Heliyon 11 (2025) e41909

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

A systematic review of the environmental and health effects of waste tires recycling

Masoumeh Hashamfirooz [a,b], Mohammad Hadi Dehghani [a,c], Mohammad Khanizadeh [a], Mina Aghaei [a], Parnia Bashardoost [a], Mohammad Sadegh Hassanvand [a,b], Mohammad Hassanabadi [a], Fatemeh Momeniha [a,c,*]

[a] Department of Environmental Health Engineering, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran
[b] Center for Air Pollution Research (CAPR), Institute for Environmental Research (IER), Tehran University of Medical Sciences, Tehran, Iran
[c] Center for Solid Waste Research (CSWR), Institute for Environmental Research (IER), Tehran University of Medical Sciences, Tehran, Iran

A R T I C L E I N F O

Keywords:
Waste tires
Recycling
End-of-life tires
Environmental and health effects

A B S T R A C T

Objectives: With approximately 1.5 billion tires produced annually, the management and disposal of waste tires pose significant environmental challenges worldwide. While tire recycling has the potential to mitigate some environmental issues, existing studies reveal notable gaps and associated risks to human health and the environment, highlighting the need for a comprehensive review.
Methods: This study utilized primary search engines, including Scopus, Web of Science, and PubMed, in conjunction with relevant keywords, to identify pertinent studies published in peer-reviewed journals. Data and information regarding the application of waste tires in environmental and health-related contexts were systematically extracted.
Results: Out of 1275 potential articles, 80 studies met the criteria for inclusion in this review. The majority of these studies focused on the use of discarded tires in the construction sector, with 49 % specifically addressing their application in artificial turf fields.
Conclusions: A comprehensive assessment of the health and environmental implications of various recycling methods is essential to determine their feasibility. The increasing utilization of recycled tires across diverse sectors raises new concerns that warrant such investigations. Understanding the health effects associated with recycled tire products can provide valuable insights for both researchers and policymakers.

Abbreviations

ACE	Acenaphthene
Acy	Acenaphthylene
ANC	Anthracene
BTEX	Benzene, toluene, ethylbenzene, and xylene
BaA	Benzo(a)anthracene

(*continued on next page*)

* Corresponding author. Department of Environmental Health Engineering, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran.
E-mail address: fmomeniha@tums.ac.ir (F. Momeniha).

https://doi.org/10.1016/j.heliyon.2025.e41909
Received 6 August 2024; Received in revised form 9 January 2025; Accepted 10 January 2025
Available online 11 January 2025
2405-8440/© 2025 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY-NC license (http://creativecommons.org/licenses/by-nc/4.0/).

(*continued*)

B(a)P	Benzo(a)pyrene
BbFA	Benzo(b)fluoranthene
B(g,h,i)P	Benzo(g,h,i)perylene
BghiP	Benzo(g,h,i)pyrene
BkF	Benzo(k)fluoranthene
BjFA	Benzo[j]fluoranthene
CHY	Chrysene
CRMs	Construction and repair materials
DB(ah)A	Dibenz(a,h)anthracene
DahA	Dibenzo[a,h]anthracene
DBaiP	Dibenzo[a,i]pyrene
DPG	1,3-diphenylguanidine
ELT	End-of-Life Tires
FLA	Fluoranthene
FLU	Fluorene
GHG	Greenhouse gas
HI	Hazard index
HQ	Hazard quotient
IP	Indeno(1,2,3-c,d)pyrene
LCA	Life Cycle Assessment
MIBK	Methyl isobutyl ketone
NAP	Naphthalene
OPAHs	Oxygenated Polycyclic Aromatic Hydrocarbons
6PPD	N-(1,3-dimethylbutyl)-N′-phenyl-p-phenylenediamine
PHN	Phenanthrene
PAHs	Polycyclic Aromatic Hydrocarbons
PYR	Pyrene
SBRR	Styrene-butadiene recycled rubber
SDA	Semi-dense asphalt
SPME	Solid Phase Micro-Extraction
SVOCs	Semi-volatile organic compounds
TDA	Tire-derived aggregate fills
TDF	Tire-derived fuel
TEQ	Toxicity equivalent
TRP	Tire rubber powder
VOCs	Volatile Organic Compounds
ZnO	Zinc Oxide

1. Introduction

The explosive development of the automotive sector and the increasing number of vehicles have increased the number of tires produced annually. Approximately 1.5 billion tires are manufactured worldwide annually, and over 17 million tons of them are disposed of. The yearly production of discarded tires is predicted to increase to 1200 million by 2030 [1–3].

The extensive output of the end-of-life tires (ELT) could pose challenges for their management. Waste tires impose an economic and environmental burden on society. Since 75 % of scrap tires consist of empty space, transportation and storage of them will result in significant costs [4]. Scrap tires are highly durable and extremely flammable if they accumulate for a long time, there is a high risk of a catastrophic fire breaking out, resulting in the release of significant amounts of smoke, hydrocarbons, toxic metals, and the spread of the contamination in soil and groundwater [4,5]. Furthermore, the empty area within tires provides an ideal platform for water collection, a habitat for rodents, insects, and reptiles, which can lead to the spread of diseases [6]. On the other hand, studies have shown that 75 % of tires end up in landfills worldwide, creating significant environmental and health problems [7]. Because of the considerable volume and non-biodegradability of waste tires, disposing of them in landfills shortens the lifespan of the landfills. Waste tires tend to float to the top when deposited in landfills, causing damage to landfill covers [8]. Therefore, if not handled correctly, they can lead to severe health, safety, and environmental problems.

Tire recycling and usage in diverse applications is one of the management approaches that are carried out to mitigate the environmental and health effects of used tires and obtain added value from waste tires [3,9]. Various research has examined the recycling and reusing of scrap tires in different forms such as whole tires, shredded tires, and granulated tires [5,10–12]. Waste tires have a significant calorific value, making them suitable as an alternative fuel in cement kilns, paper mills, or power plants [3]. Furthermore, tires are well-suited for geotechnical engineering applications due to their low density, effective insulation, efficient drainage, long-lasting resilience, and high compressibility [6]. The utilization of shredded scrap tire rubber as a construction material in many civil engineering projects is gaining popularity worldwide as the construction industry strives to employ recycled materials. Recycled tire products have been used in various applications such as construction materials, embankments, asphalt, cement concrete, sports fields, playgrounds, and artificial turf fields [13,14]. These products enhance strength, flexibility, durability, plasticity, and resistance to thermal changes [15]. Using crumb rubber in playgrounds, sports fields, and artificial turf enhances surface flexibility, improves ground drainage capacity, and offers a softer playing surface for athletes and children [12,16].

Although recycling scrap tires presents a partial remedy to the increasing pollution stemming from this waste stream, it is critical to consider the potential adverse environmental impacts and health risks associated with their utilization. Tire rubber contains potentially hazardous compounds such as rubber polymer and enhancing agents such as carbon black, aromatic enhancing oils, vulcanization additives, antioxidants, and processing aids. Extensive research has been conducted on the environmental and health effects of heavy metals and organic compounds released from recycled rubber. Zinc Oxide (ZnO) is commonly employed as a catalyst in the process of tire rubber vulcanization, and Polycyclic Aromatic Hydrocarbons (PAHs) are added as plasticizers in tire rubber, these additives can be released in the leachate from recycled tires, causing soil and groundwater contamination [17–19]. Furthermore, studies have revealed that releasing toxic chemical compounds from playgrounds and artificial turf exposed to sunlight has adverse effects on the health of children and exposed individuals [19,20].

Artificial turf manufacturers assert that their products do not threaten public health and provide an effective method for recycling used tires [21]. Conversely, research studies have challenged these claims, revealing the presence of specific contaminants that may be harmful to human health and the environment [18,22,23]. Despite this, there remain differences of opinion about these compounds and their importance in health. Moreover, due to the conflicting views by researchers regarding the available data and the knowledge gap in this field, some environmental groups and users of these products still have concerns about using these recycled products and daily exposure to compounds released from these products. These conflicting human health risk studies emphasize the need for more comprehensive research.

Conducting a comprehensive study on the environmental and health effects of using recycled tires can provide policymakers with extensive information to make informed decisions when formulating regulations on using recycled tires. Therefore, this systematic review study is conducted to investigate the potential environmental and health implications associated with various methods of tire recycling and their subsequent use in different products, such as artificial turf, playground, and cement. By reviewing and analyzing existing research and evidence, this study offers valuable insights into how these recycled tire products may impact the environment and human health. Ultimately, this study suggests valuable insights on the utilization of products derived from tire recycling for researchers to ensure that the suggested waste tire recycling process effectively reduces environmental effects.

2. Methods

2.1. Search strategy and study selection

The search strategy in this study is based on the question, does using waste tire recycling methods have obvious negative effects on the environment and human health? It was conducted on main electronic databases, i.e., Scopus, Web of Science, and PubMed. Preferred Reporting Items for Systematic Reviews and Meta-Analysis (PRISMA) guidelines were used for search strategy and study selection. Relevant studies were identified from the inception of the studies up to June 28, 2023. Sources were systematically searched based on MeSH terms by following keywords: "tire", "tyre", "recycled rubber", "recycled tire", "tire rubber", "waste tire", "waste rubber", "waste tire rubber", "crumb rubber", "tire crumb rubber", "scrap tire", "tire chips", "shredded tire", "aged tire", "end of life tire", "worn tyre", "rubber granul*", "tire crumb", "concrete pavement", "asphalt concrete", "asphalt", "railway design", "artificial turf", "artificial sports field", "pyrolysis", "embankment", "aquatic application", "playground", "pavement", "artificial reef", "synthetic turf infill", "concrete", "risk", "health effect", "risk assessment", "environmental impact", "ecotoxic*", "toxic*".

The search strategy was performed according to the syntax rules of each database, and the Boolean operators (OR, AND) were used to combine the keywords. Furthermore, grey literature was also reviewed by searching open online databases, and the references of selected literature were investigated to find more relevant studies.

All found studies were imported into Endnote X9, and then duplicate articles were manually and automatically eliminated. After duplicate elimination, the title and abstract of the remaining articles were assessed carefully for eligibility. The full texts of the retrieved articles were examined to extract the inclusion criteria. Two reviewers (FM & MH) performed the study selection; the final conclusions were reached through discussion and collaboration with the third reviewer (MA) to address any discrepancies.

2.2. Inclusion and exclusion criteria

In the present study, only original articles published in English about the different applications of recycled tires, types of tire recycling methods, and the environmental and health effects attributed to tire recycling on human health, were included. The abstracts, books, articles with unrelated topics, duplicate contents, meta-analyses, reviews, presentations, theses and dissertations, conference papers, and letters to the editor were excluded from the study.

2.3. Data extraction

After checking the eligibility of the retrieved studies, the following information were obtained from the included studies: the journal name, author, publication year, article title, the type of recycling methods, the applications of recycled tires, the hazardous effects attributed to tire recycling on human health and environment.

3. Results and discussion

3.1. Literature search and study characteristics

Based on a systematic search, a total of 1991 records were identified through literature searching in electronic databases. The PRISMA flow diagram for the search strategy and study selection process is shown in Fig. 1. After duplication removal, 1275 studies were screened by titles and abstracts, out of them 1139 articles were excluded due to exclusion criteria. The full texts of the 136 remaining articles were reviewed for eligibility. Finally, 80 articles that met the considered criteria were included in this study. No extra articles were found in references or other sources. The number of reviewed articles based on type of recycled material is illustrated in Fig. 2. Also, Fig. 3 shows the geographical distribution of included articles in this study.

3.2. Applications of waste tires

Waste tires are employed in different industries such as construction and civil engineering, energy production, etc. The most common techniques for tire recycling are depicted in Table 1. Among them, most of the research concentrated on the application of scrap tires in the construction industry. Shredded and granulated tires are commonly employed in many applications such as artificial turf fields, playgrounds, asphalt, cement additives, and sub-road filling [5,24–26].

As illustrated in Fig. 4, the predominant methods for recycling tires in the construction industry are artificial turf fields, concrete, and asphalt. Specifically, 49 % of the conducted studies focus on their application in artificial turf fields. The incorporation of recycled rubber into the synthetic turf field facilitates the development of a softened surface, mitigating potential harm to individuals. On the other hand, utilizing scrap tires for concrete production is another method for their management. Concrete is one most popular construction materials, which can be produced from both natural resources and recycled materials. The massive demand for concrete worldwide has led to a significant threat to the natural resources of concrete, therefore, recycling waste for concrete production not only reduces the consumption of natural resources but also mitigates environmental risks associated with waste [27].

Besides, another technique can be the addition of scrap tires to the cement mixture, leading to a significant improvement in the mechanical characteristics of the produced cement and clay composites. The final composites can be used for various purposes including various structural and non-load-bearing applications like foundations and sub-bases. The utilization of waste tires generally enhances durability and resistance to asphalt and cement slippage, mitigates cracking, and diminishes water permeability in the soil [28,29].

Another recommended way for tire management is the application of thermo-chemical conversion techniques, with one of the most

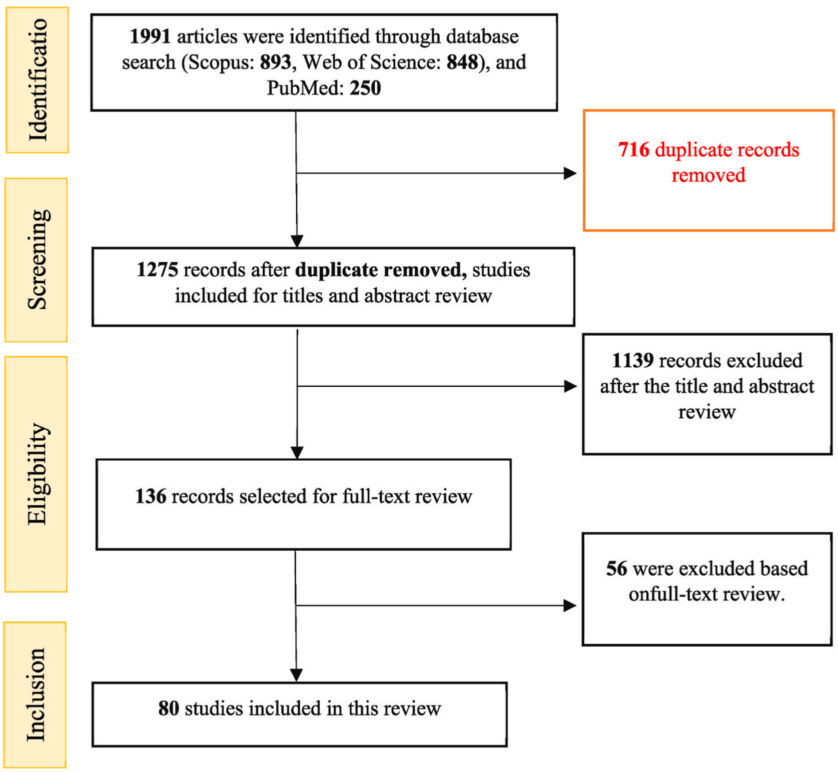


Fig. 1. PRISMA flow diagram describing literature research and selection process.

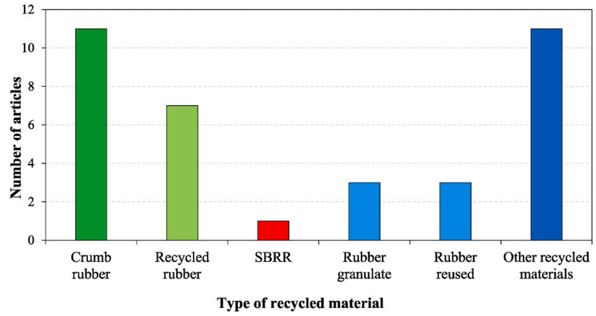
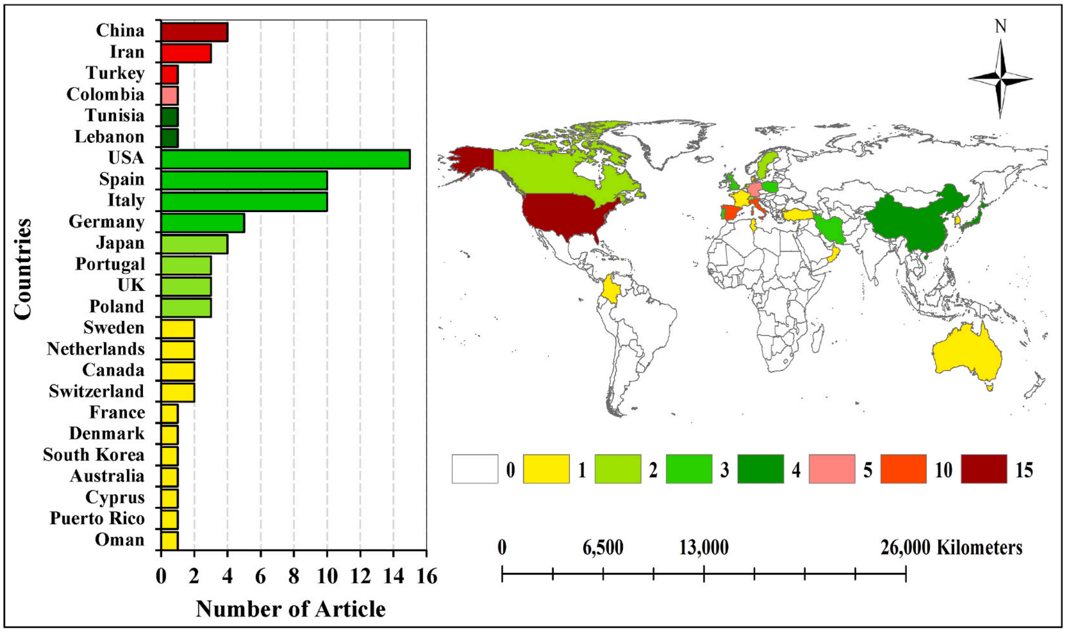


Fig. 2. The Number of reviewed articles based on the type of recycled materials.



High income: Oman, Puerto Rico, Cyprus, Australia, South Korea, Denmark, France, Switzerland, Canada, Netherlands, Sweden, Poland, UK, Portugal, Japan, Germany, Italy, Spain, USA
Upper-middle income: Colombia, Turkey, Iran, China
Lower-middle income: Lebanon, Tunisia

Fig. 3. Geographical distribution of included articles in this study.

common thermal conversion techniques used worldwide being pyrolysis, for providing energy. In this technique, energy production occurs in an anaerobic state under high temperatures in which the chemical bond between the applied waste is cracked and a pyrolytic fuel is achieved [30]. Tire-derived fuel (TDF) of this process can be used as a substitute for coal in many other industries. Tire particles burn much faster than similarly sized coal particles, releasing three to five times less NO_X, 10 percent less CO_2, and comparable SO_2 emissions [31]. Moreover, some studies have also examined the utilization of whole tires for the construction of artificial reefs, breakwaters, and buffers within harbors, as protective barriers safeguarding boats against potential harm caused by impacts or scratches on the side of the pier [32,33]. The utilization of scrap tires by retreading, which involves eliminating the old tread compound and substituting it with a rubber tread to extend the life of a tire, has also been investigated for waste tire management [34].

3.3. Environmental effects of waste tires

Tire rubber is made up of natural and synthetic rubber polymers, reinforcing agents, aromatic oils, vulcanization additives, antioxidants, and processing aids [16]. The extensive usage of tire rubber results in the release of a significant quantity of hazardous substances, including Volatile Organic Compounds (VOCs), PAHs, heavy metals, and other chemical compounds into the environment especially artificial turf and playgrounds.

Table 1
Summary of the different applications of recycled tires.

Waste tire utilization industry	Type of waste tire	Application	Country	Ref.
Construction & civil engineering	Granulated vehicle tires	Artificial turf	Italy	(35)
	Recycled tire	Concrete	Oman	(27)
	Recycled tire rubber	Self-consolidating concrete	USA-Michigan	(6)
	Crumb tire and tire chips	Concrete	Italy	(36)
	Crumb rubber	Modified asphalt concrete	Switzerland	(37)
	Recycled rubber	Asphalt	Colombia	(38)
	Waste tires crumbs	Bituminous concrete (BC) road	Tunisia	(39)
	Tire rubber powder (TRP)	Cement replacement material in soil-cement blends	Turkey	(25)
	Waste tires	Lightweight tire-derived aggregate fills (TDA)	Spain	(40)
	Ground tire rubber	Highway construction and repair materials (CRMs)	USA	(41)
	Recycled tire rubbers	Roller-compacted concrete pavement	Iran	(42)
	Crumb rubber	Reclaimed asphalt pavements	Iran	(43)
	Waste tires crumb rubber	Enhancer for polymer-modified and hybrid polymer-modified bitumen	Malaysia	(13)
	Shredded material from car tires	Hardening and filling of road embankments with vermicomposting process	Poland	(44)
	Waste tires	Three-dimensional reinforcement material	China	(45)
	Shredded tires	Embankments	USA	(5)
	Shredded, recycled SBR tires	Artificial turf	Sweden	(24)
Energy production (Fuel)	Scrap tires	Pyrolytic oil	Spain	(46)
	Scrap tires	Energy production	Puerto Rico	(47)
Other	Waste tire	Tire Retreading	Lebanon	(34)
	Tire rubber	Biochar	China	(48)
	Waste tire powder	Oil adsorbent	Taiwan	(49)
	waste tyre rubber	Activated carbons	UK	(50)
	Scrap tires	Artificial reef	UK	(33)

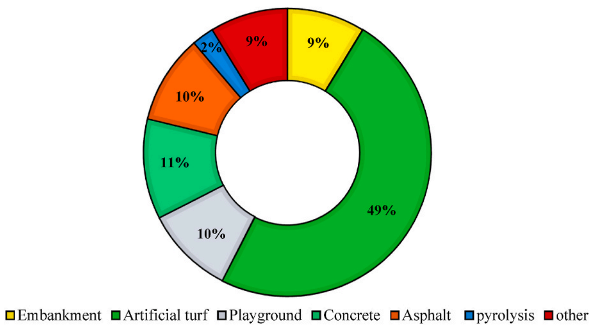


Fig. 4. Distribution of scrap tire applications.

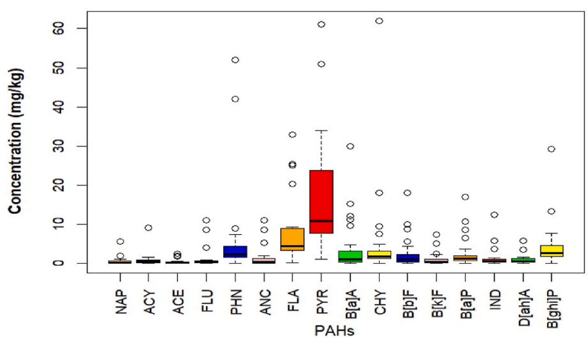


Fig. 5. Box plots of the concentration of PAHs in the waste tire recycling (based on the concentration in the included studies).

3.3.1. PAHs

Since tires contain toxic aromatic compounds, there is a major concern regarding the release of these compounds into the environment due to the extensive use of recycled tires for various purposes. Various studies have examined the concentrations of aromatic compounds in leachate, air, and soil based on the different applications of scrap tires in artificial turf fields, playgrounds, asphalt, and other areas. Studies have frequently shown the presence of these compounds in leachate from shredded scrap tires or sports fields covered with artificial turf [51,52]. Several studies have examined the concentration of PAHs in waste tires recycling, as shown in Fig. 5. Additionally, numerous studies have also examined the existence of PAHs in the atmosphere surrounding artificial turf. Overall, the concentrations of PAHs in the atmosphere above artificial outdoor turf fields were comparable to those found locally and were within the limitations set by regulations. Table 2 shows the numerous studies found through the systematic review that revealed PAHs from various tire-based material applications. According to Lu et al. (2021), the leachate produced by the artificial turf field, which used crumb rubber materials, was found to include 15 PAHs. Of these, 5 PAHs, namely ANT, BaA, BkF, DahA, and BghiP, had concentrations that raised concerns [19]. The findings of another study conducted by Celeiro et al. (2018) revealed that leachate samples gathered from multiple football fields with artificial turf, which utilized rubber crumbs as filling materials, could potentially contain approximately 16 different polycyclic aromatic hydrocarbons (PAHs). Of these, 8 PAHs, namely NAP, ACE, FLU, PHN, ANC, FLA, PYR, and CHY, were found to have levels of concern [53]. LIompart et al. (2013) analyzed the evaporation process of samples obtained from playgrounds and commercial pavements produced from recycled rubber at both 25 and 60 °C. Benzo[a]pyrene, the most carcinogenic PAHs component, was detected in some pavement samples. Additionally, all the compounds observed during the experiment, except B[a]A and CHY, were also present at ambient temperature and 60 °C [54].

3.3.2. Heavy metals

The reviewed studies demonstrated that various heavy metals particularly Pb and Cd and relatively large amounts of Zn could be released through the environmental compartments from varied applications of scrap tires (Fig. 6). The discharge of these metals to the environment has adverse effects on the environment and organisms [60]. Due to the presence of substantial quantities of heavy metals, diverse organic compounds, and hydrocarbons in the crumb rubbers, the leaching of these compounds into the turf field can change the activities of both microorganisms and earthworms. Pochron et al. (2017) evaluated the effect of used crumb rubbers from recycled tires in turf fields on indigenous bacteria and earthworms. The activity, survival, and lifespan of both indigenous microorganisms in heat and light stress and earthworms were investigated. The obtained results revealed that the respiration rate of the microbes was not affected by the contamination caused by crumb rubber in the soil. In contrast, earthworms residing in the contaminated soil exhibited reduced body weight compared to the ones living in uncontaminated soil. Except for Zinc, the concentration of other studied heavy metals such as Hg, Ni, Pb, Cu, Cd, and As in the soil did not exceed the announced allowable limit [8].

Shalaby et al. (2005) gathered and examined several representative samples to clarify the possible effects of utilizing scrap tires in full-scale construction of road embankments. The results indicated that the concentrations of Al, Fe, and Mn in the water samples obtained from the underground water source under the embankment exceeded the recommended levels, however, since the mentioned heavy metals are secondary drinking water quality parameters, no urgent considerations were required [4].

Lu et al. (2021) showed that tire crumb rubbers used in artificial turf fields may release 0.2–1.3 μg/g of Zn into leachates when

Table 2
PAHs detected in various uses of waste tires in different environments.

Media	PAHs	Description	Refs.
Leachate	15 PAHs NAP, ACE, FLU, PHN, ANT, FLA, PYR, CHY, BaA, BbFA, BkF, B(a)P, DahA, BghiP, IP	The concentration of five compounds (ANT, BaA, BkF, DahA, BghiP) was concerning.	(19)
	PYR, CHY, BaA, BbFA, BkF, B(a)P, DahA, BghiP	The leachates of the new filler materials exhibit a greater concentration of PAHs compared to the old materials.	(52)
	15 EPA PAHs	PAHs were detected at a relatively low concentration in the leachate.	(55)
	16 EPA PAHs	The concentration of 8 PAHs compounds (NAP, ACE, FLU, PHN, ANC, FLA, PYR, CHY) were worrying	(53)
	NAP, Acy, FLU, PHN, PYR	The release of PAHs induces harmful effects on V. fischeri.	(56)
Air	BaP, DBahA, BbFA, BjFA, BkFA, DBaiP	During the three sampling days, the air concentrations in the field remained relatively consistent, indicating no substantial difference from the levels detected at the background site and lower than those observed at the urban site. An increase in the amount of BaP in the air corresponds to the release of PAHs linked to particles.	(57)
	NAP, Acy, ACE, FLU, PHN, ANC, FLA, PYR, BaA	Nine investigated PAHs were identified in the vapor phase	(58)
	16 EPA PAHs	Benzothiazole compounds, amines (6PPD, DPG), MIBK, and cyclohexanone exhibited significant migration rates. No elevated levels of PAHs were detected. Nevertheless, a few unstable substances, including MIBK, benzothiazole, tert-butylamine, 2-heptanone, and cyclohexanone, exhibited a slight increase in concentration within an indoor facility.	(59)
	B(a)P, BaA, BbFA, BkF, DahA, IP, FLA, PYR, CHY, B(g,h,i)P, PHN, ANC	During two distinct sample periods, PAH concentrations in football fields and urban areas were comparable; however, the limited contribution of PAHs derived from granular materials was observed.	(16)
Ground water/ Runoff	NAP, Acy, ACE, FLU, PHN, ANC, FLA, PYR, BaA	A total of 9 PAHs were detected in the runoff/cleaning water, resulting in an increase in the overall PAHs content at ppm level.	(58)

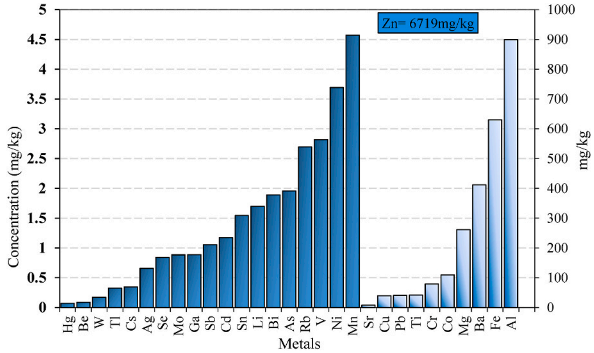


Fig. 6. The average concentration of heavy metals in the crumb tires (based on the concentration in the included studies).

exposed to UV radiation [19]. Azizian et al. (2003) analyzed the concentrations of various heavy metals in leachate samples adjacent to the roads where tire rubbers were utilized in construction. The analysis indicated that the amounts of Al, Ca, K, Mg, Sr, P, and Hg were significantly over the detection limit of the analyzer. However, the concentrations of the other 13 heavy metals such as V, Zn, As, Ba, Ni, Co, Fe, Cr, Cu, Sb, Pb, Cd, and Se, were found to be below the detection limit of the analyzer [41].

Kalbe et al. (2013) demonstrated that using scrap tires in the construction of sports fields as granular material can release various organic and inorganic toxins into the soil and groundwater. The laboratory experiment showed that the artificial weathering caused the used tire scraps to age, leading to the leachate containing high levels of Zn [55]. The results of the collected air samples by Schneider et al. (2020) demonstrated that both Co and Al were not detected [61].

3.3.3. VOCs

As previously mentioned, the findings of the conducted studies revealed that various VOCs can be released from scrap tires. Ruffino et al. (2013) found that using artificial turfs can release benzene, toluene, and xylene (BTEX) in the leachate. In addition, higher concentrations of BTEX were found in the leachate of new filling materials than the older ones [52]. Azizian et al. (2003) reported that different compounds including Pyrido, 10-(benzyloxy)-6,7-dihydro-, tetramethyl ester, Phthalic anhydride, Benzothiazole, Decanoic acid, silver (1+) salt, Benaldehyde, 3-hdroxy-4-methoxy, Glycine, N-methyl-N-(1-oxododecyl), Quinoline, 2,3-dimethyl, [1, 1-Biphenyl]-2-ol2(3H)-Benzothiazolone, and Hexadecanoic acid were detected in the collected leachate samples that were released from the crumb rubber materials used as construction materials in the highways. The results also revealed that different environmental processes of soil absorption, volatilization, and biodegradation could remove benzothiazole from the generated leachate [41].

Tandon et al. (2007) assessed representative air samples collected from a site where tire chips were utilized to fill embankments. The samples contained a variety of VOCs, such as 1,4-dichlorobenzene, dichlorodifluoromethane, ethylbenzene, styrene, tetrachloroethylene, toluene, trichloroethylene, trichlorofluoromethane, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, M&p-Xylene, and O-xylene [5]. Schneider et al. (2020) observed that some air samples at the sites utilizing rubber granules as infill materials for artificial turf contained different VOCs including benzothiazole, tert-butylamine, 2-heptanone, cyclohexane, and saturated aliphatic hydrocarbons NC9 [62].

Schilirò et al. (2013) discovered that the concentration of BTEX was considerably greater on cold and hot days in urban areas compared to air samples obtained from soccer fields utilizing artificial turf [16]. According to Li et al. (2010), crumb rubber materials could contain a variety of VOCs such as vulcanization accelerator and PAHs (NA, Phe, 1 MeNA, 2-MeNA, Flu, Pyr, BHA, BHT, 4-t-OP). These VOCs were found in the collected SPME fibers. Furthermore, volatile benzothiazole concentrations ranged from 8.2 to 69 ng in the collected samples of crumb rubber materials [63]. Shalaby et al. (2005) revealed that the levels of several chemicals, including BTEX in shredded rubber tire samples were below the detectable limit of the testing method [4].

3.4. Life cycle assessment (LCA) of recycled tires

Some of the reviewed studies also evaluated the Life Cycle Assessment (LCA) analysis. Magnusson et al. (2015) conducted an LCA analysis to evaluate the environmental impact of using recycled tires as filling materials in artificial turf. The results indicate that utilizing recycled tires would reduce energy consumption and release greenhouse gas (GHG) emissions. Moreover, the obtained samples revealed measurable levels of Zn in the leachate generated from recycled tires [64]. The potential environmental consequences of using crumb rubber materials in rubberized semi-dense asphalt (SDA) were investigated by Piao et al. (2022) through the LCA approach. Based on the findings, it is recommended not using crumb rubber products due to the possibility of PAHs entering into the groundwater [65].

Fiksel et al. (2011) carried out a study utilizing the Life Cycle Assessment (LCA) approach to identify an eco-friendly alternative for using scrap tires. The results revealed that recycling tires for cement and artificial turf purposes could reduce GHG emissions, air toxics, and also less water supplies would be used. Also, for every metric ton of TDF that is used as an alternative option in the cement kilns, around 543 kg (CO_2 equivalent) of both direct and indirect GHG emissions would be avoided [66].

3.5. Health effects of recycled tires

As stated earlier, the presence of numerous hazardous and carcinogenic substances in rubber crumbs threatens the individual's health, especially in industries such as artificial turf and children's playgrounds. Exposure can be influenced by the frequency of field use, duration of exposure, hand-to-playground contact, and hand-to-mouth contact [67]. Furthermore, a number of variables, including the age of the synthetic turf, light irradiation, ambient temperature, and ventilation rate, may have an impact on the chemical exposure from crumb rubber [18,68]. Several studies were carried out to elucidate the possible carcinogenic and non-carcinogenic effects of recycled tires on individuals. The main risk assessment studies related to recycled tire-based products are illustrated in Table 3. In a conducted study by Graça et al. (2022), a large-scale study was performed, collecting 103 samples from artificial turfs in 13 different countries including Portugal, Chile, Poland, Turkey, Italy, Finland, Sweden, Spain, France, Croatia, Germany, Albania, and Greece. The results revealed that Zn had the highest concentration among all studied compounds. The results of the health-risk assessment study also revealed that unwilling ingestion of rubber crumbs used in the artificial turfs can increase both carcinogenic and non-carcinogenic risks which was due to the Cr and Pb content [69]. Newer artificial turf fields contain higher concentrations of PAHs and benzothiazoles in their crumb rubber samples compared to older artificial turf fields [52,63]. At outdoor temperatures, artificial turf surfaces can reach 60 °C, the temperature at which semi-volatile organic compounds can be released into the ambient air. Evaporation of samples obtained from playgrounds and commercial pavements manufactured from recycled rubber at 25 and 60 °C showed that all PAHs compounds observed at 60 °C, except B[a]A and CHY, were also at ambient temperature [54].

Skin absorption, accidental ingestion, and inhalation are the main routes of exposure to dangerous substances. Individuals may be exposed to organic compounds and heavy metals present on the surfaces of artificial turf fields and playgrounds, potentially through skin contact or unintentional ingestion [18,67,70]. Nevertheless, there is currently no evidence suggesting that the exposure to hazardous substances in crumb rubber through hand-to-mouth contact can lead to any adverse health effects [71]. Assessment studies have found that the presence of crumb rubber in playgrounds and artificial turf fields does not present a substantial concern to human health though oral exposure [72]. Biological monitoring also showed that there was no increase in the amount of a biomarker of PAHs exposure (1-hydroxypyrene) in the urine of adult soccer players after they had direct skin contact with crumb rubber on artificial turf fields [73]. On the other hand, evaporation of VOCs from artificial turfs and playgrounds can be inhaled. However, studies have demonstrated that the quantities of PAHs and VOCs in the air near synthetic turf fields are negligible to pose a risk to human health [67, 72].

4. Challenges and the future research perspectives

This study provides a theoretical foundation for sustainable waste tire management by analyzing the environmental and health impacts of tire recycling. It identifies effective mechanisms to reduce pollution from waste tires, particularly through the production of rubber granules for use in building materials and sports flooring, which can decrease reliance on primary resources and lower greenhouse gas emissions. The findings will support policymakers and urban planners in creating standards for tire management that align with Sustainable Development Goals.

Practically, the research can help tire recycling industries and product manufacturers optimize processes and reduce environmental impacts by addressing weaknesses in current methods and assessing health risks of recycled materials. This can lead to the development of safer, more efficient technologies. Additionally, the study aims to raise public awareness about tire recycling, encouraging community involvement in recycling initiatives, which can further reduce waste and promote environmental protection.

The review of studies has shown that the assessment of pollution caused by the waste tires recycling faces challenges, including variations in the concentration of pollutants, the complex composition of pollutants in waste tires, pollutants created during the recycling process, and limitations in sampling and analytical techniques [84]. Furthermore, there is a lack of comprehensive knowledge regarding the environmental and long-term health consequences of recycling waste tires [3]. Additionally, the oversight and management of the disposal and recycling processes for these tires are not sufficient. The lack of regulations and standard guidelines for waste tires recycling practices should be addressed because standard regulatory protocols and enforcement mechanisms are needed to ensure compliance with environmental regulations in waste tire recycling [85]. It is also necessary to evaluate the economic feasibility and sustainability of waste tire recycling methods.

Current research has often focused on specific aspects of waste tire recycling without conducting comprehensive risk assessments. Future studies could address this limitation by conducting comprehensive risk assessments that consider multiple pollutants and exposure pathways. Strengthening regulatory frameworks by setting more stringent standards, improving enforcement mechanisms, and promoting compliance with environmental regulations can also help address specific challenges associated with pollutants such as PAHs and heavy metals in waste tire recycling. Future research can focus on developing strong regulatory frameworks, control measures, developing innovative recycling technologies to minimize environmental impacts, and improve the quality of recycled tires. It is also effective to conduct life cycle assessments to evaluate the environmental effects of waste tire recycling compared to other disposal methods.

5. Conclusion

Recycling waste tires in various industries can contribute to sustainable development by minimizing the demand for new materials, decreasing waste, and conserving energy. However, limited research has been conducted on the environmental and health impacts of products developed from used tires. This study was carried out to systematically investigate different applications of worn tires, as well

Table 3
Health effects attributed to recycled tire-based products.

Waste Tire		Descriptions	Results	Ref.
Type	Application			
Recycled tire rubber	Turf and playgrounds	An assessment was conducted to analyze the frequency, duration, and median duration of children's hand and mouth contact with different objects when playing on turf. The daily consumption rate of rubber crumbs was measured.	There was a significant difference in the median duration of children mouthing non-dietary objects and all things when playing on turf between younger children (1–6 years) and older children (7–12 years). Significant variations were observed in the mouthing frequency of young (1–6 y) and older (7–12 y) children playing on playground structures, as well as the median duration of mouthing non-dietary objects. There were no significant variations observed regarding the sex of children playing on synthetic turf-like surfaces or playground mats. The mean incidental ingestion rate was 0.08, 0.07, and 0.08 g rubber crumb/day for children <2, 2–6, and 6–11 years old, respectively.	(74)
Crumb rubber	Artificial turf	Potential exposures and associated risks to trace metals, SVOCs, and PAHs through three artificial biofluids such as lung, sweat, and digestive fluids were examined.	PAHs have been frequently below the detection limit and no SVOCs were detected at quantitative levels. The metals were discernible, however present in amounts that posed a minimal risk to human health. HQ, HI of digestive system, respiratory system, and dermal routes were determined. Two age groups of ≥2 to <6 years and age ≥6 to <7 years were considered for lead risk assessment.	(71)
Rubber granulate	Synthetic turf pitches	A selected group of samples were analysis for PAHs, phthalates, and metals in both sweat and the gastrointestinal tract. Additionally, the evaporation of volatile chemicals into the air was also examined. Three routes of exposure, oral, dermal and inhalation route were investigated.	PAHs were identified as the most harmful compounds, whereas phthalates, benzothiazoles, bisphenol A, and the metals (Cd, Co, Pb) were not a concern due to low levels of exposure.	(72)
Recycled rubber from automotive and truck scrap rubber tires	Artificial turf pitch	Urine samples of seven nonsmoking football players were collected over 3 days, the day before sporting, sporting, and the day after sporting for analyzing the 1-hydroxypyrene.	The levels of 1-hydroxypyrene remained relatively stable in four out of seven participants, while one out of four volunteers experienced an increase in hydroxypyrene in their urine after 2.5 h of training and a match on the playground. Players who play on artificial turf with rubber crumb infill have very low PAH (1-hydroxypyrene) levels.	(73)
SBRr from shredded tires	Artificial turf sports fields	The conceptual model took into account two receptors, namely an adult player and a young player, as well as three pathways of exposure: direct contact with crumb rubber, contact with rainwater that has soaked the rubber mat, and inhalation of dust and gases emitted from the artificial turf fields.	The risks associated with inhaling air dust and pollutants from vehicular traffic were considerably higher compared to those linked to playing soccer on a synthetic field. It was the primary route of exposure. The cumulative carcinogenic risk is lower than 10^{-6}, the cumulative noncarcinogenic risk lower than 1.	(52)
Discarded tires	Artificial turf	An elution test was conducted using four simulated biofluids, which included gastric and intestinal juices, saliva, and perspiration.	The actual elution amounts of all PAH compounds were less than the limits (LOQ = 0.025 μg/g)	(75)
Crumb rubbers	Synthetic turf rubber granule infill	Extraction tests were carried out using artificial biofluids, gastric fluid, intestinal fluid, saliva, and sweat.	Gastric fluid had a higher concentration of metals than other biofluids, and most metals were extracted at a rate of over 10 % in artificial gastric fluid. 16 metals (Mg, Al, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Rb, Sr, Sn, Sb, Ba, and Pb) were detected in simulated biofluids.	(76)
Recycled tire crumb rubber	Infill in synthetic football field	In-vitro oral bioaccessibility of 18 PAHs was assessed in human synthetic body fluids such as saliva, gastric, duodenal, and bile. Children exposure assessment was performed.	The presence of 17 target PAHs in the biofluids was determined. The bioaccessibility percentage levels of the most volatile PAHs, including NAP, ACY, ACE, FLU, PHN, and ANC, exceeded. B[a]P was detected in 75%of the samples at concentrations up to 2.5 ng g^{-1}.	(77)
rubber granules of ELT	Synthetic turf infill	Tire granulate (Al, aniline, Co, benzothiazoles, 6PPD, DPG, 4-tert-octylphenol, Benzothiazole, MIBK) risk characterization was assessed based on the exposure scenarios from oral, skin, and inhalation routes in different age groups.	The cancer risks associated with exposure to PAHs were found to be below 1 in 1 million. Similarly, the risk characterization ratios for non-carcinogenic substances were below 1, indicating no significant health concerns. Additionally, synthetic turfs with ELT-derived infill material were deemed safe with no identified health issues. Also, no toxicological data were found for 2-hydroxybenzothiazole.	(61)
Crumb rubber	Synthetic turf	The multipathway human health risk assessment (HHRA) of recycled rubber compounds assessed	The estimated non-cancer hazards and cancer risks for all the analyzed scenarios were found to be in	(78)

(continued on next page)

Table 3 (*continued*)

Waste Tire		Descriptions	Results	Ref.
Type	Application			
		exposure scenarios for adults, adolescents, and children by ingestion, skin contact, and inhalation.	compliance with the guidelines set by the US Environmental Protection Agency (EPA). The cancer risk levels of synthetic turf fields were reduced compared to those linked with natural soil fields.	
Used tires	Synthetic turf	Inhalation risk evaluation of PAHs from 9 samples of artificial turf was evaluated at 25 and 60 °C.	Crumb rubber emissions contribute significantly to PAH intake through multiple pathways due to their high toxicity equivalent (TEQ). The HI values in various rubber granulate samples range from 8.94×10^{-7} to 1.16×10^{-6}, while the ΣECR values range from 4.91×10^{-9} to 1.10×10^{-8}.	(79)
Rubber granules from recycled tyres	Artificial turf soccer pitch	Dangerous chemicals like BTX, PAHs, and heavy metals (Pb, Cd, Cr, Sn, and Zn) have been analyzed to measure personal and environmental exposure. In exposed individuals and the control group, PAHs and benzene biomarkers of exposure were quantified and qualitatively determined using the urine metabolites 1-Hydroxypyrene (1-0H pyrene) and trans, trans-muconic acid (t,t-MA).	No occupational exposure to the chemicals was detected other than urban environmental exposure.	(80)
Rubber granules	synthetic turf	Elution tests were conducted on eight rubber granule products using four simulated biofluids, including gastric juice, intestinal juice, saliva, and perspiration. The rubber additive and chemical concentrations in 46 rubber infills before use in synthetic turf fields were measured.	The elution rates in biofluids exhibited variability and were influenced by the presence of coatings. The majority of chemicals exhibited modest elution rates, which were either close or below the limit of quantification. The majority of chemicals exhibited negligible contamination levels in all simulated biofluids.	(81)
Recycled rubber waste	Artificial-turf granulates	To assess playground users' inhalation exposure to PAHs in the field with the highest PAH content among the 13 fields, BaP and six PAHs (BaA, DBahA, BbFA, BjFA, BkFA, and IP) were measured. Air samples were taken on filters at two fields using a high volume static sampler near the players, personal samplers worn by the athletes, and background areas outside the fields.	The athletes were exposed to 0.3 and 0.5 ng m^{-3} BaP during field exercises on the two sample days. The background amounts outside the field were 0.2 and 0.1 ng m^{-3}. An excess lifetime cancer risk of 1×10^{-6} was calculated for an intense 30-year activity.	(57)
Rubber granules of ELT	Synthetic turf infill	The migration of substances from rubber granules to artificial body fluids, including saliva, sweat, and gastric juice, was assessed.	Artificial sweat contained volatiles, Al, Co, benzothiazole, bisphenol A, and phthalates. Only MIBK, 4-tert-octylphenol, Al, and Co were found in 43 athletes' saliva, gastric juice, and skin wipe samples after playing on artificial grass. These samples only contained Al above the quantitation limit.	(61)
Tire crumb	Artificial Turf Football Fields	Artificial turf football fields and urban environments were compared for particle concentrations (PM_{10} and $PM_{2.5}$), PAHs, aromatic hydrocarbons (BTXs), and organic extract mutagenicity.	PM_{10} concentrations were similar in urban and turf football fields. Artificial turf football fields had higher PM10 organic extract mutagenicity than urban sites, whereas $PM_{2.5}$ organic extract mutagenicity was lower.	(16)
Recycled Tire Crumb	Synthetic turf fields	The possible relation between application of crumb materials in the turf fields and lymphoma in the players were examined.	There was a significant relation between using crumb rubber materials and cancer.	(82)
Crumb rubber of (ELTs)	Artificial turf pitches	Carcinogenic and non-carcinogenic risks of exposure to the Cr and Pb content of the crumb rubber from the artificial turf pitches of 13 countries were assessed.	In all individuals except for adult bystanders, exposure to Cr and Pb from the ingestion route was above acceptable values for both carcinogenic and non-carcinogenic exposure.	(69)
Crumb rubber-based materials	Synthetic turfs	The health risks of unwilling ingestion of recycled ethylene propylene diene monomers found in the crumb rubber materials in the synthetic turf were assessed using acid extraction and digestion extraction techniques.	Exposure to the Pb through the ingestion routes were calculated to be around 1.56×10^{-4}, and 4.87×10^{-5} $mgkg^{-1}day^{-1}$ for elementary school, middle and high school students respectively. Also, the related risk to the ingestion of Pb increases as the particle size gets smaller. The HQ value for the particles with the size of <250 μm was 2 times higher than that of particles with the size of >250 μm.	(83)

as environmental and health effects, using primary search engines such as Scopus, Web of Science, and PubMed. According to the results, worn tires are used in various industries depending on their geographical location and in most cases, they are commonly used in the construction industry, especially artificial artificial turf and playgrounds. Environmental studies have shown that the amount of metals, organic compounds, and PAHs in products made from worn tires is generally below acceptable limits. The release of these compounds into the surrounding soil, groundwater, and air is also relatively low and there is no special concern. Nevertheless, the findings indicated that the concentrations are different based on the product characteristics and the sampling location, and in some cases, they exceeded the permissible limits. In fact, according to the type of worn tire and its chemical composition, design, age, storage, and use conditions of the recycled products, the concentration of the pollutants released into the environment and the environmental effects related to it will also be different in site to site, therefore these variations should be considered as a knowledge gap for further development of the used tire recycling industry. Furthermore, assessing the health effects on individuals exposed to recycled products frequently revealed inconclusive results, recommending further research to explore the potential health risks associated with exposure to chemical compounds derived from recycled products. Due to the continuous discharge of compounds from recycled materials, these compounds accumulate over time. This poses both environmental and long-term health risks for individuals who are exposed to them. Typically, industries that incorporate worn tires in their products are expected to mitigate the potential health and environmental risks associated with exposure to harmful compounds like heavy metals and PAHs. Based on the information provided, it appears that establishing a standardized method for analyzing the chemical composition of worn tires and assessing the impact of using them in the production of recycled products at the manufacturing site could be a valuable approach to ensure that only products with little toxicity are introduced to the market.

The review of literature on waste tires recycling revealed significant knowledge gaps, particularly regarding human health risks, economic benefits, and technological advancements. To fill these gaps, the study proposes targeted research, including standardized methods, human health risk assessments, economic analyses, and innovations in technology. Suggested technological improvements include advanced recycling techniques, robotics, sensors, and circular economy solutions to enhance the efficiency and sustainability of recycling processes. Successful implementation will necessitate collaboration among stakeholders and the establishment of regulatory frameworks, incentives, public education, and international cooperation to promote sustainable waste tire management.

CRediT authorship contribution statement

Masoumeh Hashamfirooz: Writing – original draft, Data curation. **Mohammad Hadi Dehghani:** Supervision, Methodology. **Mohammad Khanizadeh:** Methodology, Formal analysis. **Mina Aghaei:** Writing – review & editing. **Parnia Bashardoost:** Writing – original draft. **Mohammad Sadegh Hassanvand:** Writing – review & editing, Supervision. **Mohammad Hassanabadi:** Methodology, Data curation. **Fatemeh Momeniha:** Writing – review & editing, Conceptualization.

Data Availability statement

The data used/analyzed during the present study are available from the corresponding author upon reasonable request.

Funding

This research has been financially supported by the Tehran University of Medical Science, Institute for Environmental Research (IER), Iran (grant number 1401- 2-110-58858).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] H. Jiang, Y. Zhu, J. Yu, W. Cheng, H. Yang, X. Zhang, et al., Production mechanism of high-quality carbon black from high-temperature pyrolysis of waste tire, J. Hazard Mater. 443 (2023) 130350.
[2] Q. Chen, F. Xu, P. Zong, F. Song, B. Wang, Y. Tian, et al., Influence of CaO on the thermal kinetics and formation mechanism of high value-added products during waste tire pyrolysis, J. Hazard Mater. 436 (2022) 129220.
[3] K. Formela, Sustainable development of waste tires recycling technologies–recent advances, challenges and future trends, Advanced industrial and engineering polymer research 4 (3) (2021) 209–222.
[4] A. Shalaby, R.A. Khan, Design of unsurfaced roads constructed with large-size shredded rubber tires: a case study, Resour. Conserv. Recycl. 44 (4) (2005) 318–332.
[5] V. Tandon, D.A. Velazco, S. Nazarian, M. Picornell, Performance monitoring of embankments containing tire chips: case study, J. Perform. Constr. Facil. 21 (3) (2007) 207–214.
[6] R.Z. Si, J.Q. Wang, S.C. Guo, Q.L. Dai, S. Han, Evaluation of laboratory performance of self-consolidating concrete with recycled tire rubber, J. Clean. Prod. 180 (2018) 823–831.
[7] W. Ferdous, A. Manalo, R. Siddique, P. Mendis, Y. Zhuge, H.S. Wong, et al., Recycling of landfill wastes (tyres, plastics and glass) in construction–A review on global waste generation, performance, application and future opportunities, Resour. Conserv. Recycl. 173 (2021) 105745.
[8] S.T. Pochron, A. Fiorenza, C. Sperl, B. Ledda, C. Lawrence Patterson, C.C. Tucker, et al., The response of earthworms (Eisenia fetida) and soil microbes to the crumb rubber material used in artificial turf fields, Chemosphere 173 (2017) 557–562.
[9] F.N. Archibong, O.M. Sanusi, P. Médéric, N.A. Hocine, An overview on the recycling of waste ground tyre rubbers in thermoplastic matrices: effect of added fillers, Resour. Conserv. Recycl. 175 (2021) 105894.
[10] S. Guo, Q. Dai, R. Si, X. Sun, C. Lu, Evaluation of properties and performance of rubber-modified concrete for recycling of waste scrap tire, J. Clean. Prod. 148 (2017) 681–689.
[11] A. Hamdi, G. Abdelaziz, K.Z. Farhan, Scope of reusing waste shredded tires in concrete and cementitious composite materials: a review, J. Build. Eng. 35 (2021) 102014.

[12] M.A. Sibeko, A.O. Adeniji, O.O. Okoh, S.P. Hlangothi, Trends in the management of waste tyres and recent experimental approaches in the analysis of polycyclic aromatic hydrocarbons (PAHs) from rubber crumbs, Environ. Sci. Pollut. Control Ser. 27 (2020) 43553–43568.
[13] I.B. Joohari, F. Giustozzi, Waste tyres crumb rubber as a sustainability enhancer for polymer-modified and hybrid polymer-modified bitumen, Int. J. Pavement Eng. 23 (12) (2022) 4357–4371.
[14] A. Mohajerani, H. Kurmus, D. Conti, L. Cash, A. Semcesen, M. Abdurahman, et al., Environmental impacts and leachate analysis of waste rubber incorporated in construction and road materials: a review, Sci. Total Environ. 835 (2022) 155269.
[15] A. Mohajerani, L. Burnett, J.V. Smith, S. Markovski, G. Rodwell, M.T. Rahman, et al., Recycling waste rubber tyres in construction materials and associated environmental considerations: a review, Resour. Conserv. Recycl. 155 (2020) 104679.
[16] T. Schilirò, D. Traversi, R. Degan, C. Pignata, L. Alessandria, D. Scozia, et al., Artificial turf football fields: environmental and mutagenicity assessment, Arch. Environ. Contam. Toxicol. 64 (1) (2013) 1–11.
[17] P.J. Kole, A.J. Löhr, F.G. Van Belleghem, A.M. Ragas, Wear and tear of tyres: a stealthy source of microplastics in the environment, Int. J. Environ. Res. Publ. Health 14 (10) (2017) 1265.
[18] A.N. Perkins, S.H. Inayat-Hussain, N.C. Deziel, C.H. Johnson, S.S. Ferguson, R. Garcia-Milian, et al., Evaluation of potential carcinogenicity of organic chemicals in synthetic turf crumb rubber, Environ. Res. 169 (2019) 163–172.
[19] F. Lu, Y. Su, Y. Ji, R. Ji, Release of Zinc and polycyclic aromatic hydrocarbons from tire crumb rubber and toxicity of leachate to Daphnia magna: effects of tire source and photoaging, Bull. Environ. Contam. Toxicol. 107 (4) (2021) 651–656.
[20] S. Bejgarn, M. MacLeod, C. Bogdal, M. Breitholtz, Toxicity of leachate from weathering plastics: an exploratory screening study with Nitocra spinipes, Chemosphere 132 (2015) 114–119.
[21] A. Watterson, Artificial turf: contested terrains for precautionary public health with particular reference to europe? Int. J. Environ. Res. Publ. Health 14 (9) (2017).
[22] A. Mohajerani, L. Burnett, J.V. Smith, S. Markovski, G. Rodwell, M.T. Rahman, et al., Recycling waste rubber tyres in construction materials and associated environmental considerations: a review, Resour. Conserv. Recycl. 155 (2020).
[23] A. Mohajerani, H. Kurmus, D. Conti, L. Cash, A. Semcesen, M. Abdurahman, et al., Environmental impacts and leachate analysis of waste rubber incorporated in construction and road materials: a review, Sci. Total Environ. 835 (2022).
[24] M.Z. Lauria, A. Naim, M. Plassmann, J. Faldt, R. Suhring, J.P. Benskin, Widespread occurrence of non-extractable fluorine in artificial turfs from Stockholm, Sweden, Environ. Sci. Technol. Lett. 9 (8) (2022) 666–672.
[25] L. Al-Subari, A. Ekinci, E. Aydın, The utilization of waste rubber tire powder to improve the mechanical properties of cement-clay composites, Construct. Build. Mater. 300 (2021).
[26] I. Rodríguez-Fernández, F. Tarpoudi Baheri, M.C. Cavalli, L.D. Poulikakos, M. Bueno, Microstructure analysis and mechanical performance of crumb rubber modified asphalt concrete using the dry process, Construct. Build. Mater. 259 (2020).
[27] M.B. Waris, N.N. Ali, K.S. Al-Jabri, Use of recycled tire in concrete for partial aggregate replacement, International Journal of Structural and Civil Engineering Research 5 (4) (2016) 273–276.
[28] X. Shu, B. Huang, Recycling of waste tire rubber in asphalt and portland cement concrete: an overview, Construct. Build. Mater. 67 (2014) 217–224.
[29] L.G. Picado-Santos, S.D. Capitao, J.M.C. Neves, Crumb rubber asphalt mixtures: a literature review, Construct. Build. Mater. 247 (2020).
[30] W. Han, D. Han, H. Chen, Pyrolysis of waste tires: a review, Polymers 15 (7) (2023) 1604.
[31] M.A. Sibeko, A.O. Adeniji, O.O. Okoh, S.P. Hlangothi, Trends in the management of waste tyres and recent experimental approaches in the analysis of polycyclic aromatic hydrocarbons (PAHs) from rubber crumbs, Environ. Sci. Pollut. Control Ser. 27 (35) (2020) 43553–43568.
[32] K.J. Collins, A.C. Jensen, S. Albert, A review of waste tyre utilisation in the marine environment, Chem. Ecol. 10 (3–4) (1995) 205–216.
[33] K. Collins, A. Jensen, J. Mallinson, V. Roenelle, I. Smith, Environmental impact assessment of a scrap tyre artificial reef, ICES (Int. Counc. Explor. Sea) J. Mar. Sci. 59 (suppl) (2002) S243–S249.
[34] M. Mrad, R. El-Samra, Waste tire management: Lebanon case study, Journal of Waste Management and Disposal 3 (1) (2020) 1–12.
[35] E.M. Zanetti, C. Bignardi, G. Franceschini, A.L. Audenino, Amateur football pitches: mechanical properties of the natural ground and of different artificial turf infills and their biomechanical implications, J. Sports Sci. 31 (7) (2013) 767–778.
[36] S. Sgobba, G.C. Marano, M. Borsa, M. Molfetta (Eds.), Use of Rubber Particles from Recycled Tires as Concrete Aggregate for Engineering Applications. 2nd International Conference on Sustainable Construction Materials and Technologies, 2010.
[37] I. Rodriguez-Fernandez, F.T. Baheri, M.C. Cavalli, L.D. Poulikakos, M. Bueno, Microstructure analysis and mechanical performance of crumb rubber modified asphalt concrete using the dry process, Construct. Build. Mater. 259 (2020) 119662.
[38] R.O. Diaz, C.H.H. Sandoval, Effect of the grain size of recycled rubber on the behaviour of an asphalt mix, Revista Ingenieria De Construccion 38 (1) (2023) 163–175.
[39] L. Ajam, M. Belgaied, S. Jomaa, Mechanical and environmental study of the valorization of waste tires in bituminous concrete applied in Tunisia, International Journal of Pavement Research and Technology 13 (3) (2020) 313–323.
[40] M. Arroyo, I. San Martin, S. Olivella, M.W. Saaltink, Evaluation of self-combustion risk in tire derived aggregate fills, Waste Manag. 31 (9–10) (2011) 2133–2141.
[41] M.F. Azizian, P.O. Nelson, P. Thayumanavan, K.J. Williamson, Environmental impact of highway construction and repair materials on surface and ground waters. Case study: crumb rubber asphalt concrete, Waste Manag. 23 (8) (2003) 719–728.
[42] M. Fakhri, K.F. Saberi, The effect of waste rubber particles and silica fume on the mechanical properties of Roller Compacted Concrete Pavement, J. Clean. Prod. 129 (2016) 521–530.
[43] H. Jahanbakhsh, M.M. Karimi, H. Naseri, F. Moghadas Nejad, Sustainable asphalt concrete containing high reclaimed asphalt pavements and recycling agents: performance assessment, cost analysis, and environmental impact, J. Clean. Prod. 244 (2020) 118837.
[44] M.A. Jozwiak, P. Rybinski, M. Jozwiak, G. Janowska, Vermicomposting of cis-1.4-polybutadiene rubber (Br) through culturing dense populations of the californian redworm (Eisenia foetida Sav.), Pol. J. Environ. Stud. 21 (4) (2012) 893–899.
[45] L. Li, F. Cui, P. Ferreira, H. Xiao, H. Jie, Experimental study of embankments with different reinforcement materials and spacing between layers, Geotext. Geomembranes 47 (4) (2019) 477–482.
[46] B. Acevedo, C. Barriocanal, Fuel-oils from co-pyrolysis of scrap tyres with coal and a bituminous waste. Influence of oven configuration, Fuel 125 (2014) 155–163.
[47] E.N. Laboy-Nieves, Energy recovery from scrap tires: a Sustainable option for small islands like Puerto Rico, Sustainability 6 (5) (2014) 3105–3121.
[48] F. Tang, M. Gao, F.J. Zeng, Z.L. Xu, G.M. Tian, An old story with new insights into an ignored issue of metabolites in biochar-amended soil: effect of biochar on dissipation of carbosulfan as an example, Sci. Total Environ. 790 (2021).
[49] C. Lin, C.-L. Huang, C.-C. Shern, Recycling waste tire powder for the recovery of oil spills, Resour. Conserv. Recycl. 52 (10) (2008) 1162–1166.
[50] Miguel G. San, G. Fowler, C. Sollars, The leaching of inorganic species from activated carbons produced from waste tyre rubber, Water Res. 36 (8) (2002) 1939–1946.
[51] B. Grynkiewicz-Bylina, B. Rakwic, B. Słomka-Słupik, Tests of rubber granules used as artificial turf for football fields in terms of toxicity to human health and the environment, Sci. Rep. 12 (1) (2022).
[52] B. Ruffino, S. Fiore, M.C. Zanetti, Environmental-sanitary risk analysis procedure applied to artificial turf sports fields, Environ. Sci. Pollut. Control Ser. 20 (7) (2013) 4980–4992.
[53] M. Celeiro, T. Dagnac, M. Llompart, Determination of priority and other hazardous substances in football fields of synthetic turf by gas chromatography-mass spectrometry: a health and environmental concern, Chemosphere 195 (2018) 201–211.
[54] M. Llompart, L. Sanchez-Prado, J. Pablo Lamas, C. Garcia-Jares, E. Roca, T. Dagnac, Hazardous organic chemicals in rubber recycled tire playgrounds and pavers, Chemosphere 90 (2) (2013) 423–431.

[55] U. Kalbe, O. Krüger, V. Wachtendorf, W. Berger, S. Hally, Development of leaching procedures for synthetic turf systems containing scrap tyre granules, Waste and biomass valorization 4 (2013) 745–757.
[56] P. Hennebert, S. Lambert, F. Fouillen, B. Charrasse, Assessing the environmental impact of shredded tires as embankment fill material, Can. Geotech. J. 51 (5) (2014) 469–478.
[57] E. Menichini, V. Abate, L. Attias, S. De Luca, A. di Domenico, I. Fochi, et al., Artificial-turf playing fields: contents of metals, PAHs, PCBs, PCDDs and PCDFs, inhalation exposure to PAHs and related preliminary risk assessment, Sci. Total Environ. 409 (23) (2011) 4950–4957.
[58] M. Celeiro, J.P. Lamas, C. Garcia-Jares, T. Dagnac, L. Ramos, M. Llompart, Investigation of PAH and other hazardous contaminant occurrence in recycled tyre rubber surfaces. Case-study: restaurant playground in an indoor shopping centre, Int. J. Environ. Anal. Chem. 94 (12) (2014) 1264–1271.
[59] K. Schneider, M. de Hoogd, P. Haxaire, A. Philipps, A. Bierwisch, E. Kaiser, Erasstri - European risk assessment study on synthetic turf rubber infill - Part 2: migration and monitoring studies, Sci. Total Environ. 718 (2020).
[60] G. Benoit, S. Demars, Evaluation of organic and inorganic compounds extractable by multiple methods from commercially available crumb rubber mulch, Water Air Soil Pollut. 229 (3) (2018).
[61] K. Schneider, A. Bierwisch, E. Kaiser, ERASSTRI-European risk assessment study on synthetic turf rubber infill–Part 3: exposure and risk characterisation, Sci. Total Environ. 718 (2020) 137721.
[62] K. Schneider, M. de Hoogd, P. Haxaire, A. Philipps, A. Bierwisch, E. Kaiser, ERASSTRI-european risk assessment study on synthetic turf rubber infill–part 2: migration and monitoring studies, Sci. Total Environ. 718 (2020) 137173.
[63] X. Li, W. Berger, C. Musante, M.I. Mattina, Characterization of substances released from crumb rubber material used on artificial turf fields, Chemosphere 80 (3) (2010) 279–285.
[64] S. Magnusson, J. Mácsik, Analysis of energy use and emissions of greenhouse gases, metals and organic substances from construction materials used for artificial turf, Resour. Conserv. Recycl. 122 (2017) 362–372.
[65] Z. Piao, M. Bueno, L.D. Poulikakos, S. Hellweg, Life cycle assessment of rubberized semi-dense asphalt pavements; A hybrid comparative approach, Resour. Conserv. Recycl. 176 (2022) 105950.
[66] J. Fiksel, B.R. Bakshi, A. Baral, E. Guerra, B. Dequervain (Eds.), Comparative life cycle assessment of beneficial applications for scrap tires, Clean Technol. Environ. Policy (2011).
[67] H. Cheng, Y. Hu, M. Reinhard, Environmental and health impacts of artificial turf: a review, Environ. Sci. Technol. 48 (4) (2014) 2114–2129.
[68] L.Y. Xie, K.C. Zhu, W.J. Jiang, H.D. Lu, H.Q. Yang, Y.X. Deng, et al., Toxic effects and primary source of the aged micro-sized artificial turf fragments and rubber particles: comparative studies on laboratory photoaging and actual field sampling, Environ. Int. 170 (2022).
[69] C.A. Graça, F. Rocha, F.O. Gomes, M.R. Rocha, V. Homem, A. Alves, et al., Presence of metals and metalloids in crumb rubber used as infill of worldwide synthetic turf pitches: exposure and risk assessment, Chemosphere 299 (2022) 134379.
[70] C.E. Donald, R.P. Scott, G. Wilson, P.D. Hoffman, K.A. Anderson, Artificial turf: chemical flux and development of silicone wristband partitioning coefficients, Air Quality Atmosphere and Health 12 (5) (2019) 597–611.
[71] B.T. Pavilonis, C.P. Weisel, B. Buckley, P.J. Lioy, Bioaccessibility and risk of exposure to metals and SVOCs in artificial turf field fill materials and fibers, Risk Anal. 34 (1) (2014) 44–55.
[72] M.E.J. Pronk, M. Woutersen, J.M.M. Herremans, Synthetic turf pitches with rubber granulate infill: are there health risks for people playing sports on such pitches? J. Expo. Sci. Environ. Epidemiol. 30 (3) (2020) 567–584.
[73] J.G.M. Van Rooij, F.J. Jongeneelen, Hydroxypyrene in urine of football players after playing on artificial sports field with tire crumb infill, Int. Arch. Occup. Environ. Health 83 (1) (2010) 105–110.
[74] N. Lopez-Galvez, J. Claude, P. Wong, A. Bradman, C. Hyland, R. Castorina, et al., Quantification and analysis of micro-level activities data from children aged 1–12 Years old for use in the assessments of exposure to recycled tire on turf and playgrounds, Int. J. Environ. Res. Publ. Health 19 (4) (2022) 2483.
[75] I. Nishi, T. Kawakami, S. Sakai, T. Obama, R. Kubota, K. Inoue, et al., Characterization of synthetic turf rubber granule infill in Japan: polyaromatic hydrocarbons and related compounds, Sci. Total Environ. 842 (2022) 156684.
[76] R. Kubota, T. Obama, T. Kawakami, S. Sakai, K. Inoue, Y. Ikarashi, Characterization of synthetic turf rubber granule infill in Japan: total content and migration of metals, Sci. Total Environ. 842 (2022) 156705.
[77] D. Armada, A. Martinez-Fernandez, M. Celeiro, T. Dagnac, M. Llompart, Assessment of the bioaccessibility of PAHs and other hazardous compounds present in recycled tire rubber employed in synthetic football fields, Sci. Total Environ. 857 (2023) 159485.
[78] M.K. Peterson, J.C. Lemay, S.P. Shubin, R.L. Prueitt, Comprehensive multipathway risk assessment of chemicals associated with recycled (" crumb") rubber in synthetic turf fields, Environ. Res. 160 (2018) 256–268.
[79] L. Marsili, D. Coppola, N. Bianchi, S. Maltese, M. Bianchi, M.C. Fossi, Release of polycyclic aromatic hydrocarbons and heavy metals from rubber crumb in synthetic turf fields: preliminary hazard assessment for athletes, J. Environ. Anal. Toxicol. 5 (2) (2015) 1–9.
[80] P. Castellano, A.R. Proietto, A. Gordiani, R. Ferrante, G. Tranfo, E. Paci, et al., Assessment of exposure to chemical agents in infill material for artificial turf soccer pitches: development and implementation of a survey protocol, Prevention Today 4 (3) (2008) 25–42.
[81] T. Kawakami, S. Sakai, T. Obama, R. Kubota, K. Inoue, Y. Ikarashi, Characterization of synthetic turf rubber granule infill in Japan: rubber additives and related compounds, Sci. Total Environ. 840 (2022) 156716.
[82] A. Bleyer, Synthetic turf fields, crumb rubber, and alleged cancer risk, Sports Med. 47 (12) (2017) 2437–2441.
[83] S. Kim, J.Y. Yang, H.H. Kim, I.Y. Yeo, D.C. Shin, Y.W. Lim, Health risk assessment of lead ingestion exposure by particle sizes in crumb rubber on artificial turf considering bioavailability, Environ Health Toxicol 27 (2012) e2012005.
[84] M.S. Abbas-Abadi, M. Kusenberg, H.M. Shirazi, B. Goshayeshi, K.M. Van Geem, Towards full recyclability of end-of-life tires: challenges and opportunities, J. Clean. Prod. 374 (2022) 134036.
[85] L.L. Trudsø, M.B. Nielsen, S.F. Hansen, K. Syberg, K. Kampmann, F.R. Khan, et al., The need for environmental regulation of tires: challenges and recommendations, Environ. Pollut. 311 (2022) 119974.