?* Human and Ecological Risk Assessment, 2003. **9**: p. 1505-1518.
113. U.S. EPA, *AP-42 Section 4.12, Manufacture of Rubber Products*. 1997, United States Environmental Protection Agency (U.S. EPA),.
114. Yunginger, J., et al., *Extractable latex allergens and proteins in disposable medical gloves and other rubber products*. J Allergy Clin Immunol, 1994. **93**: p. 836-842.
115. Laoprasert, N., et al., *Inhalation challenge testing of latex-sensitive health care workers and the effectiveness of laminar flow HEPA-filtered helmets in reducing rhinoconjunctival and asthmatic reactions*. J Allergy Clin Immunol, 1998. **102**(6 Pt 1): p. 998-1004.
116. Environmental Protection Agency, *Natural Rubber Latex Adhesives; Disposition of TCSA Section 21 Petition*. *EPA-HQ-OPPT-2008-0273; FRL08368-4*. 2008. p. 32573-32577.
117. Taylor, J.S. and Y. Leow, *Cutaneous reactions to rubber*. Rubber Chem & Tech, 2000. **73**: p. 427-485.
118. Chaiear, N., *Health and Safety in the Rubber Industry*. Rapra Review Reports, ed. Rapra Technology Limited. 2001.
119. Sullivan, J.P., *An Assessment of Environmental Toxicity and Potential Contamination from Artificial Turf using Shredded or Crumb Rubber*. 2006, Ardea Consulting: Woodland, CA. p. 1-43
120. U.S. EPA, *Health Effects Test Guidelines, OPPTS 870.2600, Skin Sensitization*. 1998.
121. Rozman, K.K. and C.D. Klaassen, *Absorption, Distribution, and Excretion of Toxicants*, in *Cassarett and Doull's Toxicology The Basic Science of Poisons*, C.D. Klaassen, Editor. 2001, McGraw-Hill: New York.

122. Ames, B.N., et al., *Carcinogens are mutagens: a simple test system combining liver homogenates for activation and bacteria for detection*. PNAS, 1973. **70**(8): p. 2281-2285.
123. Gualtieri, M., et al., *Toxicity of tire debris extracts on human lung cell line A549*. Toxicology in Vitro, 2005. **19**: p. 1001-1008.
124. Borchardt, S.M., *Outbreak of Methicillin-Resistant Staphylococcus aureus Skin Infections Among High School Athletes in Illinois*, in *Illinois Infectious Disease Report*. 2005, Illinois Department of Public Health,. p. 1.
125. Begier, E.M., et al., *A high-morbidity outbreak of methicillin-resistant Staphylococcus aureus among players on a college football team, facilitated by cosmetic body shaving and turf burns*. Clin Infect Dis, 2004. **39**(10): p. 1446-53.
126. Center for Disease Control and Prevention, *Methicillin-resistant Staphylococcus aureus infections among competitive sports participants- Colorado, Indiana, Pennsylvania, and Los Angeles County, 2000-2003*. Morbidity and Mortality Weekly Report, 2003. **52**: p. 793-5.
127. U.S. EPA, *Catalog of Standard Toxicity Tests for Ecological Risk Assessment*, Office of Solid Waste and Emergency Response, Editor. 1994.
128. Sheehan, P.J., et al., *Evaluating the risk to aquatic ecosystems posed by leachate from tire shred fill in roads using toxicity tests, toxicity identification evaluations, and groundwater modeling*. Environ Toxicol Chem, 2006. **25**(2): p. 400-11.
129. Humphrey, D. and M. Swett, *Literature Review of the Water Quality Effects of Tire Derived Aggregate and Rubber Modified Asphalt Pavement*. 2006, Prepared for U.S. Environmental Protection Agency Resource Conservation Challenge.
130. Hofstra, U., *Environmental and Health Risks of Rubber Infill: Rubber crumb from car tyres as infill on artificial turf*. 2007, INTRON.
131. Hofstra, U., *Follow-up Study of the Environmental Aspects of Rubber Infill*. 2008, INTRON.
132. Hofstra, U., *Zinc in Drainage Water Under Artificial Turf Fields with SBR*. 2009, INTRON.
133. Kallqvist, T., *Environmental risk assessment of artificial turf systems*. 2005, Norwegian Institute for Water Research: Oslo. p. 1-19.
134. European Chemicals Bureau, *European Union Risk Assessment Report: Aniline*. 2004, European Commission.
135. Bocca, B., et al., *Metals contained and leached from rubber granulates used in synthetic turf areas*. Sci Total Environ, 2009. **407**(7): p. 2183-90.
136. Gualtieri, M., et al., *Impact of tire debris on in vitro and in vivo systems*. Part Fibre Toxicol, 2005. **2**(1): p. 1.
137. Wik, A. and G. Dave, *Environmental labeling of car tires--toxicity to Daphnia magna can be used as a screening method*. Chemosphere, 2005. **58**(5): p. 645-51.
138. Wik, A. and G. Dave, *Acute toxicity of leachates of tire wear material to Daphnia magna-- variability and toxic components*. Chemosphere, 2006. **64**(10): p. 1777-84.
139. Kanematsu, M., et al., *Characterization and potential environmental risks of leachate from shredded rubber mulches*. Chemosphere, 2009. **76**(7): p. 952-8.
140. Marwood, C., et al., *Acute aquatic toxicity of tire and road wear particles to algae, daphnids, and fish*. Ecotoxicology, 2010. **submitted (November 2010)**.

141. Day, K.E., et al., *Toxicity of leachate from automobile tires to aquatic biota*. Chemosphere, 1993. **27**.
142. U.S. EPA, *Risk assessment guidance for Superfund Volume I. Human health evaluation manual (Part A) Interim Final*. *EPA/540/1-89/002*. 1989, Washington D.C.: Office of Emergency and Remedial Response.
143. Johns, D.M., *Initial evaluation of potential human health risks associated with playing on synthetic turf fields on Bainbridge Island*. 2008, Seattle, WA: Windward Environmental LLC.
144. American Chemical Society. *CAS Registry (SM) and CAS Registry Numbers*. 2008 [cited 2008 4/26]; Available from: http://www.cas.org/expertise/cascontent/registry/regsys.html.
145. U.S. EPA. *Integrated Risk Information System (IRIS): A-Z List of substances sorted by date*. 2009 [cited 2009 September 18]; Available from: http://cfpub.epa.gov/ncea/iris/index.cfm?fuseaction=iris.showSubstanceList&list_type=date&view=all.
146. U.S. EPA. *EPA Region III Human health risk assessment: risk based concentration table*. 2009 [cited 2009 September 18, 2009]; Available from: http://www.epa.gov/reg3hwmd/risk/human/rb-concentration_table/index.htm.
147. U.S. EPA. *Voluntary Children's Chemical Evaluation Program (VCCEP): Basic Information*. 2007; Available from: http://www.epa.gov/oppt/vccep/pubs/basic.htm#basic3.
148. Woo, Y., et al., *Use of mechanism-based structure-activity relationships analysis in carcinogenic potential ranking for drinking water disinfection by-products*. Environmental Health Perspectives, 2002. **110 Supplement 1**: p. 75-87.
149. Gold, L., T. Slone, and B. Ames, *Natural and synthetic chemicals in the diet: a critical analysis of possible cancer hazards*, in *Food Safety and Food Quality*. *Issues in Environmental Science and Technology 15*., R.E. Hester and R.M. Harrison, Editors. 2001, Royal Society of Chemistry: Cambridge, UK. p. 95-128.
150. World Health Organization. *Summary of Evaluations Performed by the Joint FAO/WHO Expert Committee on Food Additives*. 2003 April 28, 2008]; Available from: http://www.inchem.org/documents/jecfa/jeceval/jec_189.htm.
151. Burdock, G.A., ed. *Encyclopedia of Food and Color Additives*. 1997, CRC Press: New York. p. 255.
152. World Health Organization. *Environmental Health Criteria 187: White Spirit (Stoddard Solvent)*. 1996 [cited 2008 4/26]; Available from: www.inchem.org/documents/ehc/ehc/ehc187.htm.