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Analysis of energy use and emissions of greenhouse gases, metals and organic substances from construction materials used for artificial turf

Simon Magnusson[a,*], Josef Mácsik[b]

[a] Luleå University of Technology, Department of Civil, Environmental and Natural Resources Engineering, Division of Mining and Geotechnical Engineering, SE-97187 Luleå, Sweden
[b] Ecoloop AB, Mosebacke torg 4A, 11646 Stockholm, Sweden

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ABSTRACT

This study applied a life cycle analysis approach to identify significant posts for energy and greenhouse gas (GHG) emissions associated with construction, use and removal of an artificial turf field. A chemical analysis of infills was conducted to describe leachability of metals and organic substances. The infill types studied were recycled tires (RT), virgin thermoplastic elastomers (TPE), virgin ethylene propylene diene monomer (EPDM) and recycled EPDM (R-EPDM) from cables and automotive mats. The result shows that energy use and GHG emissions of an artificial turf field significantly correlates with material choice, maintenance and management of removed turf. Energy use and GHG emissions for infills was highest for TPE followed by EPDM. In summary, use of recycled material as infill, reuse of soil and rock on site and reuse of removed turf and infill could reduce energy use and GHG emissions. Leachates from RT and R-EPDM contained detectable concentrations of zinc, which was relatively high from R-EPDM. Organic substances, harmful for aquatic environments and/or humans were detected in all leachates but in highest concentration from R-EPDM followed by EPDM. In the literature, risk assessments focused predominantly on RT while assessments of other infills was less extensive or was missing. The result in this article stressed the need to include all infill types in risk assessments. Previous environmental risk assessments based on field measurements concluded risks with infills to be small or minimal. However, since these assessments are few, this study suggested verification of those results by field measurements.

1. Introduction

Artificial turf fields are used by professional athletes, amateurs and for spontaneous play. Construction of artificial turf fields has greatly increased in northern Europe, such as in Sweden and Norway (Football Association of Norway, 2015; Swedish Football Association, 2015). Artificial turf produces significantly more user hours than natural grass fields due to its durability. The design of artificial turf fields is illustrated in Fig. 1. The upper layer consists of a synthetic carpet where synthetic fibers are attached to a perforated backing of textile and latex. A layer of fine sand and shock-absorbing infill supports the synthetic fibers. Infill from recycled tires (RT) can be used. Other polymer based infill types are new materials of thermoplastic elastomers (TPE) and ethylene propylene diene monomer (EPDM) and recycled EPDM rubber (R-EPDM) originating from products such as cables and automotive carpets. A shock pad, of permeable elastic compound can be installed beneath the synthetic carpet. These layers are followed by fine sand and crushed rock forming a subbase and a drainage system.

A local environmental impact from infill materials has been a concern. The infill materials consist of polymers and additives that provides material properties such as softness and ultraviolet protection. The materials can contain metals and organics substances that could leach to water. Mainly zinc has been detected in leachates from RT (Bocca et al., 2009; Plesser and Lund, 2004) and in less concentrations from TPE (Ruffino et al., 2013) and EPDM (Nilsson et al., 2008; Plesser and Lund, 2004). Other metals have been detected in leachates of RT and TPE infill, such as aluminum, copper, magnesium in lower levels (Ruffino et al., 2013). Polyaromatic hydrocarbons (PAH: s) have been detected in leachates from RT (Gomes et al., 2012; Plesser and Lund, 2004; Ruffino et al., 2013;)

Abbreviations: LCA, life cycle assessment; RT, recycled tires; TPE, thermoplastic elastomer; EPDM, ethylene propylene diene monomer; R-EPDM, recycled EPDM; GC–MS, gas chromatography mass spectrometry; PVC, polyvinylchloride; GHG, greenhouse gas; MDI, methylene diphenyl diisocyanate; SEBS, styrene ethylene butylene styrene; DOC, dissolved organic carbon; S-VOC, semi-volatile organic compounds.

* Corresponding author.
E-mail address: simon.magnusson@ltu.se (S. Magnusson).

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Table 1
Environmental and health risk assessments of artificial turf fields and its materials, sorted on risk assessment steps (RA 1–5) included. RA (1) information statement/problem definition, (2) impact analysis, (3) exposure analysis, (4) risk characterization, and (5) overall risk assessment (European Chemicals Bureau, 2003a,b).

Reference	RA step	Materials/system studied. (Material supplied = MS)	Assessment results (Local environmental risk = ER, Health risk = HR)
Pavilonis et al. (2014)	1,2,3,4	Infill (RT) and turf fibers. Outdoor or indoor not specified. *MS*: US	*HR*: Risk due to dermal, ingestion and inhalation exposure to infill and artificial turf was generally considered de minimus. Relatively high content of lead in one turf fiber.
Ruffino et al. (2013)	1,2,3,4	Outdoor fields with (RT and TPE) infill. *MS*: Italy	*HR*: For dermal and inhalation exposure, the cumulative carcinogenic risk was lower than 10 – 6 and the cumulative noncarcinogenic risk lower than 1.
Kim et al. (2012)	1,2,3,4	Turf, infill (RT, EPDM), back coating, elastic pavement. *MS*: Korea	*HR*: Minimal direct health risk regarding dermal, inhalation and ingestion exposure, except for ingestion exposure for children with pica.
Ginsberg et al. (2011)	1,2,3,4	Outdoor and indoor fields with infill (RT). *MS*: N/A	*HR*: No elevated adverse health risks due to inhalation exposure. Adequate ventilation is recommended.
Menichini et al. (2011)	1,2,3,4	Outdoor field and Infill (RT, coated RT, TPE and R-EPDM). *MS*: Italy	*HR*: For the benzopyrene. an excess lifetime cancer risk of 1 × 10 – 6 due to inhalation was calculated for an intense 30-year activity at RT fields.
Lim and Walker (2009)	1,2,3,4	Infill material (RT) and outdoor field *MS*: USA	*ER*: No organics and low levels of metals detected in surface water. No impact on groundwater. RT entirely from truck tires was estimated to possibly have an impact on aquatic life due to zinc exposure. *HR*: Inhalation exposure does not indicate a concern for non-cancer or cancer effects. Football fields are not important contributors of exposure to particulate matter. RT is no source for lead exposure when compared to federal hazard standard for lead in soil.
Nilsson et al. (2008)	1,2,3,4	Infill (RT, coated RT, TPE, EPDM and coir), turf mats, pad and road salt. *MS*: Norway	*ER*: No major risk. *HR*: Dermal and oral exposure is concluded to cause minimal risk. Potential allergic risk due to dermal exposure for benzothiazole and amines in RT and EPDM for sensitive individuals.
Verschoor (2007)	1,2,3,4	Infill (RT) *MS*: Netherlands	*ER*: Potential ecotoxicological risk in surface water, groundwater and soil may occur.
Vidair et al. (2007)	1,2,3,4	Infill (RT), rubber surfaces (RT), soil *MS*: USA	*ER*: Small regarding exposure to soil and ground water. *HR*: Minimal regarding ingestion and dermal exposure. Slightly above minimal regarding chronic hand to mouth activity
Moretto (2007)	1,2,3,4	Infill (RT, EPDM, TPE) at outdoor and indoor fields *MS*: France	*ER*: Minimal impact on water resources and the aquatic environment in the short and medium term. *HR*: Health risks associated with the indoor inhalation of VOC and aldehydes present no actual cause for human health. No cause for concern as regards human health for the workers, general public and professional or amateur athletes, whether adults or children indoors. Good ventilation is recommended in case of workers installing artificial surfaces in small and poorly ventilated gymnasia.
Birkholz et al. (2003)	1,2,3,4	Infill (RT) *MS*: Canada	*ER*: Significant risk of contamination in surface water or groundwater is doubtful. *HR*: The cancer risk due to ingestion exposure is minimal.
NIPH and the Radium Hospital (2006)	1,2,3,4	Indoor fields and Infill (RT) *MS*: Norway	*HR*: No increased risk of leukemia due to inhalation exposure. No elevated risk for contact allergies due to dermal exposure. The possibility for latex allergy due to inhalation exposure cannot be entirely eliminated. RT should not be used indoors when infill is replaced, due to lack of knowledge about potential latex allergy risk.
Schiliro et al. (2013)	1,2,3	Outdoor fields with (RT and TPE) infill *MS*: Italy	*HR*: Inhalation exposure present no more exposure risks than the rest of the city.
USEPA (2009)	1,2,3	Outdoor field with RT infill *MS*: USA	*ER*: No conclusions on risks are made. *HR*: No conclusions on risks are made.
Joost and Jongeneelen (2010)	1,2,3	Outdoor field with RT infill *MS*: Netherlands	*HR*: Minimal uptake of PAHs regarding all exposure ways.
Johannesson and Sandén (2007)	1,2,3	Outdoor field with RT infill *MS*: Sweden	*HR*: No increased risk for cancer regarding dermal, ingestive and inhalation exposure.
Dye et al. (2006)	1,2,3	Indoor halls with infill (RT and TPE) *MS*: Norway	*HR*: The use of RT causes a considerable burden on the indoor environment. For all three halls, organic chemicals are found in air.
Tekavec and Jakobsson (2012)	1,2,3	Outdoor field and RT infill *MS*: Sweden	*HR*: Levels of PAH and phthalates was similar to levels in general population. Due to the precautionary principle, other types of infill than RT is recommended to be used.
Christensson and Antonsson (2004)	1,2,3	Indoor field with 50% RT and 50% EPDM infill *MS*: Sweden	*HR*: Levels of heavy metals and benzoaporen was significantly below air limit standards.
Ottesen et al. (2011)	1,3	Shock-absorbing surfaces with RT and EPDM *MS*: Norway	*ER*: N/a. Leaching of THC (C12–C35), PAH, PCB, A health risk assessment needs to be conducted. THC (>C5–C35), zinc, nonylphenol, PAHs and PCBs was found in all products.
Widenbrant (2011)	1,3	Outdoor fields with RT infill *MS*: Sweden	*ER*: Water quality is within drinking water standard.
Ulirsch et al. (2010)	1,3	Turf fibers. *MS*: USA and South Korea	*HR*: Synthetic turf can deteriorate to form dust containing lead at levels that may pose a risk to children. Exposure pathways have not been specified.

Table 1 (*Continued*)

Reference	RA step	Materials/system studied. (Material supplied = MS)	Assessment results (Local environmental risk = ER, Health risk = HR)
Bristol and McDermott (2008)	1,3	Outdoor field and RT infill *MS*: USA	*ER*: Aquatic toxicity not detected. Indicated levels of dissolved zinc in drainage but at concentrations less than the applicable Water Quality Standard. *HR*: No detectable concentrations of volatile nitrosamines or 4-(tert-octyl) phenol existed in the air column. Benzothiazole: present at a very low concentration directly above one of the two fields sampled. Not detected in any of the upwind or downwind locations at either field.
Zhang et al. (2008)	1,3	Turf fibers and RT infill *MS*: USA	*ER*: New RT did not contain PAHs at levels above health-based soil standards. The zinc contents in RT were found to far exceed the soil limit. *HR*: Zero or near-zero bioaccessibility in the synthetic digestive fluids regarding PAH in RT. Generally relatively low concentrations of lead in RT. Bioaccessability of lead from RT and fiber in the synthetic gastric fluid, and from fiber in intestinal fluids.
Hofstra (2007)	1,3	Infill (RT). *MS*: Netherlands	*ER*: No risk due to air emissions, to soil zink is a relative parameter. *HR*: No risk regarding ingestion, inhalation and dermal uptake.
Plesser and Lund (2004)	1,3	Infill (Recycled rubber, EPDM) and turf. *MS*: Norway	*ER*: Leachate of zinc from turf and recycled rubber indicates that the leachate water is very strongly polluted water. With the exceptions of chromium and zinc, EPDM rubber contained smaller quantities of hazardous substances than the recycled rubber types overall.
Krüger et al. (2013)	1,2	Turf fibers, Infill (RT, TPE, EPDM), Shock Pad, Sub base	*ER*: Aside from recycled rubber compounds, synthetic plastics can also pose ecotoxicological risks, which might be even more serious.

and in leachate from TPE (Ruffino et al., 2013). On this basis, local environmental risks to water and non-cancerous and cancerous health risks for turf field users have been studied. A presentation of studies is given in Table 1. Studies are sorted based on the risk assessment (RA) steps (1–5) included. The five steps of risk assessment are (1) Information statement/problem definition, (2) impact analysis, (3) exposure analysis, (4) risk characterization, and (5) overall risk assessment, as described in the Technical Guidance Document on Risk Assessment (European Chemicals Bureau, 2003a,b). Assessments are further summarized in Table 2. In general, the health risks due to exposure to substances in infills through inhalation, dermal contact and ingestion have shown to be minimal (Birkholz et al., 2003; Ginsberg et al., 2011; Kim et al., 2012; Lim and Walker, 2009; Menichini et al., 2011; Moretto, 2007; Nilsson et al., 2008; NIPH and the Radium Hospital, 2006; Pavilonis et al., 2014; Ruffino et al., 2013; Vidair et al., 2007). Exceptions could be seen in the assessment of Pica behavior by Kim et al. (2012) and the assessment of chronic hand-to-surface-to-mouth activity by Vidair et al. (2007). Further, based on primarily laboratory tests, the environmental risk from potential leaching of organic substances and

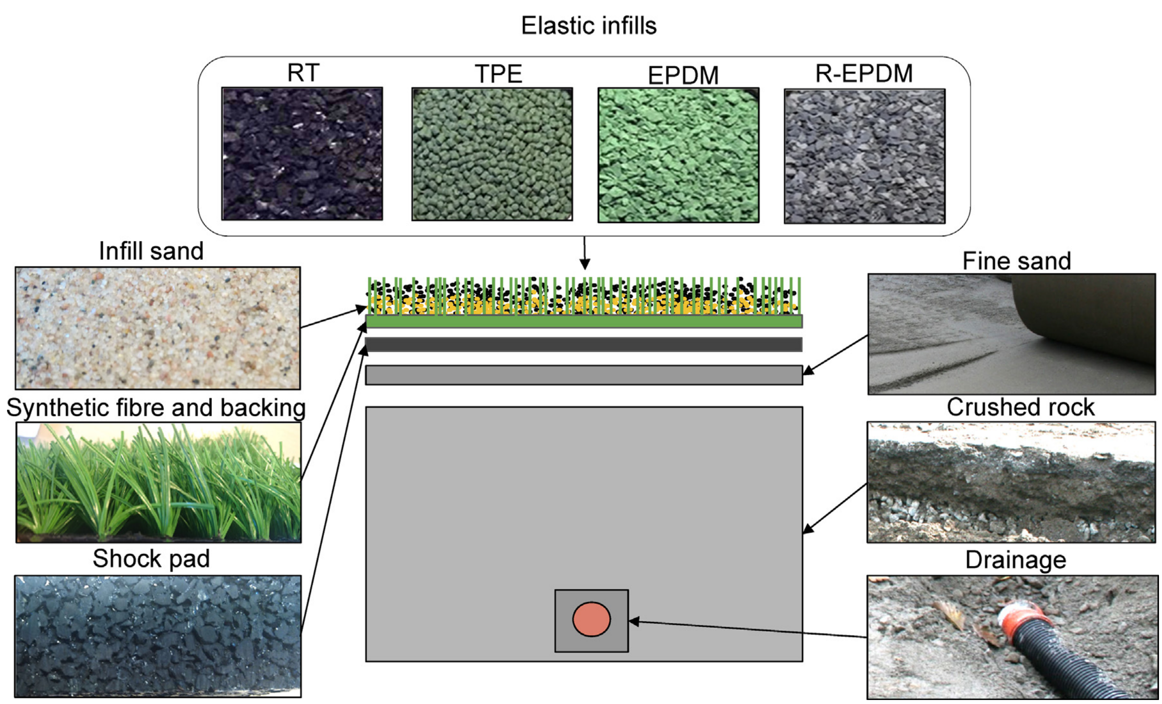

Fig. 1. Design of artificial turf fields. Pictures produced by the article authors. Illustration based on Simpson et al. (2013).

Table 2
Assessments of health risks and local environmental risks for RT, TPE, EPDM and R-EPDM infills.

Infill type:	RT	TPE	EPDM	R-EPDM
Health				
Dermal exposure	Minimal risk[1,2,3,4a,5]	Minimal risk[2,4]	Minimal risk[3,4a]	No Studies
Ingestion	Minimal risk[1,4,5,7]	Minimal risk[4]	Minimal risk[4]	No Studies
Ingestion, Pica-children/hand to mouth activity	Not minimal risk[3,5b]	No Studies	Not minimal risk[3]	No Studies
Inhalation, outdoors	Minimal risk[1,2,3,6,8,9,10]	Minimal risk[2,10]	Minimal risk[3,10]	No Studies
Inhalation, indoors	Minimal risk[8,10,11c]	Minimal risk[10]	Minimal risk[10]	No Studies
Local environment				No Studies
Ground water	Possible risk[12]			
	Small risk[4,5,6]			
	Minimal risk[7,10]	Minimal risk[10]	Minimal risk[10]	No Studies
Surface water	Possible risk[6,12]			
	Small risk[4,7]		Small risk[4]	
	Minimal risk[7,10]	Minimal risk[10]	Minimal risk[10]	No Studies
Soil	Possible risk[12]			
	Small risk[5]	No Studies	No Studies	No Studies

Note: Environmental risk assessments based on measurements of drainage water or soil quality are bolded.
[a] Nilsson et al. (2008) assess risks to be minimal, but with a potential allergic risk for particularly sensitive persons.
[b] Vidair et al. (2007) assessed the risk due to chronic hand-to-surface-to-mouth activity, which was slightly above minimal risk, however the risk assessment was concluded to have many uncertainties.
[c] NIPH and the Radium Hospital (2006) assess risks to be minimal, but latex allergy could not be entirely assessed.
The numbers 1–12 in superscript in Table 2 are citations for following studies; 1: Pavilonis et al. (2014), (2): Ruffino et al. (2013), (3): Kim et al. (2012), (4): Nilsson et al. (2008), (5): Vidair et al. (2007), (6): Lim and Walker (2009), (7): Birkholz et al. (2003), (8): Ginsberg et al. (2011), (9): Menichini et al. (2011), (10): Moretto (2007), (11): NIPH and the Radium Hospital (2006), 12: Verschoor (2007).

metals from RT to water is generally small (Birkholz et al., 2003; Moretto, 2007; Nilsson et al., 2008; Vidair et al., 2007). For TPE and EPDM, the assessments are fewer in numbers, but indicate minimal health and environmental risks. R-EPDM has not been included in any risk assessments. All together, these risk assessments are primarily focused on RT. Only in some cases, a few samples of other materials have been included in the assessments. Studies where the materials are chemically analyzed on the same premises are missing.

Environmental aspects such as energy use and GHG emissions have hardly been described in impact assessments of artificial turf. Life cycle assessment (LCA) is an established method that can be used to compare the environmental performance from a products or a services life cycle, from raw material extraction and production, use phase to final disposal (ILCD, 2012). One study found that natural grass was environmentally favorable to artificial turf, however the result was opposite if impacts was divided with the number of playing hours provided (Cheng et al., 2014). Other LCA studies starting from the perspective of tire recycling have focused on resource use, greenhouse gas (GHG) emissions, energy use and water consumption when producing EPDM, TPE and RT infill and concluded that RT was favorable to EDPM or TPE (Clauzade et al., 2010; Fiksel et al., 2011; Skenhall et al., 2012). However, the production of infill is one material input of many, there is a lack of knowledge regarding environmental life cycle impacts, from construction, maintenance, and final removal of artificial turf.

The objectives of this study was to quantify life cycle energy use and GHG emissions for the construction, maintenance and removal of artificial turf and with RT, TPE, EPDM and R-EPDM infills, and analyze the potential release of metals and semi-volatile organic compounds from infills to water.

2. Materials and methods

Analysis of energy use and GHG emissions for artificial turf fields was conducted by using an LCA approach based on the LCA guidelines presented in the ILCD handbook (2012). The system analyzed is presented in Fig. 2. The system included energy consumed and GHGs emitted in raw materials acquisition, production, use and final removal and disposal of an artificial turf field. Use of energy resources was included. Infill materials were analyzed chemically for potential emissions of primarily metals and semi-volatile organic compounds (S-VOCs) to water.

2.1. Analysis of energy use and greenhouse gas emissions

The functional unit was chosen to be the supply of an artificial turf field allowing football playing during the whole year for ten years. The time period corresponds to average life length for turf mats (Fleming, 2010). The analyzed system is illustrated in Fig. 2. Production of input materials, use of vehicles and construction machines used during the life cycle was included. Surrounding facilities such as lighting, paved areas, fencing and grandstands together with manufacturing of vehicles and machinery such as excavators and tractors were excluded. Information about activities for construction, maintenance and removal and disposal was gathered from Swedish artificial turf field owners, contractors and the Swedish Football Association's construction and maintenance recommendations (Swedish Football Association, 2016a,b). The modeled artificial turf system was selected to reflect construction and maintenance praxis in Sweden. The field was a full sized field measuring 7881 m^2 (Swedish Football Association, 2016b). Maintenance consisted of brushing, harrowing, plowing and salting to allow playing during the whole year. Information about construction and maintenance practices was gathered from literature, contractors and operators. Inventory data for energy use and GHG emissions was collected from literature and LCA studies. An excel based tool was developed for calculations. For quantification of GHG emissions, CO_2 equivalents were gathered from Rydh et al. (2002).

2.1.1. Materials

In Table 3, material used during construction, maintenance and removal of artificial turf are presented. For the modeled field, a layer of 0.5 m soil corresponding to 3940 m^3 is excavated to prepare for subbase and an extra 240 m^3 for drainage. A herringbone pattern comprising of drainage pipes of thermoplastic polyvinyl chloride (PVC) with a total length of 1500 m is installed. Drainage is sealed with geotextile and gravel. The subbase consists of a 0.4 m layer of crushed rock and a 0.05 m layer of fine sand produced in quarries. A RT – based shock pad is laid out. The artificial turf mat is manually rolled out and glued together with a strip of paper

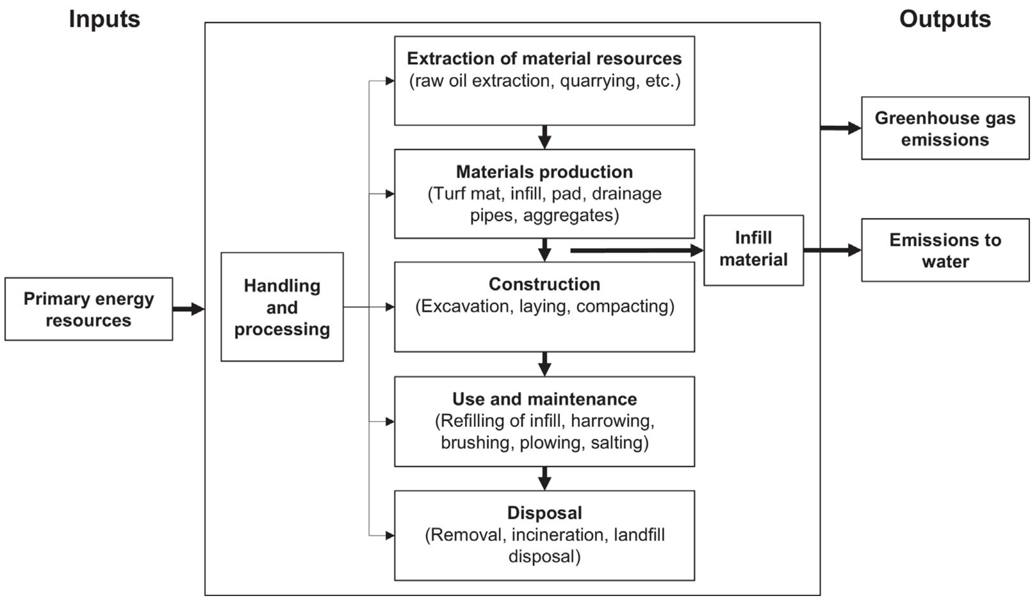

Fig. 2. System boundary for analysis of energy use and emissions of greenhouse gases throughout the life cycle of a turf pitch and emissions to water from infill materials.

Table 3
Material used and handled in construction, maintenance and removal of 7881 m^2 of artificial turf.

Material use	Construction[kg/m^2]	Maintenance[kg/m^2]	Removal[kg/m^2]
Excavated soil and rock[a]	840		
Drainage pipes[b]	0.11		
Geotextile[b]	0.06		0.01
Aggregates for subbase and drainage[b]	49 + 648		
Fine sand for subbase[b]	80		
Shock absorbing pad system[b]	8.8		
Turf mat[b]	1.87		
Two component turf adhesive[b]	0.06		
Turf line paint[b]	0.01		
Sand infill[b]	22.5		
Infill alternatives			
RT[c,d]	6.47	6.34	
TPE[c,d]	11.0	6.34	
EPDM[c,d]	7.7	6.34	
R-EPDM[c,d]	7.7	6.34	
Sodium chloride[d]		5.7	
Snow handling[e]		150	
Ash from rubber and plastic material incineration[f]			0.95
Soil for recultivation layer and sealing layer[g]			0.32 + 0.41
Crushed rock for upper/under drainage layers[g]			0.9 + 0.9
Sand for upper and under protection layer[g]			0.3 + 0.3
Bentonite[g]			0.006

[a] SAPCA Code of Practice suggest a minimum subbase of 300 mm (SAPCA, 2009). Since soil quality vary, an excavation depth of 500 mm was assumed.
[b] Calculated based on suggested construction design by Swedish Football Association (2016b).
[c] Amounts for construction are measurements by Skenhall et al. (2012). Infill density varies between material types.
[d] For maintenance, amounts are based on practices in 2014 by a field operator.
[e] Based on maintenance practices in 2014 by a field operator. Assuming 30% of annual 600 mm precipitation will fall as snow (SMHI, 2015).
[f] Calculated by assuming 5-weight% ash of incinerated polymers based waste.
[g] Data collected from construction dimensions of disposal sites by Simon (2008).

and two-component polyurethane-based adhesive. Infill sand and infill of either RT, EPDM, TPE or R-EPDM are installed and lines are painted. The infill amounts varies due to density differences between material types, which give lowest total mass for RT infill and highest total mass for TPE infill, see Table 3. For maintenance, the artificial turf is brushed and harrowed once a week. The annual refilling of infill was 5 ton. During winter time, snow is plowed. Annual snow amount is estimated to 30% of total annual rainfall which is 600 mm (SMHI, 2015). Sodium chloride is spread to remove ice, annual use is 0.57 kg/m^2. The artificial turf, infill, and shock absorbing pad is removed and incinerated after ten years of use. Incineration ash is disposed at a waste disposal site.

Composition of materials are presented in Table 4. Production and emission data for materials was gathered from Baitz et al. (2004) for drainage pipes and from Svingby and Båtelsson (1999) for geotextile. Corresponding data was gathered from Stripple (2001) for quarry products and sodium chloride, and from Olofsson and &stberg (2013) for paint.

For the calculation of energy use and GHG emissions from RT and R-EPDM production, the environmental impacts from tire manufacturing and previous EPDM products has been chosen to burden the former rubber products. However, the composition of rubber and other materials affects the shredding process. The production of RT and R-EPDM included collection, sorting and shredding of car

Table 4
Composition of materials.

Polymers based products	Composition
Turf mat	50% Polyethylene 50% polypropylene[a]
Turf and Pad adhesive	Methylene diphenyl diisocyanate (MDI) 30% and 70% Calcium carbonate[b]
Turf line paint	Water based, Styrene–Acrylic paint[c]
TPE infill	40% Calcium carbonate, 20% Polypropylene, 20% Polyethylene, 16% Mineral oil, 4% Phthalates[d]
EPDM infill	68% Calcium carbonate, 22% EPDM, 8% Mineral oil, 4% Phthalates[d]
Pad	12% adhesive, 88% RT granules[b]
PVC pipe	98% PVC Polymer, 2% stabilizers[e]
Soil and rock materials	
Sand infill	Crushed rock, 1.5 ton/m^3 [f]
All other aggregates	Crushed rock, 1.6 ton/m^3 [f]

[a] Assuming simplified composition, 50% polyethylene and 50% polypropylene fibers based on Nilsson et al. (2008).
[b] Based on data from supplier (TEC, 2015).
[c] Information from supplier.
[d] Data from Skenhall et al. (2012).
[e] Data from Baitz et al. (2004).
[f] Data from Simon (2008).

Table 5
Energy use (MJ/kg) and GHG emissions (kg CO_2 equivalents/kg) for polymers, polymer-based components, aggregates and minerals.

Material	Energy use [MJ/kg]	Total GHG emissions [Kg CO_2 eqv./kg]	References
RT and R-EPDM[a]	2.65[b]	0.06	Skenhall et al. (2012)
EPDM	16.21	0.76	Skenhall et al. (2012)
TPE	51.83	1.78	Skenhall et al. (2012)
Polyethylene	80	1.8	Biron (2015)
Polypropylene	78	2.1	Biron (2015)
MDI	57.4	2.77	Pavlovich et al. (2011)
Water based, Styrene-Acrylic paint	16.9	2.69	Olofsson and &stberg (2013)
PVC pipe	67.2	0.767[c]	Baitz et al. (2004)
Geotextile	26.1	3.12	Simon (2008)
Polymer based materials, incineration, energy recovery	−25.9	2.24	Skenhall et al. (2012), Eriksson and Finnveden (2009)
Quarry materials, crushed	5.4[b]	0.0015	Stripple (2001)
Soil and gravel from quarries, excavated	0.0014[b]	0.010	Stripple (2001)
Sodium Chloride	1.59	0.139	Stripple (2001)
Bentonite	0.0066	0.00152	Stripple (2001)

[a] Recycled material. Energy use and GHG emissions are allocated to previous tire and rubber products.
[b] Process energy use only.
[c] It is assumed that the process energy use is of 100% electricity. Calculations on GHG emissions are based on Swedish electricity mix (Stripple, 2001).

tires respectively rubber products. Production data from Skenhall et al. (2012) was used. Transportation distance for collection was assumed 200 km with a fill ratio of 38%. Further, 1 kg of tire produced 0.67 kg RT granules. In addition, about 40% of the cutting of tires was run on electricity driven and 60% was run on diesel while shredding was run on electricity. Swedish average electricity production and emission data was used (Stripple, 2001). The process for producing R-EPDM was assumed to be identical to the production of RT. Thermoplastics (TPE) are normally produced by using compounds including several additives and one or several polymers (Biron, 2015). Production data was gathered from Skenhall et al. (2012), where it is assumed that TPE infill consisted of 40% calcium carbonate, 40% Styrene Ethylene Butylene Styrene (SEBS), 16% mineral oils and 4% phthalates. Data for EPDM presented by Skenhall et al. (2012) was collected where it is assumed that the EPDM infill consist of 68% calcium carbonate, 22% EPDM, 16% mineral oils and 4% phthalates. The shock absorbing pad was assumed to consist of 88% RT granules mixed with 12% two component polyurethane binder, based on a data from BASF (2006). The two component adhesive was assumed to consist of 30% methylene diphenyl diisocyanate (MDI) and 70% Calcium carbonate (TEC, 2015). Identical content was assumed for turf adhesive. Production and emission data was gathered from Shtiza et al. (2012) and Pavlovich et al. (2011). According to Nilsson et al. (2008), polypropylene, polyethylene and polyamide are used for turf production. Calculations were based on a simplified recipe which consisted of 50% polypropylene and 50% polyethylene. Production and emission data was gathered from Biron (2015). For final removal of the artificial turf, it was assumed that all polymer based products were incinerated. Data for incineration of polymers was gathered from Eriksson and Finnveden (2009). Table 5 show energy use and GHG emissions for producing input materials or its constituents.

2.1.2. Vehicles and working machines

In Table 6, transport distances and use of vehicles and working machines is presented. Excavator is used for excavations and for loading/unloading materials. Compactor and grader complete the sub base. Transportation of materials was assumed to be made with a medium sized distribution truck. A tractor is used for maintenance practices.

Emission data for vehicles and machines was gathered from Bauman and Tillman (2004), Holmström (2013) and Stripple (2001). The excavator was assumed to be of class 1. Excavator and lorry diesel consumption was 2.65 MJ/m^3 and 1.7 MJ/ton-km respectively. Tractor and compactor diesel consumption was 140 MJ/operation h and 0.53 MJ diesel/m^2 respectively.

2.2. Material sampling and chemical analysis

Chemical analysis were performed on single material samples from new infill of RT, TPE, EPDM and R-EPDM. Sample of RT infill was taken from a tire shredding factory. Samples of TPE, EPDM and R-EPDM infill were taken from infill bags. Chemical analysis was performed by an accredited laboratory. Leachate

Table 6
Transport distances and use of vehicles and working machines.

Vehicle and working machines use	Construction	Maintenance	Removal
Lorry transport distances (Unit: kilometers, one way)			
Turf mat, elastic infills, pad, adhesives, paint, salt, drainage pipes	1000	1000	
Quarry materials, excavated soil and rock, and geotextile, snow	50	50	
Turf mat, infills, pad, adhesives and paint to incineration			50
Ashes from incineration to landfill			50
Working machines (Unit: hours, if not specified)			
Compactor	8		
Grader	10 rounds[a]		
Brushing, harrowing with tractor		2000	
Plowing, salting with tractor		600	

[a] Grading is assumed to require 10 rounds.

water from infill were produced by a single-stage shaking test at $L/S = 10$ in accordance to prEN 12457-2. Leachates were filtrated. Analysis of Antimony, Arsenic, Barium, Lead, Cadmium, Copper, Chromium, Mercury, Molybdenum, Nickel, Selenium, Zinc followed EN 12457-2 standard. Analysis of chloride, fluoride and sulfate were conducted according to EN ISO 10304-1: in 2009. Distillable phenols and dissolved organic carbon (DOC) were analyzed according to EN 028 128: 1976 and EN 1484: 1997 respectively.

Leachate water was further analyzed in laboratory for S-VOCs by using a gas chromatography–mass spectrometry (GC–MS) column instrument. The analysis detects organic compounds with boiling points from 100 to 500 degree Celsius consisting of 8–35 carbon atoms. Each substance detected is compared to a reference library and is further described with suggested name, CAS number and quantity. The method has lower measurement certainties than in methods for full quantitative assessment. Some substances are routinely search for, these are PAH 16, PCB7, phthalates, chlorobenzenes, chlorophenols, phenols and alkylated phenols, C9-10 aromatics, some chlorated organic substances and some nitrogen containing organic substances. CAS numbers for substances was used to find information on toxicity to aquatic life and humans in the Classification and Labeling Inventory Database provided by the European Chemicals Agency (ECHA, 2016).

3. Results and discussion

3.1. Energy use and GHG emissions

In Figs. 3–5 , the energy use and GHG emissions for the use of materials (including transportation) and the use of working machines throughout the life cycle of artificial turf is described.

The transportation of soil and rock materials and production of infills have large impact on total energy use and GHG emissions. The energy use for infills varied. Throughout construction and maintenance, the energy use for TPE was 7.38 Gigajoule (GJ), about 3.6 times higher than for EPDM, about 5.6 times and 6.1 times higher than for R-EPDM and RT respectively. Similarly, GHG emissions from TPE was 266 ton CO_2 equivalents, which is about 2.6 times higher than for EPDM, about 11.2 times higher than for R-EPDM and 12.3 times higher than for RT respectively. These differences give that the total energy use and GHG emissions for the artificial turf system studied as a whole can vary with a factor of 1.5 and 2.2. Reductions in infill material's bulk densities could decrease the infill material need and hence reduce energy use and climate impact from the infills. The excavation and primarily the transportation of soil, rock and quarry materials corresponded to about 2.4 GJ and 163 ton CO_2 equivalents. Studies have revealed potentials in reducing energy use and GHG emission by reusing aggregates (Magnusson et al., 2015; Hossain et al., 2016) or by constructing the subbase with alternative lightweight materials (Williams et al., 2010). With the exemption for transportation of infill materials, the

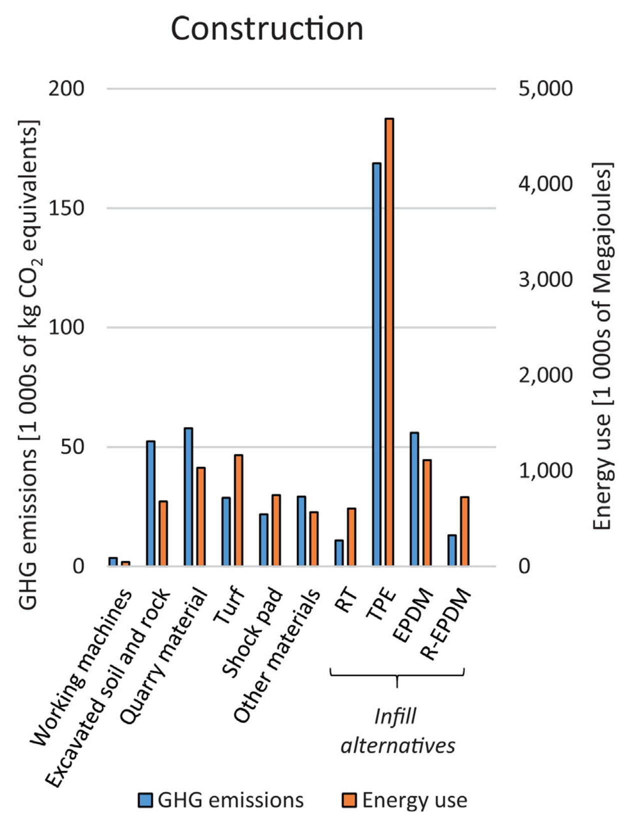

Fig. 3. The energy use and GHG emissions of materials (including transports) and the use of working machines from construction of 7881 m^2 artificial turf.

vehicle use for maintenance practices corresponded to 0.58 GJ and 50 ton CO_2 equivalents. Here, transportation distance for snow is of importance. For the final artificial turf removal, incineration contributed to a negative energy use, i.e. energy recovery, and the major part of GHG emissions. Incineration resulted in 1.9 GJ of energy recovered and 171 ton CO_2 equivalents emitted. In Figs. 6 and 7, the energy use and GHG emissions for construction, maintenance and removal is compared.

The total energy use was 5.9 GJ and the GHG emissions was 527 ton CO_2 equivalents. A mean value was used for energy use and GHG emissions for the infill. The most significant contribution to GHG emissions was primarily construction (256 ton CO_2 equivalents) followed by removal (172 ton CO_2 equivalents) and maintenance (98 ton CO_2 equivalents). The production and transportation of materials makes up the major part of energy use while also incineration are significant for GHG emissions. Avoiding incineration of infills and turf mat can therefore reduce the GHG emissions.

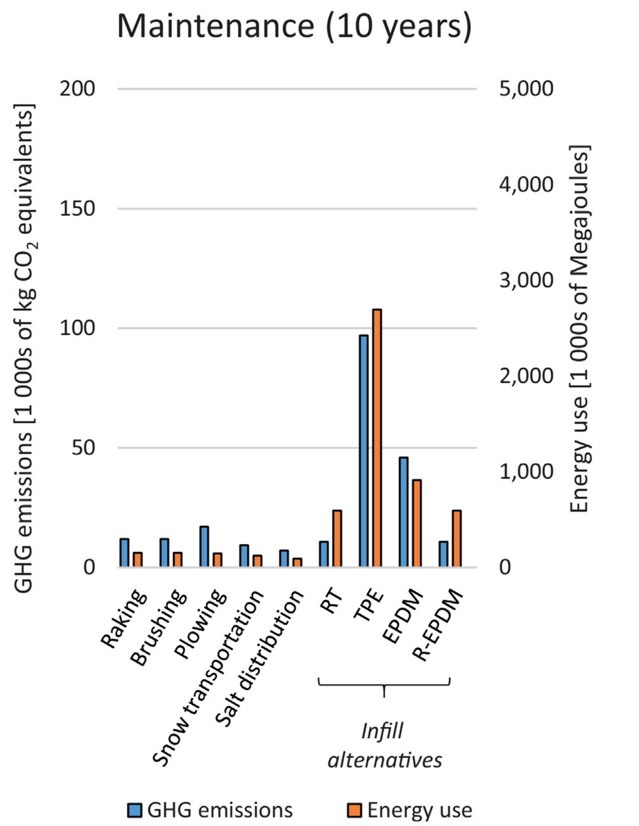

Fig. 4. The energy use and GHG emissions of materials (including transports) and the use of working machines from maintenance of 7881 m^2 artificial turf.

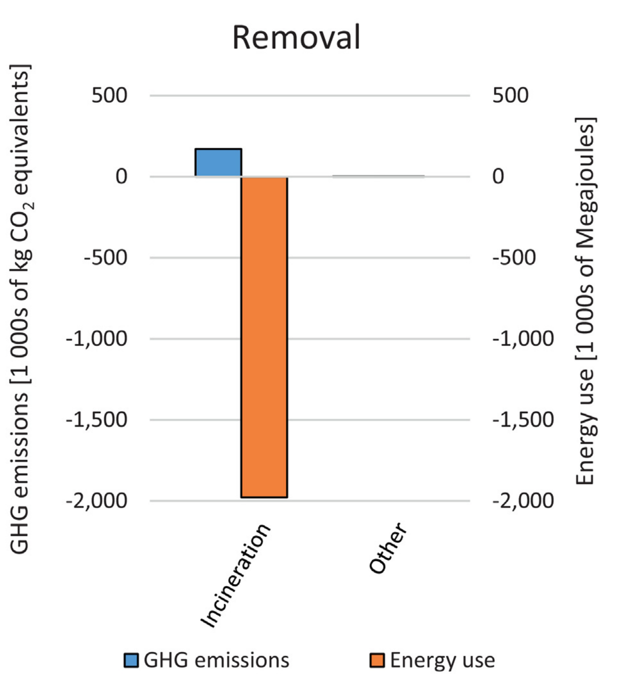

Fig. 5. The energy use and GHG emissions of materials (including transports) and the use of working machines from removal of 7881 m^2 artificial turf.

The actual benefit of annually refilling of 5 ton could be questioned, even though some infill is compacted or lost. These data was gathered from one operator, it should therefore be seen as an extreme. The energy use and GHG emissions from the RT shock pad is relatively low, however many other polymers can be used

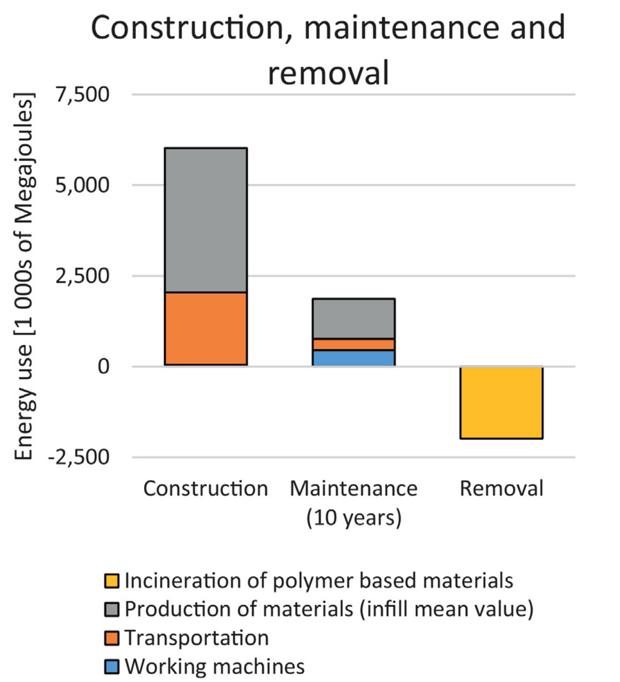

Fig. 6. Energy use from construction, maintenance and removal of 7881 m^2 artificial turf. Energy use related to infill represents the mean value between RT (min value), TPE (max value), EPDM and R-EPDM infill.

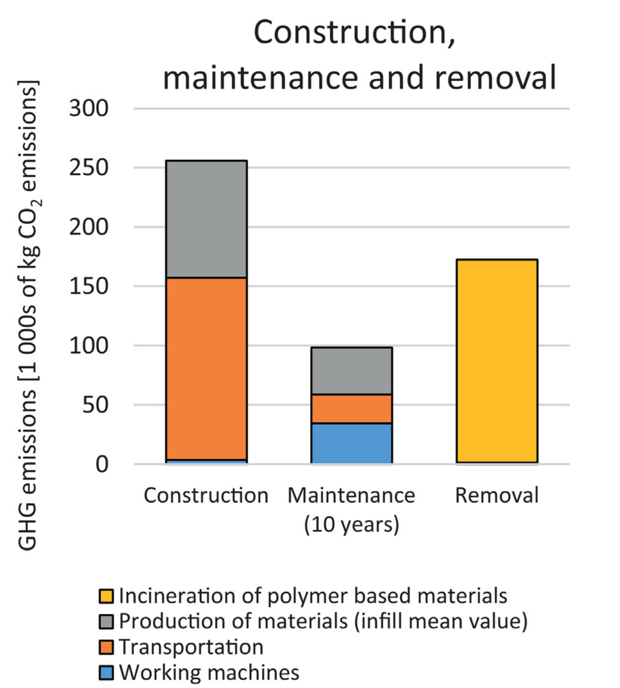

Fig. 7. GHG emissions from construction, maintenance and removal of 7881 m^2 artificial turf. GHG emissions related to infill represents the mean value between RT (min value), TPE (max value), EPDM and R-EPDM infill.

and which may have larger significance for energy use and GHG emissions.

3.2. Chemical analysis

Results from laboratory analysis of infill from single material samples for metals, chloride, fluoride and sulfate, distillable phenols and dissolved organic carbon (DOC) are presented in Table 7.

Table 7
Leaching of metals and inorganic substances of RT, TPE, EPDM and R-EPDM produced by a single stage shaking test at *L*/*S* 10 according to EN 12457-2 standard.

	RT[μg/l]	TPE[μg/l]	EPDM[μg/l]	R-EPDM[μg/l]
Antimony Sb	<0.6	<0.6	<0.6	<0.6
Arsenic A	<5	<5	<5	<5
Barium Ba	<200	<200	<200	<200
Lead Pb	<5	<5	<5	<5
Kadmium Cd	<0.4	<0.4	<0.4	<0.4
Copper Cu	<20	<20	<20	<20
Chromium Cr	<5	<5	<5	<5
Mercury Hg	<0.1	<0.1	<0.1	<0.1
Molybdenum Mo	<5	<5	<5	<5
Nickel Ni	<4	<4	<4	<4
Selenium Se	<1	<1	<1	<1
Zinc,Zn	**94**	**<40**	**<40**	**5000**
Chloride	**<1000**	**10,000**	**<1000**	**1300**
Fluoride	**120**	**<100**	**<100**	**<100**
Sulphate	**3000**	**1000**	**2200**	**<1000**
Distillable phenols	**190**	**17**	**<10**	**18**
Dissolved organic carbon	**24,000**	**8600**	**2000**	**93,000**

Note: Differences between leachates are marked as bold.

Table 8
Leached semi volatile organic compounds from infill of RT, TPE, EPDM and R-EPDM produced by a single stage shaking test at *L*/*S* 10 according to EN 12457-2 standard.

	RT[μg/l]	TPE[μg/l]	EPDM[μg/l]	R-EPDM[μg/l]
PAH16	–	–	–	–
PAH derivatives	–	3.3[a]	–	–
PCB7, chlorobenzenes, chlorophenols and chlorinated hydrocarbons	–	–	–	–
Phenols, alcylphenols	1.3	1.9	–	–
Phenol derivatives	1.4	1.8	–	11
Phthalates	–	6.2	–	–
Other specified hydrocarbons containing nitrogen	44.9	520	664	1012
Other specified hydrocarbons not containing nitrogen	0.46	37.7	9.4	–
Unspecified residual oil type, primarily straight aliphatic hydrocarbons within C20–C36	390	–	–	–
Unspecified motor oil type, primarily branched aliphatic hydrocarbons within C20–C35	–	520	–	–
Unspecified, unknown oil type, aliphatic hydrocarbons within C24–C35	–	–	–	38,000
Total leachate	437	1086	702	39,023
Leachate of specified hydrocarbons not found in CLP register	0.95	522	321	11

[a] Possible derivative.
Note: "–" marks substances not detected in leachates.

For many substances, the concentrates was under detection limit. For the detected substances, zinc, chloride, sulphate, distillable phenols and dissolved organic carbon (DOC), concentrations varied. The leaching of zinc and DOC was comparably high from R-EPDM. Zinc leaching from R-EPDM was about 53 times higher than from RT and about 125 times higher than from TPE and EPDM. The leaching of zinc from primarily RT but also from EPDM and TPE infill was relatively low compared to previous studies (Ruffino et al., 2013; Plesser and Lund, 2004). Reference values for R-EPDM was not found. The leaching of DOC from R-EPDM was about four times higher than from RT, about 11 times higher than from TPE and 47 times higher than from EPDM. The leaching of DOC from RT and EPDM was relatively low compared to results presented by Plesser and Lund (2004). Any reference values for TPE and R-EPDM could not be found. RT had comparably high leaching of distillable phenols, about 11 times higher than from TPE and R-EPDM and at least 19 times higher than from TPE. Reference values for phenol leaching has not been found. Results from laboratory analysis of S-VOCs from single infill material samples are presented in Table 8.

The analysis of S-VOC showed that the infill materials of RT, EPDM, TPE and R-EPDM contained all leachable S-VOC substances. The total leaching of S-VOCs was highest from R-EPDM, about 39 mg/l, and comparably much lower from TPE (1.1 mg/l), EPDM (0.7 mg/l) and RT (0.4 mg/l). The results are similar to previous studies where total VOC leaching from RT, TPE and EPDM was within the range of 1–44 mg/l (Nilsson et al., 2008). Any reference values for R-EPDM was not found.

No substances of PAH16, PCB7, chlorbenzenes, chlorinated hydrocarbons and chlorophenols was detected in the leachate from the infill materials with the exception of one possible PAH derivative (2,6-dihydroxynaphthalene) which was detected in the leachate from TPE. Phenols and its derivatives was detected from RT, TPE and R-EPDM, however previous studies have detected phenols also in EPDM (Nilsson et al., 2008). No reference values were found for R-EPDM. Phthalates were detected from TPE. Phthalates have been detected in previous studies in leachates from both RT, TPE and EPDM infill (Nilsson et al., 2008). The leaching of other specified hydrocarbons was highest from R-EPDM, followed by EPDM and TPE and lowest for RT. Most of these hydrocarbons contained nitrogen. For R-EPDM, TPE and RT, a large part of the leachate was of unspecified oil types. The highest leaching was from R-EPDM where aliphatic hydrocarbons within C24–C35 contributed to about 38 mg/l. TPE leachate was of motor oil types, primarily branched aliphatic hydrocarbons within C20–C35 in the level of about 0.5 mg/l. RT leachate was with about 0.4 mg/l of residual oil, primarily straight aliphatic hydrocarbons within C20–C36. No unspecified oils was detected from EPDM. Some of the specified hydrocarbons detected was not found in the Classification and Labeling Inventory Database (CLP) provided by the European Chemicals Agency (ECHA, 2016). The leaching of such substances was highest from TPE (522 μg/l), followed by EPDM (321 μg/l), and in comparison low from R-EPDM (11 μg/l) and RT (0.95 μg/l). Substances which are known to be harmful for the aquatic environment and/or humans was detected in all infill leachates. Eight harmful substances were detected from RT with a total of 46 μg/l in the leachate. Six substances were detected from TPE with a total of 45 μg/l in the leachate. Four substances were detected from EPDM with a total of 381 μg/l in the leachate. Three substances were detected from R-EPDM with a total of 1012 μg/l in the leachate. From RT, toxic substances for aquatic life found was primarily leachate of N-1,3-dimethylbutyl;-N′-phenylbenzenediamine (14 μg/l) and acetone anil (11 μg/l). The latter substances have been detected in concentrations up to 690 μg/l (Nilsson et al., 2008). It was assessed that, based on an uncertain determination of degradation product, this concentration in an aquatic environment may be above the no-effect concentration (Nilsson et al., 2008).

From TPE and EPDM the aquatic toxic substance Kodaflex txib was found in concentrations of 5.5 μg/l from TPE and 9.4 μg/l from EPDM. Kodaflex txib has been detected from EPDM infill (Nilsson et al., 2008). In addition, Alkofen B was detected in the leachate from TPE in a concentration of 1.9 μg/l. No previous risk assessments of these substances in infill material was found. From R-EPDM, the toxic substance for aquatic life detected was Benzenesulfonanilide at a concentration of 960 μg/l. No previous risk assessment of this substance was found. The results show that all infills tested produced leachates containing substances harmful to aquatic life. For the leachates from TPE, EPDM and R-EPDM, information about potential toxicity could not be found for a large share of the total S-VOCs identified and seems to be missing. However, the analysis are made on only a single material sample from each type of studied infill.

4. Conclusions

For the construction, maintenance and final removal of artificial turf, the total energy use was 5.9 GJ and the GHG emissions was 527 ton CO_2 equivalents. Differences between infill materials are large, where the use of TPE and EPDM contributes to higher energy use and GHG emissions compared to the use of R-EPDM and RT. These differences give that the total energy use and GHG emissions for the artificial turf system studied can vary with a factor of 1.5 and 2.2 respectively, depending on the infill type chosen. Incineration of materials gives relatively large GHG emissions. In addition, transport of soil and rock is also a significant source to energy use and GHG emissions. By reusing soil and rock materials on site and avoiding incineration and reusing turf mat and infill, energy use and GHG emissions can be reduced. Reductions in infill material's bulk densities could decrease the infill material need and hence reduce energy use and climate impact from the infills.

The chemical analysis shows that all infill materials could leach substances to the recipient. Zinc was detected in R-EPDM leachate in comparably high concentration. Organic substances known to be harmful for the environment was detected in leachates of all infill materials. In the literature, there is an uneven distribution of risk assessments focusing on solely RT while assessments are few for TPE and EPDM and assessments are missing for R-EPDM. Environmental risk assessments based on field measurements conclude that the risks are small or minimal. However, the number of studies are few and it is suggested to verify these results by controlled field measurements where all infill types are included.

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