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*Original*

Environmental risk analysis procedure applied to artificial turf sports fields / Ruffino, Barbara; Fiore, Silvia; Zanetti, Mariachiara. - In: ENVIRONMENTAL SCIENCE AND POLLUTION RESEARCH INTERNATIONAL. - ISSN 0944-1344. - STAMPA. - 20:(2013), pp. 4980-4992. [10.1007/s11356-012-1390-2]

*Availability:*

This version is available at: 11583/2505276 since: 2016-04-04T10:50:39Z

*Publisher:*

Springer

*Published*

DOI:10.1007/s11356-012-1390-2

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# Environmental–sanitary risk analysis procedure applied to artificial turf sports fields

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Received: 30 July 2012 / Accepted: 30 November 2012  
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**Abstract** Owing to the extensive use of artificial turfs worldwide, over the past 10 years there has been much discussion about the possible health and environmental problems originating from styrene-butadiene recycled rubber. In this paper, the authors performed a Tier 2 environmental–sanitary risk analysis on five artificial turf sports fields located in the city of Turin (Italy) with the aid of RISC4 software. Two receptors (adult player and child player) and three routes of exposure (direct contact with crumb rubber, contact with rainwater soaking the rubber mat, inhalation of dusts and gases from the artificial turf fields) were considered in the conceptual model. For all the fields and for all the routes, the cumulative carcinogenic risk proved to be lower than  $10^{-6}$  and the cumulative non-carcinogenic risk lower than 1. The outdoor inhalation of dusts and gases was the main route of exposure for both carcinogenic and non-carcinogenic substances. The results given by the inhalation pathway were compared with those of a risk assessment carried out on citizens breathing gases and dusts from traffic emissions every day in Turin. For both classes of substances and for both receptors, the inhalation of atmospheric dusts and gases from vehicular traffic gave risk values of one order of magnitude higher than those due to playing soccer on an artificial field.

**Keywords** Environmental–sanitary risk analysis · Artificial turfs · Inhalation · Dermal contact · Rainwater leaching

**Introduction** 37

In recent years, the use of artificial turfs, man-made surfaces manufactured from synthetic materials designed to look like natural grass, has become increasingly popular because fake grass is more resistant to heavy use, such as sports, than natural grass and requires no irrigation or trimming. An artificial turf is made of a mat of fibers filled with small rubber granules or a mixture of rubber granules and sand, to a depth of about 4 cm. The granules currently used in mat layers are made of rubber from exhaust tires (styrene-butadiene recycled rubber (SBRr)). Due to the manufacturing process of tires, several compounds, like vulcanizing agents, accelerators, activators, anti-ozonants, antioxidants, retarders, plasticizers and extenders are present in crumb rubber, as well as various chemicals such as benzene, phthalates, and alkylphenols that may become bonded to tires during use (Denly et al. 2008). Owing to the extensive use of artificial turfs in Europe and North America, over the past 10 years there has been much discussion about the possible health and environmental problems originating from SBRr.

In Europe, the debate arose on the back of a Norwegian study (Plesser and Lund 2004) that analyzed the total content of As, Pb, Cd, Cu, Cr, Hg, PCBs, PAHs, phthalates, and phenols in three SBRr samples and in one presumably not recycled product made of ethylene propylene diene monomer and carried out leaching and degassing tests. Finally, an assessment of the potential risk was performed in a simplified version, comparing the total content of environmentally harmful substances in the source materials to the permitted values for use in the most sensitive areas (gardens, kindergartens, schools). The authors of the study concluded that a

Responsible editor: Philippe Garrigues

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68 more detailed evaluation and further tests were required to  
 69 determine whether there is a real risk for the environment  
 70 and human health. On the other hand, a report published by  
 71 the Swedish Chemicals Inspectorate (KemI 2006) supported  
 72 the concern that the use of artificial turf pitches could have  
 73 an adverse effect on the environment and the health of their  
 74 users due to the leaching of chemical substances into the soil  
 75 and water.

76 Following these reports, several studies have been carried  
 77 out to enhance knowledge regarding the amount and the  
 78 types of chemicals in recycled tires (Nilsson et al. 2005;  
 79 Zhang et al. 2008; Beausoleil et al. 2009; Bocca et al. 2009;  
 80 EPA 2009; Wik and Dave 2009; Menichini et al. 2011;  
 81 Sadiktsis et al. 2012), their potential to leach (Birkholz  
 82 et al. 2003; Nilsson et al. 2005; Verschoor 2007; Bocca et al.  
 83 2009; EPA 2009; Lim and Walker 2009; Li et al. 2010) and  
 84 degas (NILU 2006; Beausoleil et al. 2009; EPA 2009; Lim  
 85 and Walker 2009; Li et al. 2010), and the subsequent risk to  
 86 the environment and human health. Concerning the risk to  
 87 human health, the potential exposure to chemicals in crumb  
 88 rubber could occur through several pathways. Quite a few  
 89 researchers focused their attention on dermal contact  
 90 (Nilsson et al. 2005, 2008; NIPH 2006; CalEPA 2007;  
 91 Ledoux 2007) and inhalation of particulates and off-  
 92 gassing volatile organic compounds (VOCs) from rubber  
 93 (NIPH 2006; Moretto 2007; Nilsson et al. 2008; Menichini  
 94 et al. 2011). The aforementioned studies followed very  
 95 different procedures in their characterization of the rubber  
 96 materials and the assessment of risk. However, each of these  
 97 publications indicated that the health risk from playing on  
 98 synthetic turf fields was minimal despite the leaching and  
 99 volatilization of chemicals from tire granules.

100 In this work, the authors characterized five samples of  
 101 crumb rubber and one sample of natural soil from sports  
 102 facilities, and assessed their capacity to release chemicals on  
 103 contact with water. The components of the gases and dusts  
 104 collected from the air just above the sport facilities and from  
 105 a point located in the centre of the city of Turin were also  
 106 determined.

107 Finally, an environmental–sanitary risk assessment was  
 108 carried out with the aid of the Risk Integrated Software for  
 109 Clean-ups (RISC4) software (Spence and Walden 2001), in  
 110 order to evaluate if the rubber granules in artificial turf fields  
 111 may pose a health risk to child and adult players via direct  
 112 contact with the infill material, contact with rainwater soak-  
 113 ing the rubber mat or inhalation of dusts and gases released  
 114 from the pitch. The environmental exposure models were  
 115 developed in an effort to quantify the human exposure to  
 116 chemicals via contact with the surrounding natural environ-  
 117 ment. In the international context, the procedure of environ-  
 118 mental–sanitary risk assessment has assumed a central role  
 119 in the management of contaminated sites, mainly with ref-  
 120 erence to emerging pollutants (Jin et al. 2012; Stasinakis et

al. 2012), but the same procedure can be successfully ap- 121  
 122 plied to other fields of interest, like foods and toys (Leber  
 2001; Walden 2005; Fryer et al. 2006; Hang et al. 2009). 123Q2

**Materials and methods** 124

Sample overview 125

The present study deals with six sports turf fields located in the 126  
 127 city of Turin. Barracuda (B), Carrara (C), Pellerina Gomma  
 128 (PG) and River Mosso (RM) are artificial turf fields whose  
 129 infill is made of SBRr from shredded tires. C and B are  
 130 1.5 years old, PG and RM are 3 years old, respectively. 130  
 131 Passo Buole (PB) is a 3-year-old artificial turf field whose  
 132 infill is made of a thermoplastic elastomer (TPE) specifically  
 133 produced for turf field applications. Pellerina Terra (PT) is a  
 134 natural turf field.

135 For each sporting field, a 1,200-g sample of the infill  
 136 material was collected using an Electrolux extractor fan at  
 137 12 different positions in the playing area (Bocca et al. 2009).  
 138 Natural soil (1 kg) from the PT field was also collected and  
 139 used as a blank sample.

140 Both rubber and soil samples underwent a physical and  
 141 chemical characterization involving a particle size distribu-  
 142 tion analysis and the determination of benzene, toluene,  
 143 xylenes (BTX), PAHs (B(a)A, benz(a)anthracene; B(b)F,  
 144 benzo(b)fluoranthene; B(k)F, benzo(k)fluoranthene; B(a)P,  
 145 benzo(a)pyrene; B(g,h,i)P, benzo(g,h,i)perylene; CHR,  
 146 chrysene; D(a,h)A, dibenz(a,h)anthracene; PYR, pyrene)  
 147 and metals (Na, K, Ca, Mg, Fe, Mn, Cd, Cu, Ni, Zn, Pb,  
 148 Ti, Ba, Al, Co, Cr, Sn, As). Rubber and soil samples were  
 149 subjected to a leaching test, according to the EN 12457/2  
 150 compliance test.

151 Samples of gases and dusts were collected immediately  
 152 above the ground, close to the sports fields and in a point in  
 153 the centre of the city, and underwent the determination of  
 154 BTX (gases) and PAHs (dusts). The samples of gases and  
 155 dusts from the centre of the city were collected and analysed  
 156 in order to evaluate the influence of vehicle-emitted con-  
 157 taminants on the composition of dusts and gases from the  
 158 sporting fields.

Analytical methods 159

160 The particle size distribution analysis was performed using  
 161 Tyler Standard sieves (48, 28, 20, 14, 10, 8 and 6 Tyler  
 162 meshes for crumb rubber samples and 400, 200, 100, 48, 28,  
 163 14, 8 and 4 Tyler meshes for the natural soil sample).

164 For the determination of BTX and PAHs, crumb rubber and  
 165 natural soil (three replicates for each sample) underwent a  
 166 microwave-assisted extraction (MAE, 2-g sample, 20 mL of  
 167 dichloromethane–Supelco, pesticide grade, 20 min, 600 W,

168	Milestone 1200 Mega) followed by gas-chromatograph anal-	221
169	ysis using an Agilent GCD 1800C GC-MS.	222
170	For BTX analysis, the GC-MS was equipped with a J&W	223
171	DB624 capillary column (30 m×0.25 mm×1.4 μm). The	224
172	initial column temperature was 46 °C for 4 min, and the	225
173	temperature was risen to 95 °C at a rate of 3 °C/min and then	226
174	maintained at 95 °C for 1 min. Three replicates (max standard	227
175	deviation 5 %) of each extract (5 μL) were injected in splitless	228
176	mode with a solvent delay of 1.80 min. The mass spectrometer	229
177	was operated in SIM mode, and helium was used as a carrier	230
178	gas in a constant flow mode. The injector temperature was	231
179	200 °C while that of the detector was 230 °C. Calibration	232
180	curves for each compound were obtained by injecting stan-	233
181	dard solutions at eight different concentration values, with	234
182	three replicates for each concentration value, prepared in	235
183	dichloromethane by weighing from Supelco EPA VOC mix	236
184	(2,000 μg/mL) and stored at -20 °C until use. Different	237
185	calibration curves ( $0.9935 < R^2 < 0.9996$ ), referred to specific	238
186	concentration intervals, were considered depending on the	239
187	signal given by the samples. A working standard (1 μg/L) in	240
188	dichloromethane was prepared daily. The method had a de-	241
189	tection limit of 0.001 μg/L for each of the three analysed	242
190	compounds.	243
191	For PAH analysis, the GC-MS was equipped with an	244
192	HP5-MS capillary column (30 m×0.25 mm×0.25 μm).	245
193	The initial column temperature was 60 °C for 4 min, and	246
194	the temperature was risen to 280 °C at a rate of 10 °C/min	247
195	and then maintained at 280 °C for 10 min. Three replicates	248
196	(max standard deviation 4 %) of each extract (5 μL) were	249
197	injected in splitless mode with a solvent delay of 3 min. The	250
198	mass spectrometer was operated in SIM mode, and helium	251
199	was used as a carrier gas in a constant flow rate mode. The	252
200	injector temperature was 250 °C while that of the detector	253
201	was 240 °C. Calibration curves ( $0.9886 < R^2 < 0.9997$ ) for	254
202	each compound were obtained by injecting standard solu-	255
203	tions at 12 different concentration values prepared in	256
204	dichloromethane by weighing from Supelco TCL PAH	257
205	mix (2,000 μg/mL) and stored at -20 °C until use. A	258
206	working standard (1 μg/L) in dichloromethane was prepared	259
207	daily. The method had a detection limit of 0.001 μg/L for	260
208	each of the eight analysed compounds.	
209	Metal content was determined using an MAE in a	261
210	Milestone 1200 Mega following two different procedures	
211	depending on the sample material (three replicates for each	262
212	samples)—for rubber: 0.10 g, 3 mL HNO <sub>3</sub> (65 %, Riedel de	263
213	Haen, Sigma Aldrich) and 1 mL HClO <sub>4</sub> (70 %, Merck); for	264
214	natural soil: 0.25 g, first digestion stage 2.5 mL H <sub>2</sub> SO <sub>4</sub> (95–	265
215	97 %, Riedel de Haen, Sigma Aldrich) and 2.5 mL H <sub>3</sub> PO <sub>4</sub>	
216	(85 %, Merck), second digestion stage 5 mL HF (48 %,	266
217	Merck). All the digested solutions were filtered through	
218	Whatman 542 filters, brought to a 100-mL final volume	267
219	and analysed using a Perkin Elmer Optima 2000 ICP-OES.	268
220	The detection limits for the metals analysed are shown in	269
	Table 1, and the maximum standard deviation was always	221
	lower than 3 %.	222
	Determination of in-water extractable compounds (BTX,	223
	PAHs, metals) was performed according to the EN 12457/2	224
	compliance test (deionized water, one stage, stirred, 24 h,	225
	room temperature batch test at a liquid–solid ratio of 10 L/	226
	kg for materials with particle sizes below 4 mm). The	227
	extracts obtained were filtered through Whatman 0.45-mi-	228
	cron membranes.	229
	BTX in the leachates were determined using a static	230
	headspace technique (procedure: 5 mL of filtered leachate	231
	and 1 g NaCl in a 10-mL sealed headspace vial warmed for	232
	30 min at 60 °C). The static headspace technique was	233
	followed for both samples and standard solutions so as to	234
	obtain the same recovery value. BTX were analysed using	235
	the Agilent GCD 1800C GC-MS following the previously	236
	described method by injecting 200 μL of headspace (solvent	237
	delay 1.80 min).	238
	A solid phase extraction (SPE) by means of ENVI-18	239
	tubes (Supelco, 3 mL×0.5 g; procedure: conditioning with	240
	2 mL methanol–Supelco, pesticide grade, and 2 mL deion-	241
	ized water, loading of 300 mL of aqueous samples, elution	242
	with two 1.5 mL aliquots of dichloromethane, Supelco,	243
	pesticide grade), was used to concentrate PAHs by transfer-	244
	ring them from water to CH <sub>2</sub> Cl <sub>2</sub> . SPE procedure was fol-	245
	lowed for both samples and standard solutions so as to	246
	obtain the same recovery value. The final extracts (5 μL)	247
	were injected into the Agilent GCD 1800C GC-MS follow-	248
	ing the method described for PAH analysis.	249
	A Perkin Elmer Optima 2000 ICP-OES was used for the	250
	quantification of metals in the eluate. The detection limits	251
	for the metals analysed are shown in Table 1, and the	252
	maximum standard deviation was always lower than 3 %.	253
	Anions (chloride, sulfate, nitrates and fluoride) and the	254
	chemical oxygen demand content were determined accord-	255
	ing to standard methods (APHA, AWWA, WEF 2005).	256
	BTX in the outdoor air and PAHs in the dust samples were	257
	sampled and analysed by the researchers from the Group of	258
	General and Applied Hygiene, University of Turin, according	259
	to the methods described in Gilli et al. (2007).	260
	Risk analysis	261
	A risk assessment was carried out through the steps described	262
	in the “Site conceptual model” section, “Determination of the	263
	concentration values at the point of exposure” section and	264
	“Risk quantification” section.	265
	<i>Site conceptual model</i>	266
	The site conceptual model involves the sources of contam-	267
	ination, the migration pathways (also called routes of expo-	268
	sition) and the receptors.	269

Q3 t1.1

**Table 1** Concentration of BTX, PAHs, metals and anions in the eluates obtained according to the EN 12457/2 compliance test on the samples of rubber granules and natural soil

t1.2			B	C	PB	PG	RM	PT	DL
t1.3	B	µg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
t1.4			.270	1.56	1.15	2.70	2.08	2.56	
t1.5	T	µg/L	0.43	0.41	0.18	0.29	0.33	0.25	0.001
t1.6			.1.09	1.51	1.27	0.723	0.735	681	
t1.7	X	µg/L	0.36	0.42	0.36	0.45	0.34	0.37	0.001
t1.8			.0.477	0.577	1.45	0.462	0.499	8.01	
t1.9	PYR	µg/L	0.05	0.06	0.07	0.03	0.03	<0.001	0.001
t1.10			.2.21E-03	2.32E-03	1.99E-02	1.40E-03	1.50E-03	1.67E-02	
t1.11	B(a)A	µg/L	<0.001	0.01	0.05	<0.001	<0.001	<0.001	0.001
t1.12			.2.12E-04	8.93E-04	2.50E-02	6.54E-05	1.05E-04	3.57E-03	
t1.13	CHR	µg/L	<0.001	0.04	0.02	<0.001	<0.001	<0.001	0.001
t1.14			.6.45E-04	9.50E-03	2.06E-02	3.13E-04	6.94E-04	1.43E-02	
t1.15	B(b)F	µg/L	<0.001	0.02	<0.001	0.04	<0.001	<0.001	0.001
t1.16			.5.46E-04	4.58E-03	2.89E-04	4.54E-03	ND	1.47E-03	
t1.17	B(k)F	µg/L	<0.001	0.02	0.04	<0.001	<0.001	<0.001	0.001
t1.18			.ND	8.23E-03	1.00E-02	1.99E-04	ND	1.96E-03	
t1.19	B(a)P	µg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
t1.20			.8.70E-04	7.09E-04	3.91E-04	7.94E-04	ND	3.57E-03	
t1.21	D(a,h)A	µg/L	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
t1.22			.9.80E-04	1.23E-04	1.22E-03	2.49E-04	1.39E-03	1.37E-03	
t1.23	B(g,h,i)P	µg/L	0.04	<0.001	<0.001	<0.001	<0.001	<0.001	0.001
t1.24		%	2.06E-02	2.40E-04	1.15E-03	4.37E-04	5.88E-04	1.19E-03	
t1.25	As	µg/L	<5.3	<5.3	<5.3	<5.3	<5.3	<5.3	5.3
t1.26		%	ND	ND	ND	ND	ND	ND	
t1.27	Co	µg/L	11.9	12.5	4.80	9.41	9.03	3.30	0.60
t1.28			.0.103	0.116	0.085	0.093	0.458		
t1.29	Cr	µg/L	<0.71	<0.71	<0.71	<0.71	<0.71	<0.71	0.71
t1.30		%	ND	ND	ND	ND	ND	1.51E-03	
t1.31	Ni	µg/L	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5	1.5
t1.32			.ND	ND	ND	ND	ND	ND	
t1.33	Pb	µg/L	<4.2	<4.2	<4.2	<4.2	<4.2	<4.2	4.2
t1.34			.0.014	0.112	0.122	0.210	0.213	0.042	
t1.35	Sn	µg/L	34.5	25.3	21.2	<9.6	47.7	<9.6	9.6
t1.36		%	0.265	0.074	9.42E-03	0.014	0.122	1.33E-03	
t1.37	Zn	µg/L	1,143	1,525	452	1,530	2,729	<0.18	0.18
t1.38		%	0.075	0.122	0.078	0.122	0.224	3.55E-03	
t1.39	Al	µg/L	11.0	39.8	82.0	10.4	7.97	30.5	2.8
t1.40	Ba	µg/L	10.9	12.4	88.7	21.3	15.4	<0.13	0.13
t1.41	Cd	µg/L	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	0.25
t1.42	Cu	µg/L	16.4	10.5	10.2	6.62	22.1	3.80	0.54
t1.43	Fe	µg/L	18.3	53.9	25.2	27.4	38.2	68.4	0.46
t1.44	Mn	µg/L	12.3	29.8	17.2	22.9	42.4	4.37	0.14
t1.45	Ti	µg/L	1.48	2.88	2.49	0.848	2.28	1.39	0.38
t1.46	NO <sub>3</sub> <sup>-</sup>	mg/L	2.24	<0.1	1.50	0.45	2.47	2.84	0.05
t1.47	F <sup>-</sup>	mg/L	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.05
t1.48	SO <sub>4</sub> <sup>=</sup>	mg/L	3.98	8.97	3.54	5.36	6.40	19.3	0.5
t1.49	Cl <sup>-</sup>	mg/L	0.735	1.18	0.602	0.847	2.25	2.06	0.05
t1.50	COD	mg/L	59.4	63.6	50.2	70.2	52.6	22.3	0.5
t1.51	pH		6.63	6.63	7.36	6.51	6.41	9.86	
t1.52	CE	µS/cm	71	97	145	68	83	330	

For the compounds involved in the risk analysis the percent accessibility was also calculated

*DL* detection limit for the determination of each species, *ND* impossible to calculate (both values involved in the percent accessibility calculation were below the detection limits)

**Q4**270 The receptors were adults and children who usually play  
271 on the turf. The sources of contamination were the rubber  
272 granules from the artificial turf fields and the natural soil  
273 used as a reference material. The chemicals of concern  
274 (COCs) involved in the risk assessment were: benzene, tolu-  
275 ene, xylene, pyrene, B(a)A, B(a)P, B(b)F, B(k)F, B(g,h,i)P,  
276 chrysene, D(a,h)A, lead, cobalt, tin and zinc for rubber mate-  
277 rials and the soil sample, and arsenic, nickel and chromium for  
278 the soil sample only.

279 Among the possible routes, in this work only dermal  
280 contact with the infill material (direct dermal contact  
281 (DDC)), dermal contact with the rainwater soaking the infill  
282 (rain water contact (RWC)) and inhalation of dusts and  
283 gases from the fields (dust and gas inhalation (DGI)) were  
284 taken into account. The exposure to contaminants in crumb  
285 rubber through ingestion was not evaluated because it was  
286 assumed that the potential of this route is greater for little  
287 children than older children and adults owing to the mouth-  
288 ing of their hands or objects. Older children and adults using  
289 artificial turfs can reasonably be expected to get some inad-  
290 vertent/unintentional oral exposure to crumb rubber from  
291 dusts generated in the routine use of these facilities whose  
292 extent may be deemed negligible (Denly et al. 2008).

293 For each route, a Tier 2 risk assessment was performed.  
294 The results from the scenario “outdoor inhalation of dusts  
295 and gases from a turf field” were compared with the out-  
296 comes of the risk analysis performed on the same route on  
297 both adults and children living in the centre of Turin. The  
298 latter receptors are exposed for 6 h a day and for 350 days a  
299 year to outdoor dusts and gases from traffic and domestic  
300 combustion.

301 *Determination of the concentration values at the point*  
302 *of exposure*

303 For the DDC route, the COC concentration at the point of  
304 exposure was equal to the amount of chemicals (BTX, PAHs  
305 and metals) in the rubber granules or soil shown in Table 2.

306 For the RWC route, the COC concentration at the point of  
307 exposure was calculated by way of the hypothesis that the  
308 EN 12457/2 elution test was able to extract the whole  
309 leachable amount of each COC from the rubber granules  
310 (see Table 1), simulating the transfer into rainwater. Since a  
311 risk assessment has to be performed under conservative  
312 conditions, the solid/liquid ratio between crumb rubber  
313 and the rainwater soaking the rubber granule layer during  
314 rainfall was set at 1:2, meaning that the leachable amount of  
315 each COC is dissolved in a volume equal to 1/5 of the  
316 elution test volume. This hypothesis is conservative because  
317 the release of COCs on contact with water decreases as the  
318 solid/liquid ratio increases (from 1:10 in test EN 12457/2 to  
319 1:2 in the real case). The ratio of 1:2 came from the remarks  
320 about rainfall amounts and artificial turf field constructive

features here reported. The daily average rainfall value over  
the last 10 years in Turin has been 11.7 mm/day (data from  
ARPA–Agenzia Regionale per la Protezione dell’Ambiente  
- Piemonte). According to the guidelines for the construc-  
tion of artificial turfs (The Football Association 2005), from  
bottom to top, an artificial turf field is made of a 10-mm  
silica sand layer, with a porosity of 0.4 and a 10-mm crumb  
rubber layer with a porosity of 0.5. Based on the aforemen-  
tioned remarks, it can be concluded that the solid/liquid ratio  
between the infill material and the rainwater soaking the  
rubber granules is 1:2.

For the DGI route, the COC concentration at the point of  
exposure was equal to the BTX concentration in the outdoor  
air and the PAHs in the dusts, sampled at the borders of the  
sports fields, listed in Table 3.

*Risk quantification*

For each receptor (child player or adult player), for each  
source (synthetic or natural turf field) and for each exposure  
pathway (DDC, RWC, DGI), the risks due to each contam-  
inant were divided into two categories: non-carcinogens and  
carcinogens.

According to standard EPA methods (NDEQ 2009), for  
non-carcinogenic chemicals the risk was calculated as in the  
following equation:

$$THQ = \frac{ADI}{RfD}, \tag{1}$$

where ADI (milligrammes per kilogramme per day), aver-  
age daily intake, is the estimated dose the receptor is ex-  
posed to from an exposure route; RfD (milligrammes per  
kilogramme per day) is the dose, for a given route, that is  
believed to be without effect.

For non-carcinogenic compounds, acceptable values of  
total hazard quotient (THQ) (dimensionless) are less than 1.  
The same criterion has to be assumed for both individual  
and cumulative THQ (D.lgs. 152/06). With reference to one  
field and one route, the cumulative THQ has to be seen as  
the sum of the THQ calculated as in Eq. (1) for each  
contaminant.

For carcinogenic chemicals, the risk was calculated as in  
the following equation:

$$CR = LDI \times CSF, \tag{2}$$

where CR (dimensionless) is cancer risk, that is, the proba-  
bility of cancer occurring in the exposed population over a  
70-year lifetime; LDI (milligrammes per kilogramme per  
day), lifetime daily intake, is the dose of contaminants the  
receptor is exposed to for all their life through an exposure  
route; CSF (kilogramme per day per milligramme) is the  
cancer slope factor for each exposure route derived from  
dose–response studies.

**Table 2** Concentration of BTX, PAHs and metals in the samples of rubber granules and natural soil

	Turf field/COC		B	C	PB	PG	RM	PT	CTC residential	CTC industrial
t2.3	B	µg/kg	0.37	0.64	0.87	0.37	0.48	0.39	0.10	2
t2.4	T	µg/kg	393	272	142	401	449	36.7	0.50	50
t2.5	X	µg/kg	754	728	248	975	682	46.2	0.50	50
t2.6	PYR	mg/kg	22.6	25.9	3.51	21.4	20.0	0.06	0.50	50
t2.7	B(a)A	mg/kg	4.72	11.2	2.00	15.3	9.55	0.28	0.50	10
t2.8	CHR	mg/kg	1.55	4.21	0.97	3.19	1.44	0.07	5	50
t2.9	B(b)F	mg/kg	1.83	4.37	3.46	8.81	<0.01	0.68	0.50	10
t2.10	B(k)F	mg/kg	<0.01	2.43	3.99	5.02	<0.01	0.51	0.50	10
t2.11	B(a)P	mg/kg	1.15	1.41	2.56	1.26	<0.01	0.28	0.10	10
t2.12	D(a,h)A	mg/kg	1.02	8.13	0.82	4.01	0.72	0.73	0.10	10
t2.13	B(g,h,i)P	mg/kg	1.94	4.16	0.87	2.29	1.70	0.84	0.10	10
t2.14	Na	%	0.039	0.050	0.025	0.036	0.027	4.33	–	–
t2.15	K	%	0.062	0.075	0.068	0.056	0.052	0.979	–	–
t2.16	Ca	%	0.885	2.21	9.16	0.284	0.409	2.51	–	–
t2.17	Mg	%	0.044	0.053	0.095	0.041	0.036	1.66	–	–
t2.18	Fe	%	0.037	0.092	0.585	0.055	0.105	2.26	–	–
t2.19	Mn	mg/kg	<0.14	5.50	13.7	<0.14	4.00	421	–	–
t2.20	Cd	mg/kg	<0.25	<0.25	<0.25	<0.25	<0.25	<0.25	2	15
t2.21	Co	mg/kg	116	108	56.7	125	97.0	7.20	20	250
t2.22	Cr (tot)	mg/kg	<0.71	<0.71	<0.71	<0.71	<0.71	471	150	800
t2.23	Cu	mg/kg	34.5	60.5	77.0	29.0	43.7	16.5	120	600
t2.24	Ni	mg/kg	<1.5	<1.5	<1.5	<1.5	<1.5	<1.5	120	500
t2.25	Zn	%	1.53	1.25	0.578	1.25	1.22	0.005	150	1,500
t2.26	Pb	mg/kg	308	37.5	34.3	20.0	19.7	99.1	100	1,000
t2.27	Ti	mg/kg	36.0	48.5	101	47.0	47.3	1,740	–	–
t2.28	Ba	mg/kg	167	1,325	1,036	1,775	10.7	296	–	–
t2.29	Al	%	0.094	0.092	0.483	0.077	0.068	3.57	–	–
t2.30	Sn	%	0.013	0.034	0.225	0.021	0.039	0.687	1	350
t2.31	As	mg/kg	<5.3	<5.3	<5.3	<5.3	<5.3	324	20	50

Soil quality guidelines (CTC) for residential and industrial areas according to Italian Decree 152/06

369 For small values of average daily intake, in which the CR is linearly proportional to the exposed contaminant concentration, as in Eq. (2), an additional lifetime cancer risk of  $10^{-6}$  is retained to be acceptable for the individual CR while for

371  
372

**Table 3** Concentrations (milligramme per cubic metre) of BTX and PM10 in the samples of gases and concentrations (nanogramme per cubic metre) of PAHs in the samples of dusts collected above the playgrounds and in the centre of the city (traffic)

			B	C	PB	PG	RM	PT	Traffic
t3.3	B	µg/m <sup>3</sup>	2.2	1.3	3.0	1.8	1.4	1.4	3.0
t3.4	T	µg/m <sup>3</sup>	5.3	5.6	6.9	10.2	4.2	5.0	12.9
t3.5	X	µg/m <sup>3</sup>	8.8	7.9	8.3	20.9	7.6	7.4	6.4
t3.6	PM10	µg/m <sup>3</sup>	62	63	72	33	54	39	31
t3.7	PYR	ng/m <sup>3</sup>	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
t3.8	B(a)A	ng/m <sup>3</sup>	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
t3.9	CHR	ng/m <sup>3</sup>	<0.09	<0.09	0.10	0.10	<0.09	<0.09	<0.09
t3.10	B(b)F+B(k)F	ng/m <sup>3</sup>	<0.09	0.12	<0.09	0.17	0.12	0.15	<0.09
t3.11	B(a)P	ng/m <sup>3</sup>	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
t3.12	D(a,h)A	ng/m <sup>3</sup>	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09	<0.09
t3.13	B(g,h,i)P	ng/m <sup>3</sup>	<0.09	0.09	<0.09	0.12	<0.09	0.10	<0.09

373 cumulative CR the maximum acceptable value is  $10^{-5}$  (D.lgs.  
374 152/06). As said before, with reference to one field and one  
375 route, the cumulative CR is the sum of the CR calculated as in  
376 Eq. (2) for each contaminant.

377 The daily intake, ADI for non-carcinogenics and LDI for  
378 carcinogenics, is the product of the specific exposition rate  
379 ( $E$ , daily amount, normalized on the body weight, of crumb  
380 rubber or rainwater contacted, or air breathed) and the  
381 concentration  $C$  of COC in the taken media at the point of  
382 exposure.

383 The exposition rate was calculated by RISC4 for each  
Q8384 exposition route as in the following equations:

385 Direct dermal contact

$$E \left[ \frac{\text{mg}}{\text{kg} \cdot \text{day}} \right] = \frac{\text{SA} \cdot \text{AF} \cdot \text{ABS} \cdot \text{EF} \cdot \text{ED} \cdot \text{BIO}}{\text{BW} \cdot \text{AT}}$$

386 Dermal contact with rainwater

$$E \left[ \frac{\text{cm}^2}{\text{kg} \cdot \text{day}} \right] = \frac{\text{SA} \cdot \text{PC} \cdot \text{EFg} \cdot \text{EF} \cdot \text{ED}}{\text{BW} \cdot \text{AT}}$$

389 Inhalation of outdoor dusts and gases

$$E \left[ \frac{\text{m}^3}{\text{kg} \cdot \text{day}} \right] = \frac{\text{Bo} \cdot \text{EFg} \cdot \text{EF} \cdot \text{ED}}{\text{BW} \cdot \text{AT}}$$

392 The parameters utilized to calculate the specific exposi-  
395 tion rates are listed in Table 4.

396 For the non-carcinogenic ADI values, the average time  
397 was assumed to be equal to 6 years for children and 30 years  
398 for adults (equal to ED), while 70 years (lifetime) was  
399 assumed for the calculation of LDI for carcinogenic sub-  
400 stances. Pertinent RfD and CSF values are listed in the ISS-  
401 ISPESL (Istituto Superiore di Sanità–Istituto Superiore per  
402 la Prevenzione e la Sicurezza del Lavoro) Database and are  
403 reported in Table 5. For both direct and indirect contact  
404 routes, RfD and CSF values for ingestion were considered.

## 405 Results and discussion

### 406 Sample characterization

407 All the samples of rubber granules analysed were character-  
408 ized by sizes ranging from 1 to 3 mm, with the exception of  
409 the PG sample, which showed a sharper particle size distri-  
410 bution, from 1 to 2 mm, and the C sample, which had 6 %  
411 by weight (b.w.) of 0.6–1 mm material. The PT natural soil  
412 sample showed a larger particle size distribution, ranging  
413 from 0.01 to 10 mm.

414 The BTX and PAH content for the six examined samples  
415 is shown in Table 2. The PB thermoplastic sample had a  
416 lower total content of both BTX and PAHs than the samples  
417 made of SBRr. The PT sample showed quite a substantial

concentration of BTX and some PAHs. In particular, the 418  
concentration of benzene in PT was similar to those found in 419  
artificial turf fields (B, PG, RM). The turf field materials 420  
originating from recycled tires were characterized by a pyrene 421  
concentration of approximately 20 mg/kg. Similarly, B(a)A 422  
was contained in all the SBRr samples, with a concentration of 423  
about 10 mg/kg (with the exception of the B sample, charac- 424  
terized by a B(a)A concentration which was slightly lower 425  
than 5 mg/kg). 426

Zinc concentrations in the artificial turf materials were 427  
substantially higher than any of the other test metals 428  
(Table 2). All of the SBRr samples showed a zinc content 429  
ranging from 1.22 % b.w. to 1.53 % b.w due to the zinc 430  
oxide used as an activator in the vulcanization process. Iron, 431  
cobalt and manganese were detected at significant levels in 432  
spite of the efforts to separate steel from the crumb rubber. 433  
High concentrations of barium are possibly a result of its use 434  
to catalyze the synthesis of polybutadiene rubber. Lead was 435  
also identified, possibly due to the use of lead oxide as an 436  
activator of the vulcanization process (CalePA 2007; Denly 437  
et al. 2008). The PT sample had a considerably high con- 438  
centration of potentially hazardous metals like nickel, lead, 439  
chrome, tin and arsenic. 440

Figure 1 shows the average value of PAHs from the four 441  
SBRr samples, the TPE infill from the PB field, the average 442  
value of the dust samples collected from the air just above 443  
an SBRr artificial turf field, the dust collected from just 444  
above the thermoplastic turf field and the dust collected 445  
from just above the natural turf field. 446

The results in Fig. 1 highlight that the three samples of 447  
dust had a very similar composition, but this was remark- 448  
ably different from the composition of the infill materials 449  
made of exhaust tires or non-recycled thermoplastic rubber, 450  
in particular with reference to the content of pyrene and B 451  
(a)A. This demonstrates that the majority of the dust sam- 452  
ples did not come from the infill material but from other 453  
sources, like domestic combustion and urban traffic, in line 454  
with the outcomes found by Castellano et al. (2008). 455

The concentration of both organic and inorganic substan- 456  
ces in the rainwater after contact with the infill materials was 457  
simulated using the EN 12457/2 leaching test. The results of 458  
the elution tests are shown in Table 1. For the four SBRr 459  
samples, the BTX and PAH concentration in the leachate 460  
from the new infill materials (B and C) was higher than in 461  
the leachate from the old ones (PG and RM). This is in line 462  
with the data from Birkholz et al. (2003) and Moretto 463  
(2007), demonstrating that the toxicity of leachate decreases 464  
with the age of the infill material in place. The PB sample 465  
showed a high capacity for mobilizing PAHs compared to 466  
the other infill materials. The results shown in this work are 467  
in line with the outcomes from field studies (Moretto 2007), 468  
although a laboratory leaching test alone is not able to 469  
predict the real concentration in rainwater because it 470



t4.1 **Table 4** List of parameters utilized for the calculation of the specific exposition rates

t4.2	Parameter (acronym)	Parameter description	Unit of measurement	Numeric value
t4.3	BW	Body weight	kg	Adult, 70–child, 25
t4.4	ATn	Average exposure duration for non-carcinogenic substances	years	ED
t4.5	ATc	Average exposure duration for carcinogenic substances	years	70
t4.6	ED	Exposure duration	years	Adult, 30–child, 6
t4.7	Direct dermal contact			
t4.8	SA	Amount of exposed skin to crumb rubber	cm <sup>2</sup>	Adult, 8,600–child, 4,000
t4.9	AF	Soil-to-skin adherence	mg/cm <sup>2</sup> /day	1
t4.10	ABS	Dermal adsorption factor	Dimensionless	0.1–0.01
t4.11	EF	Exposure frequency	days/year	100
t4.12	BIO	Biodisponibility factor	Dimensionless	<sup>a</sup>
t4.13	Rainwater contact			
t4.14	SA	Amount of exposed skin to rainwater	cm <sup>2</sup>	Adult, 8,600–child, 4,000
t4.15	PC	Permeability coefficient	cm/h	<sup>b</sup>
t4.16	EFg	Daily exposure frequency	h/day	2×0.05=0.1 <sup>c</sup>
t4.17	EF	Exposure frequency	days/year	24 <sup>d</sup>
t4.18	Inhalation of outdoor dusts and gases			
t4.19	Bo	Breathed air rate	m <sup>3</sup> /h	Adult, 3.2–child, 1.9
t4.20	EFg	Daily exposure frequency	h/day	2
t4.21	EF	Exposure frequency	days/year	100
t4.22	Inhalation of outdoor dusts and gases: residential scenario			
t4.23	Bo	Breathed air rate	m <sup>3</sup> /h	Adult, 0.9–child, 0.7
t4.24	EFg	Daily exposure frequency	h/day	6
t4.25	EF	Exposure frequency	days/year	350

<sup>a</sup> BIO is the amount of contaminant in crumb rubber that may actually be extracted by water thus being absorbed by the skin. It was calculated in a conservative manner, for each family of compounds (BTX, PAHs and metals) from values of Tables 1 and 2. For SBRr and TPE fields, the following BIO values were assumed: BTX BIO, 10<sup>-1</sup>; PAH BIO, 10<sup>-3</sup>; metal BIO, 10<sup>-2</sup>. For the PT field, the following BIO values were assumed: BTX BIO, 10<sup>-1</sup>; PAH BIO, 10<sup>-2</sup>; metal BIO, 10<sup>-3</sup>. The risk calculation for the DDC route keeps into account that a player is in contact with rubber granules for the whole length of his training session (2 h)

<sup>b</sup> PCs for each substance are listed in Table 5 (see Supplementary Material)

<sup>c</sup> The evaluation of the EFg to rainwater soaking the crumbed rubber and leaching from it keeps into account that a player can come in contact with rainwater only in cases of falls on the ground. Accordingly, the EFg was calculated as the product of the number of hours per day (Eq. (2)) sportsmen play on the field and the number of minutes per hour (3 min equals 0.05 h) a player spends on the ground after a fall

<sup>d</sup> The calculation of the EF for the RWC route keeps into account that in the town of Turin, there are, on the average, 85 rainy days per year; that means that a player who trains on the field for 100 days per year may contact rainwater for 24 days per year (24=85×100/365)

471 produces better contact between the infill material and the  
472 contact liquid than what occurs in a real field.

473 The maximum concentration (C') of each substance in  
474 the leachate can be calculated as in the following equation:

$$C' \text{ (milligramme/litre)} = C \text{ (milligramme per kilogramme)} / 10, \quad (3)$$

476 where C is the amount of a given substance found in the  
477 solid sample (rubber or soil) and 10 is the b.w. ratio between  
478 the liquid and solid phases.

479 Considering the maximum amount of chemicals that may  
480 be mobilized in a leaching test, calculated as in Eq. (3), the  
481 per cent accessibility of each compound for each sample can  
482 be calculated by dividing the amount of each chemical

released into the water from a sample by the maximum 483  
concentration (C') of the given chemical in the leachate 484  
generated by the given sample and eventually multiplying 485  
the result by 100. As shown in Table 1, the per cent acces- 486  
sibility of each PAHs for the PT and PB samples is lower 487  
than 10<sup>-3</sup> (10<sup>-1</sup>%), and that for all four SBRr samples is 488  
lower than 10<sup>-4</sup>, with the exception of B(g,h,i)P for the B 489  
sample. The BTX fraction released in water by all the tested 490  
samples, both artificial and natural, is lower than 10<sup>-1</sup>, and 491  
the highest values were detected in the natural soil sample. 492  
The higher amount of PAHs and BTX mobilized in the 493  
natural soil sample can be explained taking into account 494  
that the PAH and BTX content in soil is entirely due to the 495  
deposition of atmospheric particulate on the ground. PAHs 496  
and BTX in atmospheric dusts are more easily mobilized 497

**Table 5** ISS-ISPEL database

t5.2		CAS number	Carcinogen catalogue UE	Carcinogen class EPA	SF ingestion [mg/kg/day]	SF inhalation [mg/kg/day]	RfD ingestion (mg/kg/day)	RfD inhalation (mg/kg/day)	Dermal adsorption factor	Permeability coefficient [cm/h]	
t5.3	Inorganic compounds										
t5.4	Arsenic	7440-38-2	–	A	1.50E+00	1.50E+01	3.00E-04	3.00E-04	0.01	0.001	
t5.5	Cobalt	7440-48-4	2	–	–	–	6.00E-02	2.90E-04	0.01	0.00121	
t5.6	Total chromium	16065-83-1	–	–	–	–	1.50E+00	1.50E+00	0.01	0.0013	
t5.7	Nickel	7440-02-0	3	A	2.00E-02	8.40E-01	2.00E-02	2.00E-02	0.01	0.001	
t5.8	Lead	7439-92-1	1/3	B2	–	–	3.50E-03	3.50E-02	0.01	0.000342	
t5.9	Tin	7440-31-5	–	–	–	–	6.00E-01	6.00E-01	0.01	0.00288	
t5.10	Zinc	7440-66-6	–	D	–	–	3.00E-01	3.00E-01	0.01	0.0006	
t5.11	Aromatic										
t5.12	Benzene	71-43-2	1	A	5.50E-02	2.91E-02	4.00E-03	8.55E-03	0.1	0.021	
t5.13	Toluene	108-88-3	–	D	–	–	8.00E-02	1.14E-01	0.1	0.045	
t5.14	Xylenes	1330-20-7	–	D	–	–	2.00E-01	2.00E-01	0.1	0.08	
t5.15	PAHs										
t5.16	Benzo(a)anthracene	56-55-3	2	B2	7.30E-01	6.00E-01	–	2.85E-01	0.1	0.81	
t5.17	Benzo(a)pyrene	50-32-8	2	B2	7.30E+00	7.32E+00	–	3.14E+00	0.1	1.2	
t5.18	Benzo(b)fluoranthene	205-99-2	2	B2	7.30E-01	6.00E-01	–	2.85E-01	0.1	1.2	
t5.19	Benzo(g,h,i)perylene	191-24-2	–	D	–	–	3.00E-02	3.00E-02	0.1	1.66	
t5.20	Benzo(k)fluoranthene	207-08-9	2	B2	7.30E-02	3.10E-02	–	2.85E-02	0.1	1.2	
t5.21	Crysene	218-01-9	2	B2	7.00E-03	–	3.00E-02	3.00E-02	0.1	0.81	
t5.22	Dibenzo(a,h)anthracene	53-70-3	2	B2	7.30E+00	6.10E+00	–	1.14E-01	0.1	2.7	
t5.23	Pyrene	129-00-0	–	D	–	–	3.00E-02	3.00E-02	0.1	0.324	

498 than the same compounds fixed in the rubber framework, 522  
 499 which leads to the conclusion that the release of chemical 523  
 500 compounds in water after leaching tests seems not to depend 524  
 501 on the amount of chemicals in the infill material but only on 525  
 502 the way they are connected within the rubber framework. 526

503 As for the metal concentration in the leachate, the lowest 527  
 504 mobilization ( $<10^{-3}$ ) was observed for the natural soil sam- 528  
 505 ple and the highest ( $\cong 10^{-2}$ ) for the SBRr granules. The PB 529  
 506 sample showed an intermediate behaviour. The better ca- 530  
 507 pacity of the soil to retain inorganic substances was due to 531  
 508 the inclusion of metals in the soil framework. 532

509 Risk assessment

510 The cumulative risk values from non-carcinogenic substances, 533  
 511 THQ, calculated as in Eq. (1) and from carcinogenic substan- 534  
 512 ces, CR, calculated as in Eq. (2), for each field and for each 535  
 513 receptors (adult player and child player) are shown in Fig. 2. 536  
 514 In each diagram, for each turf field (natural or synthetic), the 537  
 515 cumulative risk values for each of the three routes are 538  
 516 reported. The last bar of the histogram represents the cumula- 539  
 517 tive risk value to what a citizen living in the centre of Turin 540  
 518 was exposed through the outdoor inhalation of dusts and gases 541  
 519 from traffic and domestic combustion every day. 542

520 As shown in Fig. 2, the CR was higher for an adult player 543  
 521 than for a child player. This comes from the equation used 544

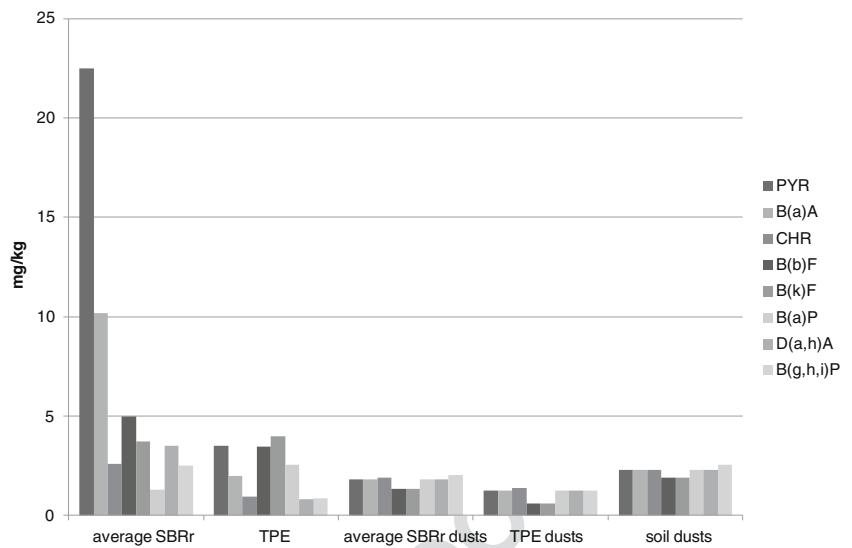
522 for the calculation of the specific exposition rate ( $E$ ). In fact, 523  
 524 an adult player is exposed to carcinogenic compounds (ED) 525  
 526 for 30 years, a child only for 6. 527

528 For all the routes considered, the non-carcinogenic risk 529  
 530 was higher for children than for adults, in line with the fact 531  
 532 that children are more sensitive to non-carcinogenic sub- 533  
 534 stances than adults. 535

536 For the DDC route, the highest cumulative THQ value 537  
 538 was reported for the B field because its concentration of lead 539  
 540 and zinc in the rubber granules was higher than that of other 541  
 542 artificial turf fields (see Table 2). The high non-carcinogenic 543  
 544 risk value of the B field was not due to the presence of BTX 545  
 546 or PAHs because the amount of these compounds was not 547  
 548 different from that in other synthetic fields. On the other 549  
 550 hand, regarding the CR for the DDC route, the B field 551  
 552 showed quite a low value because of its low content of 553  
 554 carcinogenic compounds like benzene, B(a)A, B(b)F and 555  
 556 B(a)P. The PT field showed the highest carcinogenic risk 557  
 558 for the DDC route due to its content of arsenic (not detected 559  
 560 in the rubber granules) and D(a,h)A. The presence of nickel 561  
 562 showed a negligible effect in the determination of the total 563  
 564 CR, in fact the CR due to nickel was two orders of magni- 565  
 566 tude lower than that due to the most relevant substances. 567

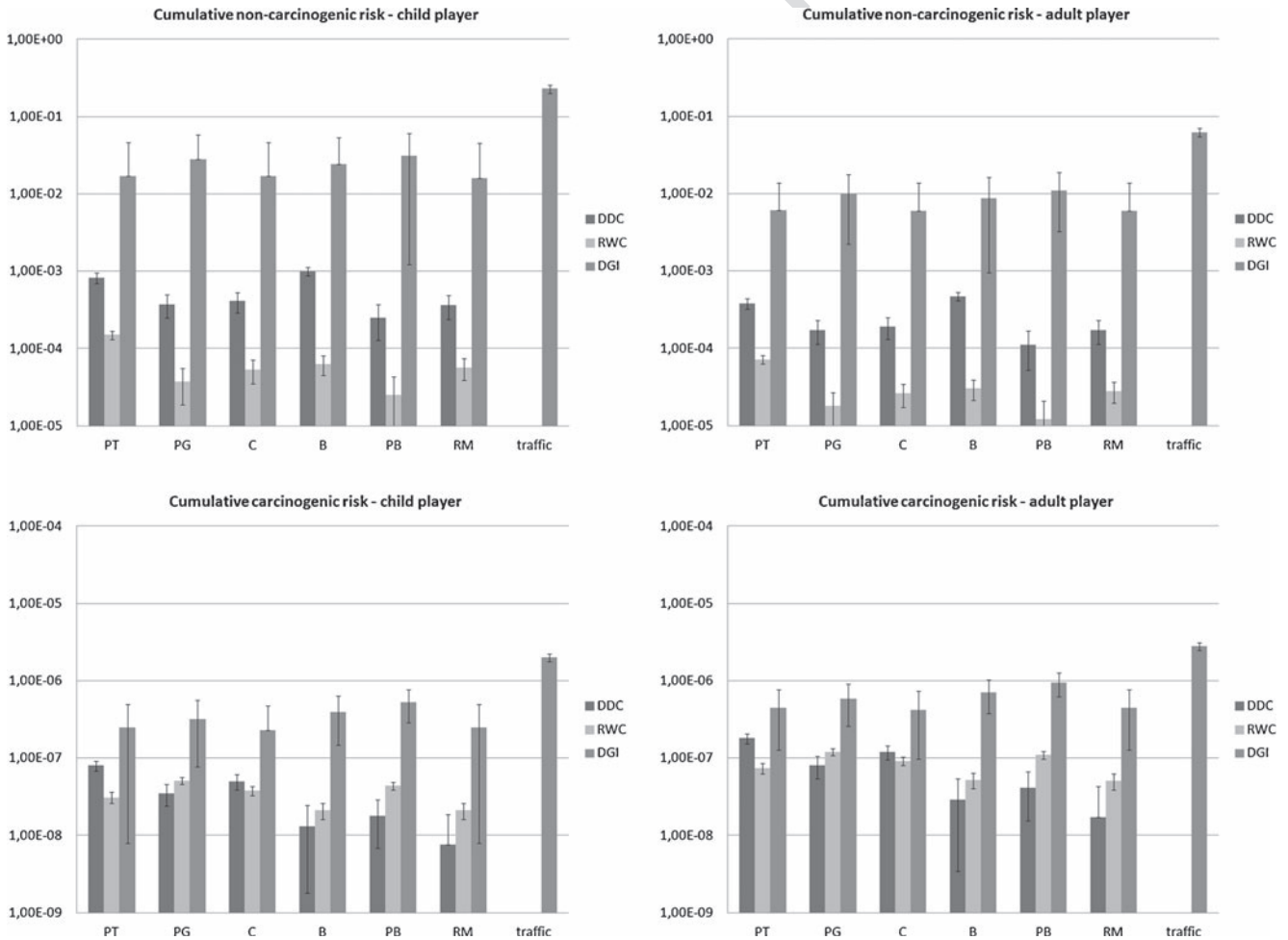
568 The PB thermoplastic field showed the lowest cumulative 569  
 570 THQ among the sport fields investigated for both DDC and 571  
 572 RWC routes. The low cumulative THQ for the DDC route 573

**Fig. 1** Average value of PAHs from the four SBRr samples (*first* group of bars), the TPE infill from the PB field (*second* group of bars); average value of the dust samples collected from the air just above an SBRr artificial turf field (*third* group of bars), the dust collected from the air just above the thermoplastic turf field (*fourth* group of bars) and the dust collected from the air just above the natural turf field (*fifth* group of bars)



548 was due to the low content of cobalt, zinc, toluene, xylene  
 549 and PAHs (with the exception of B(b)F, B(k)F and B(a)P),  
 550 so most of the substances considered in the risk analysis. On

the other hand, the low THQ for the RWC route (in spite of 551  
 the capacity of the PB field to release PAH compounds) was 552  
 mainly due to the remarkably low concentration of zinc in 553



**Fig. 2** Results of the calculation of the risk performed for each field and for each route on four scenarios: cumulative non-carcinogenic risk for a child player, cumulative non-carcinogenic risk for an adult player,

cumulative carcinogenic risk for a child player, cumulative carcinogenic risk for an adult player

554 the leachate, of one order of magnitude lower than in the  
555 leachates from SBRr granules.

556 The highest cumulative THQ value for the RWC route  
557 was found in the natural soil field; as shown in Fig. 3, this  
558 was due to the presence of arsenic. The leaching tests  
559 performed on both the rubber granule and natural soil sam-  
560 ples showed that arsenic concentration in all the eluates was  
561 under the detection limit. However, only for the natural soil  
562 sample was the concentration of arsenic in the eluate set to  
563 be equal to the detection limit (5 µg/L), owing to quite a  
564 substantial concentration of arsenic found in the soil. On the  
565 contrary, as shown in Table 2, the arsenic content was under  
566 the detection limit in all the rubber granule samples.

567 Among the artificial turf fields, the highest cumulative  
568 THQs for the RWC were observed for the B and C fields.  
569 These fields were characterized by being relatively new  
Q13/584 (1.5 years old) and, according to literature studies (Birkholz  
571 et al. 2003; Moretto 2007), rubber materials show the greatest  
572 capacity to release BTX and PAH compounds into water in the  
573 short term. The same observation could not be made for zinc  
574 because, according to Verschoor (2007), the zinc concentra-  
575 tion in the leachates increases with age when tires are  
576 laboratory-aged, whereas in samples aged under field condi-  
577 tions, the zinc concentration increases with age for car tire  
578 crumbs but not for truck tire crumbs.

579 The outdoor inhalation of dusts and gases was the main  
580 exposition route for both carcinogenic and non-carcinogenic  
581 substances. The relevance of the inhalation pathway for dusts  
582 and gases from artificial turf pitches was compared with the  
583 same route for dusts and gases from vehicular traffic. The  
584 cumulative CR due to the inhalation of contaminants from  
585 traffic was equal to  $2.0 \times 10^{-6}$  for the child receptor and  $2.8 \times$   
586  $10^{-6}$  for the adult receptor. The non-carcinogenic risk was

587 equal to 0.23 for the child receptor and 0.062 for the adult  
588 receptor. For both classes of substances and for both receptors,  
589 the inhalation of atmospheric dusts and gases from vehicular  
590 traffic gave risk values of one order of magnitude higher than  
591 those due to playing soccer on an artificial field.

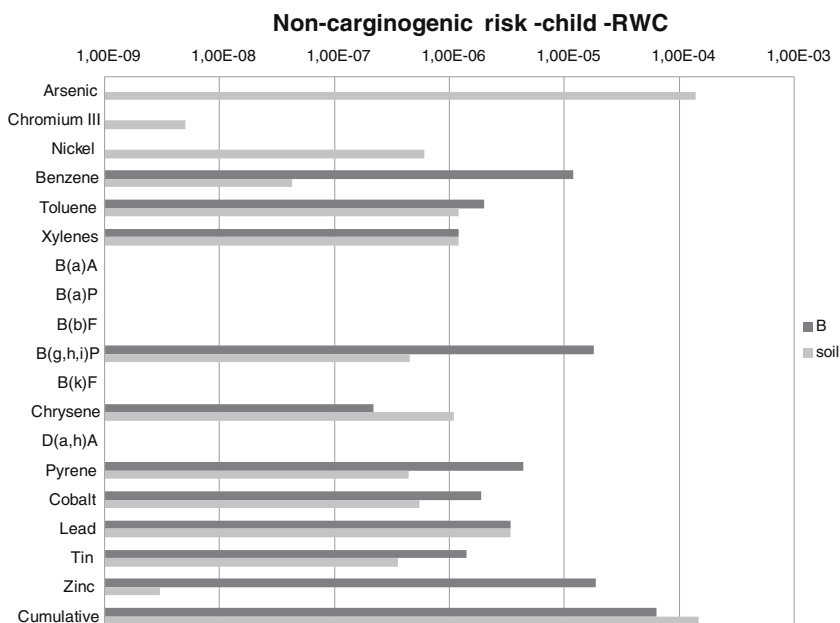
**Conclusions** 592

593 On the basis of the chemical characterization results, the PB  
594 turf field, made of thermoplastic material, shows a BTX and  
595 PAH content that is lower than in the samples made of rubber  
596 from exhaust tires. The PT field shows a low but not negligi-  
597 ble concentration of BTX and some PAHs. As regards heavy  
598 metals, zinc was detected at the highest levels. All the samples  
599 from exhaust tires show a zinc content ranging from 1.22 %  
600 b.w. to 1.53 % b.w. The PB sample is characterized by a zinc  
601 content equal to 0.58 % b.w., and the PT sample shows a  
602 considerable amount of hazardous metals, like nickel, lead,  
603 chromium, tin and arsenic.

604 On the other hand, the results of the leaching tests show  
605 that among the four SBR samples, the concentration of BTX  
606 and PAHs is higher in the leachates from the new infill  
607 materials than from the old ones. The Passo Buole sample  
608 shows the highest leaching release of PAH compounds. This  
609 may be due to the different chemical bonds which exist in  
610 thermoplastic materials compared to SBRr granules. The  
611 higher amount of PAHs and BTX mobilized in the natural  
612 soil sample can be explained by taking into account that the  
613 soil content of PAHs and BTX is only due to the deposition  
614 of atmospheric particulate on the ground.

615 The characterization of the atmospheric dusts sampled  
616 just above the artificial turfs shows that the composition of

**Fig. 3** Non-carcinogenic risk value for each chemical (and cumulative value) for the scenario child player, rainwater contact for the Barracuda field and natural soil



617 dust samples is very different from that of the infill materials  
 618 made of exhaust tires or non-recycled thermoplastic rubber,  
 619 thus implying that these dusts originate from traffic.

620 The results of the risk analysis performed show that for  
 621 all the turf fields examined and for all the routes considered,  
 622 the cumulative CR proved to be lower than  $10^{-6}$  and the  
 623 non-carcinogenic risk (for the sum of COCs) lower than 1,  
 624 in line with Italian guidelines.

625 Outdoor inhalation of dusts and gases is the main expo-  
 626 sition route for both carcinogenic and non-carcinogenic  
 627 contaminants. The relevance of the inhalation pathway—  
 628 the most dangerous among the three pathways considered—  
 629 for dusts and gases from artificial turf pitches was compared  
 630 with the same pathway for dusts and gases from vehicular  
 631 traffic. For both classes of COCs, carcinogenic and non-  
 632 carcinogenic, and for both receptors, the inhalation of atmo-  
 633 spheric dusts and gases from vehicular traffic gave risk  
 634 values on average one order of magnitude higher than those  
 635 due to activity on a turf field.

637 **Acknowledgments** The authors wish to thank the researchers from  
 638 General and Applied Hygiene Group (MED\_42), University of Turin,  
 639 for their support in the experimental activity.

640 **Conflict of interest** All authors declare they have no actual or  
 641 potential competing financial interests.

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