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Health Risk Assessment for Artificial Turf Playgrounds in School Athletic Facilities: Multi-route Exposure Estimation for Use Patterns

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ABSTRACT

Hazardous chemicals can be released from artificial turf used in some school playgrounds. To distinguish between Health risk assessment (HRA) exposure scenarios for this study, the ratio of elementary, middle and high schools was considered before final selection. Considering exposure pathways (inhalational, oral and dermal), media and materials were examined, targeting hazardous chemicals released from artificial turf playground-related products. Upon evaluation, the quantity of infill chips was shown to exceed the domestic product content standard (90 mg/kg) at eight (16%) out of 50 schools. PAHs were shown to exceed standards (10 mg/kg) at two (4%) out of the 50 schools. The excess cancer risk (ECR) of carcinogens was shown to be 1×10^{-6} in most users for the worst exposure scenario. In children with pica, who represented the most extreme exposure group, the ECR was expected to be as high as 1×10^{-4}, showing the low risk level of carcinogens. The hazard index (HI) for individual chemicals was shown to be low, at around 0.1 or less, except for children with pica, according to the mean exposure scenario of artificial turf playground exposure. However, the HI was shown to exceed 1.0 in children with pica. Therefore, no direct health risk was found in using artificial turf playgrounds and urethane flooring tracks for the mean exposure scenario, except in children with pica.

Key words: Artificial turf playground, Health risk assessment, Multi-route exposure

1. INTRODUCTION

Construction of artificial turf playgrounds has recently been actively undertaken in many Korean schools. Accordingly, the health risk of artificial turf playgrounds has become a major concern, as it has in many advanced foreign countries such as Europe, the United States and Canada (NJDHSS, 2008; Muller, 2007; Birkholz *et al.*, 2003). The health issues and ecological risks are a major concern due to exposure to toxic metals (Reddy *et al.*, 2005; Niederer *et al.*, 1995), polycyclic aromatic hydrocarbons (PAHs) (Yang *et al.*, 2009; Niederer *et al.*, 1995), phthalates (Naito *et al.*, 2006; Stringer *et al.*, 2000) and volatile organic compounds (VOCs) (Vilavert *et al.*, 2012; Bruin *et al.*, 2008) that are released from the materials that comprise artificial turf playgrounds (Bocca *et al.*, 2009). Because of the activities that take place on artificial turf playgrounds, such as playing and exercise, exposure through inhalation, skin contact and ingestion may occur (Birkholz *et al.*, 2003).

Currently, few countries manage artificial turf playgrounds through systematic legislation. In some countries, such as the USA and Europe, standards for the hazardous chemical contents of artificial turf (Federation International de Football Association, 2006) as well as environmental standards on soil and water quality around these physical facilities have been established (DIN, 18035-7:2002-06). In the European Union, a draft concerning synthetic turf surfaces for sports areas primarily designed for outdoor use has been prepared, as the construction of artificial turf playgrounds has increased for the revitalization of outdoor sports (Councell *et al.*, 2004). For infill chips, materials affecting biodiversity and those hazardous to human health were proposed to not exceed 0.85% of the total rubber chip weight (Federation Internationale de Football Association, 2006). In Korea, a "Hazardous Chemical Content Certification Standards of Artificial Turf Rubber Chips (KS M, 6956:2007)" recommendation was prepared by the Korean Agency for Technology and Standards (KATS, 2007) of the Ministry of Knowledge and Economics. The recommendation was prepared by an assessment committee after considering toy standards and soil standards, such as EN71 for metals, regulations put forth by other countries and workplace environmental standards for total VOCs (TVOCs) and PAHs.

To develop domestic and international safety standards, a variety of testing methods for hazardous chemicals related to artificial turf have been devised. Organic chemicals, excluding metals, are managed by identical extraction tests in most countries. For metals, total content tests or extraction tests, however, are conducted depending on purpose. The Swedish Chemicals Inspectorate, KemI, studied and reported differences in the detection concentrations between different testing methods of hazardous chemicals in rubber chips for artificial turf (Swedish Chemicals Inspectorate, 2006). The US EPA (2007) conducted a study on the extraction concentration of toxic metals from recycled rubber chips used in artificial turf.

Lacking sufficient overall risk assessments, reviews of chemicals such as metals and VOCs used in artificial turf playgrounds and the construction of elastic compound pavements (urethane flooring tracks) in school playgrounds and physical facilities have gradually increased. Accordingly, the main purpose of this study was to identify major exposure pathways and to calculate total risk through a health risk assessment (HRA) of hazardous chemicals released from artificial turf playgrounds and urethane flooring tracks via multiple routes of exposure.

2. MATERIALS AND METHODS

2.1 Sampling Sites and Artificial Turf Playground Determination

We selected 50 surveyed schools from urban areas that had constructed artificial turf and urethane flooring through the support of the Ministry of Education, Science and Technology and the Foundation of Gymnastics Promotion. Well preserved records about the composition of artificial turf (e.g., infill materials and back coating types) and management (e.g., replacement date and type), limited air emissions sources (e.g., factory or heavy traffic road) within 1 km from the school, and willingness to participate in this study were also considered.

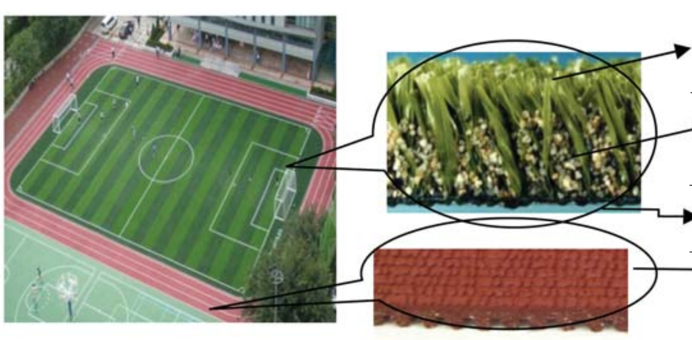
Artificial turf playgrounds mainly consist of rubber chips, artificial turf piles, and back coating, while a track consists of urethane flooring materials (Table 1).

Infill chips are used to fix artificial turf and enhance impact absorption. Back coating is a frame constituting the bottom of the artificial turf and is used for the prevention of shape deformation in artificial turf playgrounds and physical facilities such as those constructed in schools and pavements in Seoul and other metropolitan areas. Artificial turf pile and back coating were excluded from the classification criteria because product classification was unclear, and major differences were seen between manufacturers. To distinguish between HRA exposure scenarios, the ratio of elementary, middle and high schools was considered before final selection. Nine elementary schools and 13 middle and high schools in Seoul, as well as 18 elementary schools and 10 middle and high schools in other metropolitan areas were selected as the 50 subject schools.

2.2 Target Compounds

Exposure to VOCs and formaldehydes (HCHO) was assumed to be via outdoor air from volatile surfaces through inhalation pathways, while exposure to metals and semi-VOCs (PAHs, phthalates) were assumed to be via pathways of dermal uptake, ingestion and inhalation of fine particles. In total, 18 chemicals consisting of five metals, including Pb, Cd, Hg, Cr and Zn, four VOCs, including benzene, toluene, ethylbenzene and xylene, eight PAHs, including benzo(a)anthracene, chrysene, benzo(b)fluoranthene, benzo(j)fluoranthene, benzo(k)fluoranthene, benzo(e)pyrene, benzo(a)pyrene

Table 1. Exposure scenarios assumption for type of products.

Artificial turf field and urethane track	Type of products	Exposure routes	Compounds
	Artificial turf	Inhalation, Oral uptake, Dermal uptake	Metals
	Infill chip (rubber etc)	Inhalation, Oral uptake, Dermal uptake	PAHs
	Back coting	Oral uptake, Dermal uptake	Phthalates
	Elastic compound pavement	Inhalation	VOCs
		Inhalation	Formaldehyde

and dibenzo(a,h)anthracene, as well as four phthalates, including di(2)-ethylhexyl phthalate (DEHP), diethyl phthalate (DEP), di-n-butyl phthalate (DnBP) and butyl benzyl phthalate (BBzP), and HCHO were investigated.

To minimize the effect from external air emissions except from the artificial turf playground and urethane flooring, air sampling was conducted on top of the central playground which was possible no emission source around.

2. 3 Analysis

2. 3. 1 Trace Metals

Dust was collected at a rate of 5 L/min for 8 hours using a mini volume air sampler (Model 4.1, Airmetrics Co., USA). A glass-fiber filter (Quartz filter, 47 mm, Whatman, USA) was used for dust collection. After dust collection, the filter was stored in a desiccator for more than 48 hours to allow for a constant weight, followed by measurement using a chemical balance (Ohaus, USA) with a sensitivity of 0.001 mg. For the analysis of heavy metals in air dust (PM-10), pretreatment of the collected dust was conducted using a microwave pretreatment apparatus (Questron Co., Model Q-15 MicroPrep, USA) according to the Clean Water Act (CWA) of the US EPA.

To test urethane-flooring materials, a urethane layer was collected from flooring materials in schools, and an infill chip layer was collected from chip flooring materials in parks. The samples were collected from the middle and both ends of the artificial turf playgrounds at a point 100 mm from both sides of and 300 mm away from the end of the field. The infill chip samples were collected after putting on poly gloves and were transferred after wrapping with aluminum foil, followed by storage in a freezer (temperature at 4°C or less) before analysis. Approximately 10 g of turf pile, back coating, and flooring material samples were cut using sterile scissors after putting on poly-gloves and were transferred after wrapping with aluminum foil, followed by storage in a freezer (temperature at 4°C or less) before analysis. Trace metal testing was conducted according to the US EPA 3062 testing method of hazardous chemicals in recycled infill chips.

To test product surfaces, surface samples of the artificial turf and flooring material tracks were collected by installing a texwipe texture to an apparatus (1.3 kg of disk, 56.7 cm^2 of surface area), which was constructed based on the basic frame of an apparatus invented by the US Consumer Product Safety Commission (CPSC). Texwipe, made of polyester, was cut to a size of 10 × 10 cm and was attached to the facilities (artificial turf, flooring material track and hand surface).

For hand surface samples, subjects were asked to wash their hands with 100 mL of distilled water before playing in the artificial turf playground. After wet hands were completely dried, playing time was individually provided to the children. The amount of exposed chemicals from the facility was directly measured after playing without time limitation. The polyester texwipe, which was used for collecting samples from the product surface, was also used for hand sample collection. Pretreatment identical to that used for the surface samples was used.

For quantification analysis, the analysis of Pb, Cr, Ni, Cd and Zn in the samples was conducted using a graphite furnace atomic absorption spectrometer (HGA 900, PerkinElmer, USA) equipped with an autosampler (AS 800, PerkinElmer, USA). The analysis of Zn in the samples was conducted using an atomic absorption flame emission spectrometer (AA-6701F, Shimadzu, Japan) equipped with an auto-sampler (ASC-6100, Shimadzu, Japan). Hg analysis was conducted using a flow injection system (FIAS 100, PerkinElmer, USA) and a cold vapor generation method. Deionized water, which was used for reagent preparation, was prepared as 18.2 Ω/cm using a pure water production apparatus (Millipore, Milford, MA, USA). In each item, 1000 ppm of special reagents (Junsei Chemical Co., Japan) were used for the standard solution of metals used in this study and were prepared whenever the calibration curve was drawn, considering concentration change due to chemical changes such as absorption.

2. 3. 2 VOCs

VOC samples were collected into a stainless steel Tenex absorption tube (1/4″ × 20 cm, Supelco, USA) using a personal air sampler (Gillian Inc., USA). Air samples from the artificial turf playgrounds were collected at a rate of 0.2 L/min at an approximate height of 1.5 m for 2 hours. After sample collection, the absorption tube was placed into a Swagelok, and both ends were sealed with a teflon cap, followed by cryopreservation at −70°C before analysis (all samples were analyzed within 2-3 days after cryopreservation). For VOC sample analysis, the air was collected using absorptive materials according to the method of VOC collection provided by the US EPA and was then analyzed with a gas chromatograph/mass selective detector (GC/MSD, Hewlett Packard, USA) after desorption. For VOC samples from the field products, a collection method identical to that used for heavy metal collection was used.

Analysis of VOCs among the contents of the artificial turf products was conducted according to the analysis method of chemicals among recycled infill chips, which is recommended by the Korean Standard (KS). That is to say, VOC analysis was conducted according to the method of US EPA 5021. For sample pretreatment, approximately 5 g (approximately 10 g for the prototype) of sample was put into a 25 mL (50 mL for prototype) flask, approximately 10 mL of internal standard solution was precisely added, and methanol was then added up to the final volume. After closing the lid, extraction was performed for 30 minutes (temperature less than 20°C) using an extractor.

2. 3. 3 PAHs

PAHs in the air were collected using a high-volume air sampler (Graseby Andersen, USA). The sample collection method for the field materials was identical to that used for the sample collection of metals. For sample pretreatment, PAH analysis of the contents of the artificial turf was conducted according to the analysis method (KS M 6956:2007) (KATS 2007) of chemicals in recycled infill chips recommended by the KS, which was based on that put forth in US EPA 8100. For sample pretreatment, approximately 0.5 g of sample was mixed well with diatomaceous earth and was put into an 11 mL porous thimble. PAHs were extracted by installing the porous thimble in an ASE extraction cell. After extraction, the extract was slowly concentrated to 200-250 μL using a nitrogen evaporator. The concentrated extract was transferred to a silica cartridge cleaned with dichloromethane/hexane and hexane and was then washed with a small quantity of hexane that was allowed to infiltrate the silica cartridge. The extraction solution (dichloromethane/hexane, 2 : 8) of 5 mL or more was used to elute PAHs absorbed into the silica. The elute was concentrated and then put into a 1 mL vial for cold storage, followed by analysis with GC/MSD (Agilent Technologies, USA) according to the analysis condition. Sample collection from the surfaces of materials and hands was excluded in this study due to a lack of generalized methods from previous studies.

2. 3. 4 Phthalates

Phthalates count among the omnipresent environmental chemicals in water and soil, but rarely occur in the air due to their low volatility (Kim *et al.*, 2011; Kim *et al.*, 2009; Bornehag *et al.*, 2005b) Therefore, phthalate exposure due to inhalation exposure to indoor air was excluded from this study, considering the utilization efficiency of the results of this study. Sample collection from the artificial turf materials was identical to that used for metals. Analysis of phthalates in the contents of the artificial turf materials was conducted according to US EPA 8061A.

Sample collection from the surfaces of the materials and hands was identical to that used for metals. Glass products were used for all the testing vessels during sample preparation, and analysis was conducted using GC-MSD (Agilent Technologies, USA).

2. 3. 5 Experimental Approach for Bioavailability of Metals in the Products

As trace metals in infill chips should be assessed as part of the total content concentration of metals included in the material, subject to current management laws, the bioavailability of metals included in the products should also be considered to estimate the actual amount exposed to the body. However, for the PAHs and VOCs included in the materials, the concentration obtained by an extraction method with an organic solvent sufficiently reflects actual body exposure. Thus, an estimation adjusting for bioavailability was required. Accordingly, in this study, to assess the possibility of exposure to the body of metals included in the materials, along with the total content measurement method recommended by the Korean Agency for Technology and Standards for the safe management of hazardous chemicals in these materials, an acid extraction test and in vitro digestion test were conducted to estimate the bioavailability of metal composites, reflecting the conditions under which chemicals included in the materials are released due to gastric acid and digestive fluids and absorbed into the body via the gastrointestinal tract.

The total content test was conducted according to the analysis method of hazardous chemicals in recycled rubber chips described in the KS (KS M 6956:2007) (KATS, 2007) based on US EPA 3052. The metal analysis method by acid extraction was conducted according to section 4 (extraction of hazardous elements), “Toys”, of the “Safety Standard of Products Subject to Autonomous Safety Inspection” under the “Quality Management and Product Safety Management Law” (KATS, 2010). Analysis using an artificial digestive extraction was conducted according to the method of “Development and Suitability of In Vitro Digestion Models in Assessing Accessibility of Lead From Toy Matrices” (RIVM, 2007). All samples that were processed by the three pretreatment methods were analyzed using an inductively coupled plasma mass spectrometer (DRC ICP-MS, PerkinElmer, USA).

2. 4 Quality Control

To evaluate the recoveries of an apparatus, analysis was performed using two certified standard materials: ERM®-EC680k and ERM®-EC681k. For ERM®-EC680k and ERM®-EC681k, which are the most widely used certified standard materials, metal concentration was measured according to the total content test used for artificial turf samples. Calibration curves obtained from the standard solutions of metals, including Pb, Cr, Ni, Cd, Zn and Hg, were shown to be fairly linear with a correlation factor (R^2) of 0.99 or higher in all of the materials. The recovery of the methods was in the range of 92-115%. The analytical results of the selected PAHs, VOCs and phthalates of interest indicated good agreement between the reference and analytical values. Also, the recovery rates for the selected PAHs, VOCs and phthalates from the standard reference material were around 85-112%.

2. 5 Dose-response Assessment and Additional Sensitivity Factor for Children

An adjustment coefficient, which considered the sensitivity of exposure to children using adult carcinogenic information, was applied to obtain dose-response information. For the adjustment coefficient of the sensitivity of exposure to children, values presented by the Rubber Manufacturers Association (2008) were used. According to the Rubber Manufacturers Association (2008), the age-dependent adjustment factor (ADAF) was recommended to be 10 for children aged less than 2 years, 3 for children aged 2-15 years, and 1 for children aged 16 years or higher. Thus, in this study, ADAFs of 3 and 1 were applied to children aged 7-16 years and greater than 16 years, respectively (Table 2).

Among the non-carcinogens, no chemicals had quantitative dose-response information on exposure in childhood. The toxicity value was available for adults but was unavailable for children. In most cases, information on adults was used for health risk assessments in children. For non-carcinogens, dose-response informa-

Table 2. Dose-response assessment of carcinogenic target compounds.

Compounds		Exposure route	Endpoint	Adults	Children			
				Dose-response data	Age (yr)	ADAF	CPF (mg/kg-day)$^{-1}$	UR (μg/m^3)
VOCs	Benzene	Inhalation	Leukemia	6.0×10^{-6}	7-16 16-18	3 1	– –	1.8×10^{-5} 6.0×10^{-6}
	Formaldehyde	Inhalation	Lung cancer	1.3×10^{-5}	7-16 16-18	3 1	– –	4.5×10^{-5} 1.3×10^{-5}
PAHs	(B(a)P)	Oral/ Inhalation	All cancer	7.3×10^{0}	7-16 16-18	3 1	22 7.3	2.6×10^{-1} 8.7×10^{-2}

ADAF: Age Dependent Adjustments Factors, CPF: Cancer Potency Factor, UR: Unit Risk

Table 3. Dose-response assessment of non-carcinogenic target compounds.

Compounds		Exposure route	Endpoint	N(L)OAEL (mg/kg-day)	UF	RfD(C) (mg/kg-day)
Metals	Lead	All	Neurobehavioral Neurobehavioral	10 μg/dL 54 μg/dL	– –	6.0E-04 3.5E-04
	Chromium (III)	Oral	Systemic toxicity	1468	1000	1.5
	Cadmium (Cd)	Oral	Kidney toxicity	0.005	10	5.0E-04
	Zinc	All	Enzyme repression	0.91	3	0.3
	Mercury	All	Neurotoxicity	–	–	0.02
VOCs	Toluene	Inhalation	Neurotoxicity/ Reproductive toxicity	79 mg/m^3	300	0.26
	Ethylbenzene	Inhalation	Growth toxicity	434 mg/m^3	300	1
	Xylene	Inhalation	Ataxia	39 mg/m^3	300	0.1 mg/m^3
	Formaldehyde	Inhalation	Respiratory irritation	1.0 mg/m^3	10	0.1 mg/m^3
Phthalates	DEHP	All	Reproductive /Growth toxicity	0.245	100	0.025
	DnBP	All	Reproductive /Growth toxicity	6	100	0.06
	BBzP	All	Reproductive /Growth toxicity	20	100	0.2

N(L)OAEL: No (Lowest) Observed Adverse Effect Level, UF: Uncertainty Factor, RfD(C): Reference Dose (Concentration)

tion was calculated without using the value presented by the US EPA and was applied under an assumption that the information is identical for children and adults (Table 3).

2.6 Assessment of Exposure Patterns and Formula Application

Subject facilities and age were divided into five groups: lower grades in elementary schools (7-9 years), higher grades in elementary schools (10-12 years), middle school students (13-15 years), high school students (16-18 years) and adults. For the subject students, a survey was conducted on classes subject to video inspection. Survey contents focused on the characteristics of student use of artificial turf playground and urethane flooring materials (mean number of uses, duration, mean number of uses during lunch break, and mean number of uses after school). For adults, an interview was performed using a questionnaire. A total of 10 elementary, middle and high schools that showed a high degree of subject material contamination among the subject facilities were selected, and a survey on exposure was conducted at these facilities. A survey on the determination of factor values and exposure type analysis for the calculation of exposure amount was conducted on a total of 28 subjects in five groups consisting of 5-6 subjects.

For observation methods, video recording and interpretation were conducted on a 50-minute lunchtime and 50-minute class and exercise. In addition, other specific exposures, i.e., dermal contact with rubber chips and turf piles, was examined on the field. Specific exposure types during playtime and class time that took place on artificial turf grounds and flooring materials were investigated, as was time and frequency of touching of the mouth with hands. Standing, sitting, running and tumbling were also examined to describe types of playing. We made a recommendation for assessment and considered pica. Pica is defined as the ingestion of any inedible substance (Fovel *et al.*, 1989). Pica is the most dangerous form of self-injurious behavior (Williams and McAdam, 2012; Matson *et al.*, 2011) (Table 4).

For VOCs and aldehydes, inhalation exposure due to volatile outdoor air from the surfaces of artificial turf playgrounds and urethane flooring materials was assumed. For metals and SVOCs (PAHs and phthalates), dermal uptake from the surfaces of artificial turf playgrounds and urethane flooring materials was assumed. For metals and SVOCs, ingestion exposure to fine par-

Table 4. Exposure factors by video and observation.

Factor site	Age groups (years)	Activity type	Exposure routes	Specificity
Elementary school students - the upper grades	7-9	Sitting/lying/ standing/walking /running/wallowing	Inhalation, Dermal, Ingestion (infill chip, hand)	Weekday time spent 2-3 time/wk Mean time spent 20-75 min/day Usage frequency of lunch time is high Form of Pica
Elementary school students - the lower grades	10-12	Sitting/lying/ standing/walking /running/wallowing	Inhalation, Dermal, Ingestion (infill chip, hand)	Weekday time spent 2-3 time/wk Mean time spent 15-540 min/day Usage frequency of lunch time is high
Middle school students	13-15	Sitting/lying/ standing/walking /running/wallowing	Inhalation, Dermal, Ingestion (infill chip, hand)	Usage frequency of lunch and after-school time is low in girl's school
High school students	16-18	Sitting/lying/ standing/walking /running/wallowing	Inhalation, Dermal, Ingestion (infill chip, hand)	Usage frequency of lunch and after-school time is low in girl's school Usage frequency of test period is low
Adults	Over 19	Sitting/ standing/walking /running/wallowing	Inhalation, Dermal, Ingestion (infill chip, hand)	Individual difference is high Hand-to-mouth exposure is not applicable

Table 5. Exposure factor by age group.

	Exposure factor	Symbol	Age (years)					Probability distribution	Source
			7-9 (pica)	10-12	13-15	16-18	Over 19		
Physiological variables	Body weight (kg)	BW	28	40	54	60	60	Log-normal	KEHF (2007)
	Body surface area (cm^2)	SA	10057	12902	14000	17084	17084	Log-normal	
	Skin surface area ratios for external exposure (unitless)	Fsa_nood	0.463	0.453	0.492	0.529	0.485	Uniform	US EPA (2002b)
	Ratio of hand to mouth (unitless)	Fhm	0.130	0.130	0.130	0.130	–	Uniform	
Time variables	Daily exposure (hr)	ETj	0.54	0.92	0.86	0.95	0.59	Uniform	This study (Survey) KEHF (2007)
	Exposure period (year)	EDfac	3	3	3	3	50	–	
	Number of year exposure (days/yr)	EFfac	134.4	177.6	168	168	144	–	
	Number of standard time exposure (days)	ATnc	1095	1095	1095	1095	18250	–	This study
	Number of life time exposure (days)	AT	25550	25550	25550	25550	25550	Triangle	
Contact ratio variables	Daily inhalation rate (m^3/day)	BRm	12.0	13.5	14.0	13.3	13.3	Log-normal	US EPA (2002b)
	Activity inhalation rate (m^3/hr)	BRh	1.8	3.6	4.8	6	6	Triangle	US EPA (2002b)
	Rubber powder ingestion rate (mg/day)	IRdust	1000 (10000)	200	100	100	50	Log-normal	KEHF (2007) US EPA (2002b)
	Number of hand sucking (time/hr)	Nhm	1.8	2.7	0.9	1.3	0	Log-normal	This study (Video survey)
	Once hand to mouth (sec/time)	Thm	3.08	3.66	0.59	1.04	0	Triangle	
	Ratio of an hour per lying	CTsll	0.02	0.03	0.02	0.00	0.00	Triangle	
	Ratio of an hour per crawl	CTcw	0.11	0.17	0.04	0.07	0.26	Triangle	
	Ratio of an hour per standing	CTseat	0.06	0.07	0.09	0.04	0.18	Triangle	
	Ratio of an hour per sitting	CTwkk	0.18	0.27	0.18	0.25	0.10	Triangle	
	Ratio of an hour per wallow	CTrr	0.000	0.002	0.004	0.000	0.001	Triangle	
	Remove suck the ratio	PFhm	0.78	0.78	0.78	0.78	0.78	Log-normal	KEHF (2007)
	Ratio of skin contact when lying	CFfa	0.33	0.33	0.33	0.33	0.33	Log-normal	U.S. EPA (2003)
	Ratio of skin contact when standing	CFlg	0.2	0.2	0.2	0.2	0.2	Log-normal	
	Ratio of percutaneous absorption	AP	0.02	0.02	0.02	0.02	0.02	–	IPCS (2004)

ticles (rubber) was finally assumed. The formulas for each exposure pathway and evidence of value calculations are presented in Table 5.

1) Inhalation route

$$LADD_{(inh.)}=(C_{air}*BR_{k,i}*ET_j*EF_j*ED_j)/(BW_i*AT_l)$$

2) Ingestion route

$$LADD_{(ing.\_dust)}=(C_{dust}*IR_{dust}*EF_j*ED_j)/(BW_i*AT_l)$$

3) Dermal contact route

$$LADD_{(derm)}=(C_{prod}*SA_{i.}*FA_m*CN_{m,\ prod.}*(CT_{m,\ prod.}/3600)*TF_c*(ET_j/24)*EF_j*ED_j)/(BW_i*AT_l)$$

$LADD_{(inh.)}$: Lifetime Average Daily Dose via inhalation (mg/kg/day)
$LADD_{(ing.\_dust)}$: Lifetime Average Daily Dose via ingestion of dust (mg/kg/day)
$LADD_{(derm.\_surf.)}$: Lifetime Average Daily Dose via dermal contact with floor surfaces (mg/kg/day)
$C_{air.}$: Concentration of pollutants in the air (mg/m^3)
$C_{dust.}$: Concentration of pollutants as dust in the playground (mg/kg)
$BR_{k.}$: Hourly breath rate for exposure scenario, k, and age, i (m^3/hr)
IR_{dust}: Daily ingestion rate of dust for age, i (kg/day)
SA_i: Surface area for age, i (cm^2)
FA_m: Fraction of exposed skin, m (face, hands, arms, feet, etc.), to surface area (unitless)
$CN_{m,\ prod.}$: Number of contacts per hour between exposed skin, m (face, hands, arms, feet, etc.), and the product (floor) (times/hr)
$CT_{m,\ prod.}$: Exposure time per contact between exposed skin and the product (sec/time)
TF_c: Transfer factor as amount of pollutant that migrates to the skin per unit amount of product and permeability of the skin to the pollutant (unitless)
$ET_{j.}$: Exposure time per day for facility, j (hrs/day)
$EF_{j.}$: Exposure frequency per year for facility, j (days/yr)
$ED_{j.}$: Exposure duration for facility, j (yrs)
$BW_{i.}$: Average body weight for age, i (kg)
$AT_{l.}$: Average time in days during lifetime for carcinogenic pollutant or days of exposure for non-carcinogenic pollutants (days)

2. 7 Risk Calculation

Risk calculation followed the US EPA's risk assessment framework (US EPA, 2002b, 2001). For carcinogens, excess cancer risk (ECR) was calculated considering both the cancer potency factor (CPF) and ADAF application using information for adults. For non-carcinogenic toxic materials, the hazardous quotient (HQ) was calculated using reference dose (RfD) determination. Final hazardous probability distribution values were calculated using probability distribution values of LADD for facilities, materials, and age. Corresponding values of 50% and 95% for hazardous probability distributions were used, and the risk level was assessed considering ECR, 10^6-10^4, as well as HI and HQ > 0.1-1.

1) Excess cancer risk

$$ECR_{r,p,i} = LADD_{r,p,i} * CPF_{r,p} * ADAF_i$$
$$ECR_{p,i} = \sum ECR_{r,p,i}$$

$ECR_{r,p,i}$: Excess cancer risk via exposure route, r, of pollutant, p, at age, i
$ECR_{p,i}$: Total excess cancer risk via multi-media and route of pollutant, p, at age, i
$LADD_{r,p,i}$: Lifetime Average Daily Dose via exposure route, r, of pollutant, p, at age, i (mg/kg/day)
CPF_r: Cancer potency factor via exposure route, r, of pollutant, p ((mg/kg/day)$^{-1}$)
$ADAF_i$: Age-dependent adjustment factor for age group, i, from the US EPA (ADAF during the first 2 years of life is a 10, ADAF for ages 2 through < 16 is 3 and ADAF for ages greater than 16 is 1)

2) Hazard Quotient and Hazard Index

$$HQ_{r,p,i} = LADD_{r,p,i} / RfD_{r,p}$$
$$HI_i = \sum HQ_{r,p,i}$$

$HQ_{r,p,i}$: Hazard quotient via exposure route, r, of pollutant, p, at age, i
HI_i: Hazard index via multi-media and multi-route exposure at age, i, for a complex mixture pollutant
$LADD_{r,p,i}$: Lifetime Average Daily Dose via exposure route, r, of pollutant, p, at age, i (mg/kg/day)
$RfD_{r,p}$: Reference dose per day via exposure route, r, of pollutant, p (mg/kg/day)

3. RESULTS AND DISCUSSION

3. 1 Multi-route Exposure Assessment in Artificial Turf Playgrounds

3. 1. 1 Content Monitoring

The content distribution of the field materials is presented in Table 6. In this study, the subject materials were shown to contain Zn > Pb > Cr in order of greatest quantity, and Zn was the highest content in the infill chips (3752 mg/kg). Although the infill chips were not classified and are presented in Table 6, among the trace metals, Zn was detected in EPDM black chips (19 cases) at 4451 mg/kg > SEBS chips (18 cases), 3865 mg/kg > EPDM color chips (12 cases), 3011 mg/kg > natural chips (4 cases), 2142 mg/kg. Zinc is added to the chips during processing in the hardening treatment (a process that enhances elastic and restoring forces by bridging raw materials). Zinc is added during all kinds of rubber production in the USA and Europe and is regarded as a hazardous chemical that needs to be managed (Councell *et al.*, 2004; Smolders and Degryse, 2002).

Infill chips were found to have the second highest Pb content after flooring materials. Among the infill chips, recycled ethylene propylene diene monomer (EPDM) chips were used in approximately 60% of all artificial turf playgrounds in schools and were the most frequently used material for this purpose. Generally, ZnO is used as a vulcanizing agent in rubber products, and Pb is added during mixing processes (MoT, 1996).

Table 6. Results of contents survey for field samples.

Compounds (mg/kg)		Rubber chip (n=50)		Elastic pavement (n=14)		Artificial turf (n=5)		Back coting (n=5)	
		Mean	95%	Mean	95%	Mean	95%	Mean	95%
Metals	Pb	38.58	55.36	63.16	146.03	9.86	19.47	7.82	14.16
	Cr	10.74	18.60	8.75	11.71	2.88	4.49	1.12	1.75
	Cd	0.46	0.74	0.02	0.05	N.D	–	0.001	0.004
	Zn	3752	4327	1944	2805	2114	3168	2204	3632
	Hg	0.21	0.37	0.06	0.17	0.0002	0.001	0.02	0.05
PAHs		1.52	2.77	0.18	0.69	N.D	–	N.D	–
Phthalates	DEHP	N.D	–	0.04	0.11	0.41	0.47	N.D	–
	BBzP	N.D	–	1259	2745	309	428	N.D	–

PAHs: polycyclic aromatic hydrocarbons, DEHP: Di(2)-ethylhexyl phthalate, BBzP: Butyl benzyl phthalate

Table 7. Environmental samples of artificial turf fields and urethane-constructed places.

Compounds		Air ($\mu g/m^3$) (n=50)		Surface of products ($\mu g/cm^2$) (n=37)		Surface of hand ($\mu g/cm^2$) (n=37)	
		Mean	95%	Mean	95%	Mean	95%
Metals	Pb	0.06	0.06	0.13	0.24	0.01	0.02
	Cr	0.037	0.046	0.016	0.041	0.001	0.001
	Cd	0.001	0.001	< LOD	–	< LOD	–
	Zn	140	162	1.37	1.72	1.86	3.26
	Hg	0.003	0.004	0.004	0.006	0.001	0.002
PAHs		0.0004	0.001	–	–	–	–
TVOC		74	87	–	–	–	–
Phthalates	DEHP	–	–	0.003	0.004	0.005	0.006
	BBzP	–	–	7.02	11.75	0.55	0.82

PAHs: Polycyclic aromatic hydrocarbons, TVOC: Total volatile organic compound, DEHP: Di(2)-ethylhexyl phthalate, BBzP: Butyl benzyl phthalate

Although not shown in Table 6, Pb content exceeded 15% of the standard product content recommended by domestic standards for infill chips. Lead was shown to exceed the standard in eight of the 50 schools. For metal, Pb was shown to exceed the domestic standard (10 mg/kg) in two (4%) of the 50 schools.

Lead, which significantly affects juvenile health, has safety standards (90 mg/kg in Korea and 100 mg/kg in the USA) on its total content in artificial turf in Korea and the USA (CPSC, 2008), which are similar to the safety standard of toys based on extraction tests in Korean and European children. Thus, in reality, it is strictly managed. In Europe, for products like powder, which is easily exposed to children via the mouth or inhalation, a safety standard of approximately 1/3-1/10 of oral extraction has been recommended (Plesser and Lund, 2004).

Among the components of artificial turf playgrounds, a mean of 9.82 mg/kg Zn was detected in the artificial turf pile. Also, 0.2-0.3% of Zn was confirmed to be used during turf pile production for improvement of yarn processing in turf pile production. Among the components of the artificial turf playground, Pb was shown to have the lowest presence in back coatings (mean 7.82 mg/kg). The manufacturers confirmed that they used Pb (less than 10 ppm) and Zn (0.3-0.4%) to increase viscosity during fabric coating for back coating. Therefore, according to the assessment of the components of artificial turf playgrounds collected from the fields, the results of this study demonstrate comprehensive exposures to Zn included in rubber and Pb included in artificial turf piles and back coating.

Lead and Zn were detected in all components that constitute artificial turf including infill chips, urethane flooring materials, artificial turf piles, and back coating. This is likely to be attributable to the following reasons. First, they are contained in the raw materials. High Zn concentrations result from the manufacturing of tire rubber, from which the synthetic turf granules are derived (Zhang *et al.*, 2008). Zinc is added to tires, at about 1.5%, to strengthen the rubber (Snyder, 1998). Second, glue used during construction, contained in flooring sealing materials, and additional exposure of Pb during spraying of the materials is significant.

3. 1. 2 Environmental Monitoring

Results from testing air, product surfaces of artificial turf playgrounds and urethane flooring materials, as well as the hands of users, are presented in Table 7. Among the trace metals, Zn was detected with the highest concentration, which was consistent with the results of the content testing. Lead was detected in all air, product surface and hand surface samples (100%). Zinc levels in air were very high, about 10 times greater than that of an industrial area (about 10-40 μg/m^3) in Korea. Lead levels in air were slightly higher than that of a typical residential area, but were about 10% of ambient air standards (0.5 μg/m^3) in Korea. The levels of other chemicals in air were similar or lower to a residential area in Korea (KMOE, 2011). Zinc concentrations were shown to be the highest in a study conducted by San Miguel *et al.* (2002), while Pb content was shown to be higher in a study conducted by Sadiq *et al.* (1989), which could contribute to environmental contamination. However, in this study, most infill chips were shown to not be manufactured from waste automobile tires and, therefore, are incomparable to those from waste automobile tires of the studies conducted by San Miguel *et al.* (2002) and Sadiq *et al.* (1989). Nonetheless, they showed similar results. The results

Table 8. Estimation of bioavailability for trace metals.

Metals	Type of product	Bioavailablilty (%)		
		Acid elution/content	Gastric fluid/content	All elution/content
Pb	Rubber chip	0.10±0.12 (0.01-0.44)	5.72±11.29 (<0.01-41.02)	2.91±8.32 (<0.01-41.02)
	Elastic pavement	0.42±0.56 (0.03-0.81)	1.25±1.71 (0.04-2.46)	0.83±1.14 (0.03-2.46)
	Back coting	0.14±0.01 (0.14-0.15)	3.86±2.86 (1.97-7.15)	2.00±2.72 (0.14-7.15)
	Artificial turf (pile)	0.22±0.17 (0.03-0.33)	7.19±3.39 (4.74-11.05)	3.71±4.38 (0.03-11.05)
Cr	Rubber chip	0.01±0.01 (<0.01-0.04)	1.43±2.73 (<0.01-8.99)	0.72±2.02 (<0.01-8.99)
	Elastic pavement	Not available	0.10±0.15 (<0.01-0.21)	0.05±0.10 (<0.01-0.21)
	Back coting	0.02±0.03 (0.01-0.05)	0.51±0.75 (0.00-1.38)	0.27±0.55 (0.00-1.38)
	Artificial turf (pile)	0.02±0.03 (0.00-0.05)	0.54±0.37 (0.19-0.92)	0.28±0.37 (<0.01-0.92)
Cd	Rubber chip	0.66±1.10 (<0.01-4.05)	1.51±3.40 (<0.01-10.15)	1.09±2.51 (<0.01-10.15)
	Elastic pavement	0.13±0.05 (0.09-0.16)	0.08±0.01 (0.07-0.08)	0.10±0.04 (0.07-0.16)
	Back coting	0.77±0.68 (0.05-1.38)	0.40±0.68 (0.00-1.19)	0.58±0.64 (0.00-1.38)
	Artificial turf (pile)	3.02±3.93 (0.42-7.54)	0.01±0.02 (0.00-0.04)	1.52±2.98 (0.00-7.54)
Zn	Rubber chip	0.30±0.78 (<0.01-2.72)	0.07±0.16 (<0.01-0.56)	0.18±0.56 (<0.01-2.72)
	Elastic pavement	0.01±0.00 (0.01-0.02)	0.03±0.02 (0.02-0.05)	0.02±0.01 (0.01-0.05)
	Back coting	0.04±0.02 (0.02-0.06)	0.02±0.02 (0.00-0.04)	0.03±0.02 (0.00-0.06)
	Artificial turf (pile)	0.00±0.01 (0.00-0.01)	0.00±0.01 (0.00-0.01)	0.00±0.01 (0.00-0.01)

Table 9. Comparisons of bioavailability for metals in several studies.

Compounds	Type of product	Bioavailability (%)			
		Acid elution/content		Gastric fluid/content	
		US EPA (2009)	This study	Zhang *et al.* (2008)*	This study
Pb	Rubber chip	4.7 (1.6-10.1)	0.10 (0.01-0.44)	34.5 (24.7-44.2)	5.72 (0.00-41.02)
	Artificial turf (pile)	34.2 (0.2-86.8)	0.01 (0.00-0.04)	34.6	1.43 (0.00-8.99)
Cr	Rubber powder	–	0.22 (0.03-0.33)	23.3	7.19 (4.74-11.05)
	Artificial turf (pile)	–	0.02 (0.00-0.05)	N.D	0.54 (0.19-0.92)

from this study are likely to be attributable to the Zn and Pb contained in rubber and the illegal use of low-quality waste rubber during rubber chip construction by some manufacturers.

Phthalates were shown to be detected in the order of BBzP > DEHP and were detected in Pb, Zn, and BBzP, in agreement with the results of the content analysis.

3. 1. 3 Bioavailability Assessment

Bioavailability values, estimated for calculating the exposure amount of metals to the body, which can be absorbed into the body, in contrast to the total contents of hazardous metals contained in the subject materials, are presented in Table 8.

For infill chips, which are used to maintain artificial turf elasticity, acid extraction and gastric solution extraction levels were shown to be 10-10,000 times lower than the measured content level, despite some variations among materials. Among the metals, a difference between the content level and the extraction level was shown to be the lowest for Pb, whereas Zn was assessed to have a very low extraction level compared to its high content level. Lead content of infill chips was shown to be 1.22-76.65 mg/kg, whereas its acid extraction level was < 0.001-0.1 mg/kg, and its gastric solution extraction level was 0.002-0.66 mg/kg. Thus, bioavailability by gastric solution extraction was estimated up to 41.02%. Chromium was measured to have a content level of 1.03-4.85 mg/kg and an extraction level of < 0.001-0.46 mg/kg, and its bioavailability was estimated up to 8.99%. Cadmium was shown to have a content level of 0.02-3.64 mg/kg, an acid extraction level of < 0.001-0.01 mg/kg, and a gastric solution extraction level of < 0.001-0.03 mg/kg. Its acid extraction and gastric solution extraction levels were shown to be 100 times lower than its content level. Zinc was shown to have a content level of 11-143 mg/kg, an acid extraction level of < 0.001-2.13 mg/kg, and a gastric solution extraction level of < 0.001-2.38 mg/kg. Its acid extraction and gastric solution extraction levels were shown to be approximately 10,000 times lower than its content level.

Soft metals such as Pb and Cr contained in the rubber chips were detected 10 times higher in the gastric solution extraction than in the acid extraction. Meanwhile, hard metals such as Cd and Zn were detected in a similar concentration between the acid extraction and the gastric solution extraction. Metal concentrations contained in the urethane flooring materials were shown to be similar to those contained in the infill chips. Meanwhile, their bioavailability was estimated to be approximately 10 times lower than those of the infill chips (Kim *et al.*, 2012).

According to the US EPA (2009), the bioavailability of Pb by an acid extraction test of infill chips and artificial turf piles was estimated to be 4.7% (maximum 10%) and 34.2% (maximum 87%), respectively (Table 9). According to Zhang *et al.* (2008), the mean bioavailability of Pb and Cd in artificial turf piles by gastric solution extraction testing was estimated to be 35% and 23%, respectively. The aforementioned values were somewhat higher than those found in this study. The studies conducted by the US EPA and Zhang *et al.* investigated the bioavailability of SBR products made from recycled tires that have a higher possibility of metal contamination. On the other hand, this study estimated the bioavailability of products made of recycled rubber (EPDM black), showing somewhat of a difference. Currently in Korea, EPDM and SEBS are mainly used for infill chips for artificial turf.

3. 2 Health Risk Assessment

The results of lifetime ECR are presented in Table 10. As the inhalation exposure route was only assessed for benzene due to its physical properties, no results of RA on ingestion and dermal intake were found. Carcinogenic chemicals that may be released from the subject materials included benzene and PAHs (8 species). The ECR for individual chemicals was estimated to be a level of one person out of one million (1×10^{-6}) or less. The ECR for carcinogens in children with pica, who represent the most extreme exposure type among the facility users, was shown to be 1.14×10^{-7} for benzene and 8.47×10^{-7} for PAHs. Muller (2007) reported that PAH levels were low in rubber particles and minimally affected by air contamination. In contrast, based

Table 10. ECR of carcinogenic compounds by average and worst exposure scenarios.

Carcinogenic compounds	Exposure route	Elementary school students - the lower grades		Elementary school students - the upper grades		Middle school students		High school students		Adults		Pica	
		Average	Worst	Average	Worst	Average	Worst	Average	Worst	Average	Worst	Average	Worst
Benzene	Ingestion (direct)	–	–	–	–	–	–	–	–	–	–	–	–
	Ingestion (Hand-to-mouth)	–	–	–	–	–	–	–	–	–	–	–	–
	Inhalation	1.14E-07	1.49E-06	3.61E-07	5.65E-06	2.93E-07	3.47E-06	1.28E-07	1.27E-06	1.21E-06	8.49E-06	1.14E-07	1.49E-06
	Dermal contact	–	–	–	–	–	–	–	–	–	–	–	–
	Total risk	1.14E-07	1.49E-06	3.61E-07	5.65E-06	2.93E-07	3.47E-06	1.28E-07	1.27E-06	1.21E-06	8.49E-06	1.14E-07	1.49E-06
PAHs	Ingestion (direct)	8.35E-08	1.01E-05	2.64E-08	4.51E-06	8.74E-09	1.67E-06	2.47E-09	5.64E-07	4.21E-10	2.27E-06	8.35E-07	1.01E-04
	Ingestion (Hand-to-mouth)	–	–	–	–	–	–	–	–	–	–	–	–
	Inhalation	1.20E-08	8.87E-08	3.79E-08	3.37E-07	3.28E-08	2.50E-07	1.36E-08	8.42E-08	1.21E-07	6.78E-07	1.20E-08	8.87E-08
	Dermal contact	–	–	–	–	–	–	–	–	–	–	–	–
	Total risk	9.55E-08	1.02E-05	6.42E-08	4.85E-06	4.16E-08	1.92E-06	1.61E-08	6.49E-07	1.22E-07	2.95E-06	8.47E-07	1.01E-04

PAHs: Polycyclic aromatic hydrocarbons

on the worst exposure scenario, PAH level in children with pica was estimated to be up to 1×10^{-4}. Except for children with pica, the ECR was shown to be highest in adults (50 years old), whose exposure time was the longest. According to a preliminary study conducted in Norway (Norwegian Institute of Public Health and the Radium Hospital, 2006), when a carcinogenic risk assessment was conducted on the users of indoor football artificial turf playgrounds according to exposure scenario, the worst case of lifetime ECR was estimated to be 1×10^{-5}, which was acceptable.

In that study, the subject chemicals for carcinogenic assessment were benzene and PAHs, and the study was conducted on inhalation, ingestion and dermal intake in adults, juniors, and children, which was similar to this study. The infill chips used in the indoor football ground were also EPDM, which was the most frequently used type of chip found in this study. The results of the study conducted in Norway (Norwegian Institute of Public Health and the Radium Hospital, 2006) were consistent with the results of this study. However, due to differences in exposure scenarios, variables used, toxicity information and indoor/outdoor subjects, a direct comparison is not possible.

For non-carcinogenic toxic materials that may be released from artificial turf playgrounds, 10 chemicals including Pb, Cr, Cd, Hg, Zn, toluene, ethylbenzene, xylene, formaldehyde, and PAHs (4 species) were assessed. Except for children with pica, the HI based on the mean exposure scenario of the facilities was shown to be 0.1 or less, which is low (Table 11). The HI in children with pica who represented the most extreme exposure group among the facility users was shown to be 0.067 for Pb, less than 0.001 for Cr, Cd and Hg, 0.005 for Zn, 0.001 for VOCs and 0.273 for PAHs, all of which were low except for PAHs. The HI in children with pica was shown to exceed 1.0 in some cases, but the HI never exceeded 1.0 in other users. The effects of pica may not be this severe in all children, but a number of studies have reported that as many as 4.3-25.8% of young children have pica (Danford and Huber, 1982). Pica is demonstrated in many forms (Matson *et al.*, 2011). Among the items children and adults have eaten and which are reported in the studies are stones, grass, plastic gloves, sand, ashes and paint chips (Baheretibeb *et al.*, 2008; Calabrese and Stanek, 1992).

In the worst exposure scenario, the HI for all facility users was estimated to be 0.01 for Cr, Cd and Hg. In addition, "the worst-case scenario" (poorly ventilated small gymnasium) was applied via chamber release testing in a preliminary study related to health, but no direct health problems of the users were found (ALIAPUR, 2007). The health risk of football players

Table 11. Hazard Index (HI) of non-carcinogenic compounds by average and worst exposure scenarios.

Non-carcinogenic compounds	Exposure route	Elementary school students - the lower grades		Elementary school students - the upper grades		Middle school students		High school students		Adults		Pica	
		Average	Worst	Average	Worst	Average	Worst	Average	Worst	Average	Worst	Average	Worst
Pb	Ingestion (direct)	0.007	0.090	0.002	0.202	0.001	0.075	0.001	0.045	< 0.001	0.011	0.066	0.451
	Ingestion (hand-to-mouth)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	N.D	N.D	< 0.001	< 0.001
	Inhalation	0.001	0.017	0.004	0.063	0.003	0.043	0.002	0.026	0.002	0.015	0.001	0.017
	Dermal contact	< 0.001	0.020	0.001	0.041	0.001	0.048	< 0.001	0.015	< 0.001	0.000	< 0.001	0.020
	Total risk	0.008	0.127	0.007	0.307	0.004	0.165	0.004	0.086	0.002	0.027	0.067	0.488
Cr	Ingestion (direct)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Ingestion (hand-to-mouth)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	N.D	N.D	< 0.001	< 0.001
	Inhalation	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Dermal contact	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Total risk	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
Cd	Ingestion (direct)	< 0.001	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.011
	Ingestion (hand-to-mouth)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	N.D	N.D	< 0.001	< 0.001
	Inhalation	< 0.001	< 0.001	< 0.001	0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.001	0.001	< 0.001	< 0.001
	Dermal contact	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Total risk	< 0.001	0.001	< 0.001	0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.001	0.001	< 0.001	0.011
Hg	Ingestion (direct)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.002
	Ingestion (hand-to-mouth)	N.D	< 0.001	N.D	< 0.001	N.D	< 0.001	N.D	< 0.001	N.D	N.D	N.D	< 0.001
	Inhalation	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Dermal contact	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Total risk	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.002
Zn	Ingestion (direct)	< 0.001	0.106	< 0.001	0.095	< 0.001	0.007	< 0.001	0.002	< 0.001	0.001	0.003	1.058
	Ingestion (hand-to-mouth)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	N.D	N.D	< 0.001	< 0.001
	Inhalation	0.002	0.031	0.006	0.118	0.004	0.083	0.002	0.028	0.001	0.015	0.002	0.031
	Dermal contact	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
	Total risk	0.002	0.137	0.006	0.213	0.004	0.090	0.002	0.030	0.001	0.015	0.005	1.089
VOCs	Ingestion (direct)	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D
	Ingestion (hand-to-mouth)	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D
	Inhalation	0.001	0.036	0.004	0.138	0.003	0.053	0.003	0.045	0.019	0.192	0.001	0.036
	Dermal contact	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D
	Total risk	0.001	0.036	0.004	0.138	0.003	0.053	0.003	0.045	0.019	0.192	0.001	0.036
Phthalates	Ingestion (direct)	0.003	0.040	0.009	0.193	0.006	0.133	0.004	0.101	0.002	0.036	0.273	3.971
	Ingestion (hand-to-mouth)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	NA	NA	< 0.001	< 0.001
	Inhalation	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D	N.D
	Dermal contact	< 0.001	0.001	< 0.001	0.015	0.004	0.067	0.001	0.034	0.002	0.020	< 0.001	0.007
	Total risk	0.003	0.040	0.009	0.193	0.006	0.133	0.004	0.101	0.002	0.036	0.273	3.971

VOCs: volatile organic compound

due to swallowing, inhalation and skin contact of chemicals caused by exposure to rubber chips used in artificial turf playground was reported to have no significant correlation (INTRON, 2007).

Because the types of products and raw materials used in the construction of artificial turf playgrounds vary, limitations exist in the results of the assessment of material contents and the results of the HRA. In this study, we investigated 50 artificial turf playgrounds and 18 chemicals, and the selected facilities and targeted hazardous chemicals may not be representative. Important uncertainties in our exposure scenarios of potential exposures and health risks remain.

Nonetheless, the health risk of artificial turf playgrounds and urethane flooring materials in Korea was not shown to be serious. However, as ZnO and Pb were shown to be used in the components of artificial turf playgrounds, such as infill chips, in an amount up to several thousand ppm, there is a possibility of health risks due to excessive use without regulation.

In the future, hazardous chemical monitoring via all processes from product production to construction and disposal and an institutional strategy to protect the health of facility users, including children who are sensitive to chemicals, should be prepared.

4. CONCLUSIONS

In this study, an HRA was conducted to investigate the multi-route exposures (inhalation, ingestion and dermal) of various users to hazardous chemicals released from artificial turf playgrounds and urethane flooring materials in schools via a survey on the content of materials and the environment. A survey was conducted at the facilities of 50 schools in Seoul and other metropolitan areas, which is not completely representative of all scenarios. The ECR for each chemical according to the mean exposure scenario of the subject facilities was estimated to be 1×10^{-6}. The ECR for carcinogens according to the worst exposure scenario was shown to be 1×10^{-6}, indicating a low possibility of direct exposure risk. However, the ECR for children with pica who represented the most extreme exposure group was estimated to be as great as 1×10^{-4}.

Non-carcinogenic toxic materials, which can be released from the subject materials, included 10 chemicals such as Pb, Cr, Cd, Hg, Zn, toluene, ethylbenzene, xylene, formaldehyde, and phthalates (4 species). The HI of the facility users for each individual chemical according to the mean exposure scenario was shown to be less than 0.1, which was low, except for children with pica. The HI of children with pica for non-carcinogenic materials was shown to be less than 0.001 for Pb, 0.067 for Cr, Cd and Hg, 0.005 for Zn, 0.001 for VOCs; and 0.273 for phthalates, all of which were low, except for phthalates. The HI for Pb, Zn, and phthalates according to the mean exposure scenario was estimated to be greatest in the following order: children with pica > elementary children > teenagers > adults. Meanwhile, the HI of children with pica according to the worst exposure scenario was shown to exceed 1.0 in some cases, but no case exceeding 1.0 was found in other users.

This study has two limitations. First, we did not consider asthma or allergies from artificial turf and urethane flooring. Reservations must be acknowledged regarding the development of asthma/airway allergies, as the knowledge that is currently available is limited. This particularly applies to exposure to latex allergens, as no information is available on the occurrence of latex allergens from artificial turf, yet such allergens have been demonstrated in car tire rubber.

For the other limitation, we assumed that the concentration of chemicals in air samples was only caused by artificial turf and urethane flooring materials, not at all influenced by different air emission sources. Although we collected air samples in the middle and on top of playgrounds, it was possible there were other emission sources present.

On the basis of the knowledge that is currently available concerning health effects and exposure linked to the use of artificial turf playgrounds, we did not find a direct health risk for users, except for children with pica. We do not see any necessity to replace the recycled materials in artificial turf and urethane flooring at the present time. However, there is a need for sustainable and long-term risk assessments and management of good quality artificial turf, because recycled rubber granules contain many chemical substances.

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