Journal of Environmental Management 319 (2022) 115716

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Review

Is asbestos still a problem in the world? A current review

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ARTICLE INFO

Keywords:
Asbestos
Hazardous waste
Public health
Environment

ABSTRACT

Asbestos has been used by automobile, construction, manufacturing, power, and chemical industries for many years due to its particular properties, i.e. high tensile strength, non-flammable, thermal and electrical resistance and stability, and chemical resistance. However, such a mineral causes harmful effects to human health, including different types of cancer (e.g., mesothelioma). As a result, the use of asbestos has been banned since the 1980s in many countries. Nonetheless, asbestos is still part of the daily life of the population as asbestos-containing materials (ACMs) are still present in many buildings constructed and renovated before the 1990s. This work aims to present a current literature review about asbestos. The literature review was composed mainly of research articles published in international journals from the medical and engineering disciplines to provide an overview of asbestos use effects reported in interdisciplinary areas. The literature review comprised asbestos characteristics and its relationship to the risks of human exposure, countries where asbestos use is permitted or banned, reducing asbestos in the built environment, and environmental impact due to use and disposal of asbestos. The main findings were that ACMs are still responsible for severe human diseases, particularly in areas where there is a lack of coordinated asbestos management plans, reduced awareness about asbestos health risks, or even a delay in the implementation of asbestos-ban. Such issues may be more prevailing in developing countries. The current research in many countries contemplates several methodologies and techniques to process ACMs into inert and recyclable materials. The identification and coordinated management of ACM hazardous waste is a significant challenge to be faced by countries, and its inadequate disposal causes severe risk of exposure to asbestos fibres. Based on this work, it was concluded that banning asbestos is indicated in all countries in the world.

1. Introduction

Asbestos has been widespread ever since the industrial age (Janela and Pereira, 2016), and due to its properties, figured for many years as an essential mineral for many activities (INCA, 2010). As a building material, asbestos was widely used prior to the 1970s (Leonelli et al., 2006; Bloise et al., 2018).

Since then, asbestos has been used in a wide range of manufactured goods, mostly in building materials (roofing, wall cladding, ceiling and floor tiles, insulation material, gutters, water tanks, pipelines, paper products, and asbestos cement products), friction products (automobile clutch, brake, and transmission parts), heat-resistant fabrics, packaging, gaskets, and coatings (EPA, 2021).

Asbestos refers to a group of fibrous silicate minerals including amphibole, chrysotile, amosite, and crocidolite (Mazzeo, 2018), but the asbestos definition depends on the subject and interest area. The United States Environmental Protection Agency (EPA) defines asbestos as a mineral fibre in rock or soil with heat resistance and fire-retardant properties (EPA, 2021). For the National Cancer Institute (NCI, 2021), asbestos is a group of minerals with minuscule fibres used as insulation against heat in buildings. The loose fibres of asbestos in free form can cause serious diseases, such as lung cancer and malignant mesothelioma when air with asbestos particles enters the respiratory system (NCI, 2021). Gastrointestinal tract cancer was also reported in the literature due to exposure through water (Cope et al., 2010; Neonila et al., 2012; Christensen, 2013).

Even known long ago, the diseases and health problems caused by asbestos were hidden or not considered (Janela and Pereira, 2016).

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https://doi.org/10.1016/j.jenvman.2022.115716
Received 7 March 2022; Received in revised form 27 June 2022; Accepted 8 July 2022
Available online 18 July 2022
0301-4797/

Moreover, EPA adds that asbestos-related diseases can be challenging to identify, and the symptoms may take many years to develop following exposure (EPA, 2021).

Workers who have experienced asbestos exposure have a very high chance of developing severe diseases as confirmed by some studies (Koskinen et al., 2002; Lange et al., 2008; Welch et al., 2015; Consonni et al., 2015; Tamura et al., 2018; Vimercati et al., 2019). Although workers may be exposed to low doses of asbestos, the constant frequency of exposure to asbestos fibres represents a considerable health risk (Binazzi et al., 2022).

Other activities in which there is an increased risk of asbestos exposure are mining, grinding and bagging asbestos-containing materials (ACMs), manufacturing asbestos-cement products and textiles with asbestos, which may lead to inhalation of asbestos fibres. Contact with contaminated clothes and objects with asbestos, living in the vicinity of asbestos factories, mines, contaminated areas, storage or disposal of asbestos-containing materials may also increase the risk of exposure to asbestos fibres (IARC, 2012).

In the first century A.D., the Roman historian Pliny noted that people wearing asbestos cloth sickened and died. In 1898, British factory safety inspectors showed concern about the harmful effects of asbestos dust. The Prudential Insurance Company in the United States published a study showing premature death in the asbestos industry in 1918, and in 1926 a worker with asbestos-related diseases claimed and won financial compensation from the Massachusetts Industrial Accidents Board (ADFA, 2021).

Afterwards, asbestos became the subject of health research, and its impacts have been associated with many diseases. Several countries classify asbestos as hazardous, and most of them have banned its use.

The scientific production within the asbestos subject is broad, however sometimes fragmented into different interdisciplinary fields, such as medicine and engineering. Besides, due to the vast literature available, it is not easy to follow the current state of the art.

This work aims to present a current literature review about asbestos. The literature review was composed mainly of research articles published in international journals (medicine and engineering) to provide an overview of the effects of asbestos use reported in interdisciplinary areas.

The work was divided into four sections:

i. Asbestos characteristics and its relationship to human exposure;
ii. Countries where asbestos use is permitted or banned;
iii. Reducing asbestos in the built environment;
iv. Environmental impact due to use and disposal of asbestos.

This work made it possible to assess the prevailing research findings and showed evidence on the areas that need more research to contribute to the ban of asbestos.

2. Asbestos characteristics and its relationship to human exposure

Evidence on the carcinogenicity of asbestos has been reported since the 1930s. The most recent assessment of the carcinogenicity of asbestos was carried out in 2009 and published in 2012 (IARC, 2012) by the International Agency for Research on Cancer (INCA, 2021).

Asbestos comprises a hydrated silicate of magnesium, iron, calcium and sodium, divided into two fibre groups. The groups are (i) serpentines, characterised by their curved shape under the microscope; and (ii) amphiboles that have a straight and rigid morphology (Castro et al., 2003). In the two asbestos groups, there are six types. The serpentine group includes chrysotile, while the amphibole group comprises crocidolite, amosite, anthophyllite asbestos, tremolite asbestos, and actinolite asbestos (IARC, 2012).

Table 1 shows the general characteristics and typical applications of asbestos. Knowing the asbestos applications in the past is essential to identifying the asbestos-containing materials so that these can be avoided and removed in a safe manner by proper abatement.

Table 1
Asbestos characteristics and applications (Based on ATSDR, 2001a; IARC, 2012; TRIMEDIA, 2015; INCA, 2021).

Name	Chemical formula	Colour	Common applications
Chrysotile (white asbestos)[a]	$[Mg_3Si_2O_5(OH)_4]_n$	White, grey, green, yellowish	Building materials, including cement, roofing materials, brake linings, home appliances, and protective clothing
Amosite (brown asbestos)[a]	$[(Mg,Fe^{2+})_7Si_8)O_{22}(OH)_2]_n$	Brown, green, greenish	Insulation materials and ceiling tiles
Tremolite (asbestos)[a]	$[Ca_2Mg_5Si_8O_{22}(OH)_2]_n$	White to pale green	Stucco, plasterboard, fireproofing materials, and other construction products
Actinolite (asbestos)[a]	$[Ca_2(Mg, Fe_5^{2+)}Si_8O_{22}(OH)_2]_n$	Green	Paints, drywall, and insulation
Anthophyllite (asbestos)[a]	$[(Mg,Fe^{2+})_7Si_8O_{22}(OH)_2]_n$	White green, grey-brown	Asbestos-containing cements and insulation
Crocidolite (blue asbestos)[a]	$[NaFe_2^{+3}Fe_3^{+2}Si_8O_{22}(OH)_2]$	Lavender, blue, green	Asbestos-cement production

[a] In parentheses - generic name.

As for the methods to undertake asbestos air testing and evaluate fibres size, Boulanger et al. (2014) assert that transmission electron microscopy (TEM) and phase-contrast microscopy (PCM) can be used. Scanning electron microscopy (SEM), as well as TEM, can differentiate between asbestos and non-asbestos fibres or different types of asbestos; and both methods can detect smaller fibres than PCM. Depending on the method, the results can be presented in different units, such as ng/m^3 (measured by midget impinger counting analysis), TEM f/mL (fibres measured by transmission electron microscopy), and PCM f/mL (fibres measured by phase-contrast microscopy) (ATSDR, 2001a). Another technique is polarised light microscopy (PLM), as well as methods using x-ray diffraction spectrometry (XRD) for identifying asbestos mineral phases and quantitative analysis (Kominsky et al., 2008). Table 2 shows the main characteristics of the methods.

The North American Agency for Toxic Substances and Disease Registry (ATSDR, 2001a) considers that the TEM method is more accurate and sensitive for measuring asbestos fibre content in the air. Ideally, TEM and SEM should be used rather than PCM, which cannot differentiate between asbestos and non-asbestos fibres or different types of asbestos.

It is essential to evaluate the fibres sizes and their relationship with the development of health diseases. According to the World Health Organization (WHO, 1986), asbestos fibres have a length greater than 5 μm, diameter less than 3 μm, with a defined aspect ratio (length of the particles divided by the width) greater than or equal to 3:1, that are long asbestos fibres. Many health agency regulations follow the WHO definition for asbestos fibres size. Boulanger et al. (2014) alert that short asbestos fibres (length (L) less than 5 μm; diameter (D) less than 3 μm and length/diameter ratio greater than 3) are not regarded as hazardous.

Considering that limit levels for asbestos exposure are established based on fibre size and concentrations, in general, following the WHO definitions, Boulanger et al. (2014) highlight that it is necessary to establish asbestos fibre dimensions properly. In their study, the authors observed the presence of short asbestos fibres (L less than 5 μm) with a concentration greater than or equal to 10 fibres.L^{-1} in air samples,

Table 2
Characteristics of the methods to evaluate fibres size (Based on ATSDR, 2001a; Kominsky et al., 2008).

Method	Uses	Characteristics
TEM[a]	Analysis of fibres in air or in bulk materials	Magnifications from about 5000 to 20,000 times or more, and fibres with diameters of about 0.01 µm can be detected
PCM[b]	Monitoring airborne levels of asbestos in the places where the fibre type is known	It detects fibrous materials but cannot distinguish asbestos fibres from others. Fibres are observed in a bright field at a magnification of 100–400 times. It detects fibres as thin as 0.25 µm in thickness
PLM[c]	Determining asbestos and other fibres, and minerals in bulk samples	Fibres are examined at magnifications 100–500 times and identified by their optical properties including morphology (characteristic shape), colour, refractive indices, birefringence, extinction angle, and sign of elongation
SEM[d]	Analysis of fibres in air or in bulk materials	Magnifications may range from 2000 to 20,000 times and higher. Detected fibres much thinner than by optical microscopy (PCM or PLM). An energy dispersive spectrometer EDS can be used in combination to detect the chemical composition of the fibres.

[a] TEM – Transmission electron microscopy.
[b] PCM – Phase contrast microscopy.
[c] PLM – Polarised light microscopy.
[d] SEM – Scanning electron microscopy.

showing the importance of measuring such fibres to detect air pollution and mitigate potential health risks.

Researchers also demonstrated this concern once fibre size distributions vary between industries and processes. The diseases associated with fibre size, in general, suggest that long and thin fibres may have a greater carcinogenic potential than shorter fibres (Gibbs and Hwang, 1980; Dement et al., 2008). Loomis et al. (2009a) complement that fibre size distribution must be evaluated.

Dement et al. (2008) and Loomis et al. (2009b) state that airborne asbestos fibres are usually shorter than 5 µm. However, most of the asbestos regulations enclose only fibres greater than 5 µm long (with a ratio of length to width equal to 3), excluding the evaluation of fibres less than 0.25 µm in diameter. This occurs mainly due to the low resolution of light microscopes and the PCM method as the standard procedure. As a result, regulatory compliances exclude a substantial fraction of asbestos fibres causing disease.

Based on a literature review, Loomis et al. (2009a) estimated the risk of lung cancer in textile manufacturing workers exposed to chrysotile. Different fibre lengths and diameters were measured using TEM. The authors reported that cumulative exposure to all fibres (every length and diameter) measured by TEM was notably associated with lung cancer, mainly when each dimension was considered separately. Also, the model for total TEM fibres did not fit as a model estimated by the PCM method. The risk of lung cancer among workers exposed to chrysotile increased with exposure to longer fibres (between 0.25 and 1.0 µm in diameter).

Gualtieri (2017) confirms that inhalable elements such as asbestos fibres with width less than 3 µm, length greater than 5 µm and aspect ratio greater than or equal to 1:3 (in this case, aspect ratio refers to the ratio between the largest and the smallest size) are hazardous to human health, and their evaluation is necessary to define the risks of getting asbestos-related diseases. Militello et al. (2020) assert that exposure to asbestos may cause adverse effects, but there is still a lack of an evident relationship between mineralogy and texture of fibres versus toxicity.

Berman and Crump (2003, 2008a, 2008b) provide extensive studies about asbestos exposure metrics, and some observations were pointed out. The limitations of the data available for characterising asbestos exposure led to restrictions on the metrics that can be currently evaluated. They observed that not all fibres included in the PCM exposure metric have similar potential. The research conducted by Berman and Crump (2003) showed that fibre length greater than 20 µm need to be differentiated from shorter fibres to adequately predict, for instance, the human cancer risk.

Berman et al. (1995) suggest that even though fibre length is considered more relevant than width, fibre width correlates best with biological activity. The measures have to be performed using methods with the accuracy required because the fibre width can be thinner than the PCM method can evaluate, which leads to difficulties in its direct relationship with diseases. Stayner et al. (1996) concluded that lung cancer was related to long fibres (greater than 10 µm) and thin (less than or equal to 0.25 µm) fibres, corroborated by Berman et al. (1995), that found that thin (less than or equal to 0.4 µm) fibres generated lung cancer potential in animals.

Detailed information provided by measurements on fibre size and type in environments must be improved to assist epidemiological studies. The development and improvements of exposure metrics are essential to acceptably support asbestos-related disease risk prediction (Berman and Crump, 2003).

Wylie et al. (1993) declare that asbestos cause lung cancer and pneumoconiosis; fibre width is also related to mesothelioma and respiratory diseases, so fibre width is an important parameter. The authors assert that fibres from a tenth to 200 µm long have been found in human lung tissue, and the narrow width of these fibres was responsible for their access to the human body. Fibres 15 µm long and 5 µm width meet the National Institute for Occupational Safety and Health (NIOSH) criteria; however, they are unlikely to cause disease in humans because they cannot access the lung. The research proposed that NIOSH fibre size parameters used in the quantification of asbestos be modified to include only particles longer than 5 µm with width less than 1 µm and that the aspect ratio criterion established by WHO (1986) be forsaken.

Lippmann (2014) associated the risk of asbestos-related disease with fibre sizes (D – diameter; L – length) as follows:

- Fibrosis: $D < 3.00$ µm and $L \geq 5$ µm;
- Mesothelioma: $D < 0.10$ µm and $L \geq 5$ µm;
- Lung cancer: $D < 0.15$ µm and $L \geq 10$ µm.

Barlow et al. (2017) conducted and also evaluated numerous researches, and concluded that fibre length is an essential factor in the pathogenicity of fibres and the size of fibre determines its residence time in the lung. The authors affirm that chemical and crystalline composition and fibre size parameters represent essential factors in defining asbestos exposure's toxicological and pathological effects. They assert that the data from literature reported that exposure to fibres longer than 10 µm and perhaps 20 µm is required to significantly increase the risk of developing an asbestos-related disease in humans, and the risk associated with exposure to fibres shorter than 5 µm is low.

The main places where asbestos pollution can be associated with human activities include buildings and areas connected with the asbestos-containing waste generation and illegal storage dumps of asbestos-containing waste. Human exposure can also occur in building structures, equipment, asbestos plants or local asbestos-containing products (Klojzy-Karczmarczyk et al., 2021).

Asbestos alone is the primary occupational carcinogen, accounting for most occupational lung diseases (Straif, 2008). Several scientific publications have reported the relationship between exposure to asbestos and incidence of asbestos-related diseases (Hein et al., 2007; Lenters et al., 2011; van der Bij et al., 2013; Nielsen et al., 2014; Menvielle et al., 2016; Olsson et al., 2017). The International Agency for Research and Cancer (IARC) included asbestos in Group 1 (carcinogenic to humans) because there is enough evidence to conclude that it can cause cancer in humans. The inhaling of asbestos fibres suspended in the air causes diseases such as pneumoconiosis (asbestosis), pleural changes, lung cancer, and mesotheliomas. Besides, the pathogenic effects of asbestos can appear even 60 years after exposure (IARC, 1987; IARC, 2002; IARC, 2012).

Asbestos-related disease rates vary according to the type of exposure and different fibre sizes (Becklake et al., 2007). Asbestos fibres deposited in terminal respiratory bronchioles and alveolar ducts result in inflammation that can lead to activation of fibroblasts, collagen deposition, development of autoimmunity and deoxyribonucleic acid (DNA) damage (Schinwald et al., 2012).

Although there is epidemiological evidence that the chrysotile is less toxic than amphiboles concerning the potential to induce mesotheliomas, all asbestos-related diseases are found in workers exposed to chrysotile, including an excess of mesotheliomas (Pira et al., 2017). The main problems and respiratory diseases associated with asbestos exposure are (Capelozzi, 2001; ATSDR, 2001b; Roggli et al., 2010):

- Pleural effusion – abnormal accumulation of fluid in the pleural cavity;
- Diffuse pleural thickening – visceral pleural disease, which can occur even in patients with minimal pulmonary fibrosis;
- Pleural plaques – damage to the tissue surrounding the lungs and the thoracic cavity;
- Round atelectasis – respiratory complication resulting from obstruction of a bronchus or lung, preventing the flow of air;
- Asbestosis – occurs due to excessive exposure to asbestos. It may affect people who live in or transit through areas with high levels of asbestos in the environment. It is characterised by cough, dyspnea, basilar rales inspiration and digital clubbing.

About 20% of lung cancer cases in developed countries are attributable to the work occupation (Straif, 2008), and asbestos is responsible for 4%–10% of these cases (Markowitz et al., 2013). The risk of lung cancer in workers exposed exclusively to chrysotile in mining was demonstrated by Liddell et al. (1997) and in textile manufacturing by Hein et al. (2007) and Elliott et al. (2011). In China, Courtice et al. (2016) and Wang et al. (2014) confirmed significant increases in the relative risk of death in workers with lung cancer by cumulative exposure to chrysotile. However, asbestosis is not an essential precondition for the attribution of cancer to asbestos exposure (Markowitz et al., 2013).

Due to its high specificity, mesothelioma is considered the "fingerprint" of the use of asbestos in society. Mesothelioma affects the pleura, peritoneum, pericardium and tunica vaginalis testis (INCA, 2021). Pleural mesothelioma is predominant (92.9%), followed by peritoneal (6.4%) (Marinaccio et al., 2012). On the other hand, a Brazilian study showed that 77.1% of the mortality was due to pleural mesothelioma, while 15.9% was peritoneal (Algranti et al., 2015). In Brazil, low death rates from mesothelioma, similar to countries that did not use asbestos, are strong signs of underreporting and under-registration of cases (Pedra et al., 2008; Algranti et al., 2015).

There is an increased risk of oesophagus, stomach and colorectal cancers associated with occupational asbestos exposure (Offermans et al., 2014). There were cases of gastric cancer in Chinese miners caused by chrysotile (Lin et al., 2014). Besides, a high risk of colorectal cancer was reported in French workers exposed to chrysotile and amphiboles (Clin et al., 2011). In general, the incidence rates of oesophagus, liver and colorectal cancers occurred when the exposure duration was longer than 25 years (Boulanger et al., 2015). In Italy, a study conducted with more than 50,000 workers exposed to asbestos showed not high digestive tract cancers rates (Ferrante et al., 2017).

Moreover, few authors assert that there are no studies on and evidence of adverse effects of asbestos in the water, for example, in the water conducted by asbestos cement pipes (Pyssa and Rokita, 2007; Klemczak and Biegańska, 2009).

Ervik et al. (2021) analysed asbestos fibres from a corrugated cement roof aged 60-year-old collected from a domestic house in Southern Norway. Many fibres found in the run-off water and the weathered roof debris sample demonstrated that exposed fibres are prone to be carried away by the wind into air and soil or be washed out by rainwater. The primary chemical element of the fibres was unaltered. Their main finding was that people have to take care when handling old corrugated asbestos cement roof because asbestos fibres might be released.

Klojzy-Karczmarczyk et al. (2021) asserted that the sources related to human activities generally occur in regions of high population density. In addition to workers directly exposed to asbestos, Airoldi et al. (2021) consider essential to assess the risk of people who live near asbestos mines and asbestos product plants developing diseases.

A research was carried out in a neighbourhood near an asbestos cement plant in Casale Monferrato (Northwest Italy), and the neighbouring people that were developing malignant mesothelioma were evaluated. The malignant mesothelioma cases were high up to 5 km from the asbestos plant, both for plant workers and neighbours (Fig. 1). For non-occupationally exposed subjects, some cases were possibly associated with asbestos materials used in the houses (Airoldi et al., 2021).

In Russia, asbestos is permitted, but there is also a concern about its toxicity. Scognamiglio et al. (2021) studied cryogenic milling of asbestos chrysotile. A length class of fibres (<5 μm and > 5 μm) was milled without modifying the crystal-chemical original properties. They achieved successive fibre length reduction through Scanning Electron Microscopy (SEM) images. Compared to the usual method applied for different size classes of fibres preparation, cryo-milling allowed rapid preparation of the two desired size classes without the need for further separation. The cryo-milling can contribute to less time of workers' exposure during asbestos production.

3. Countries where asbestos use is permitted or banned

The extensive use of asbestos has been due to properties such as versatility for application, low cost, high tensile strength, chemical and thermal stability, high flexibility, low electrical conductivity, and large surface area (Jo et al., 2017; USGS, 2021).

Nowadays, Brazil is still an asbestos producer and exporter and made extensive use of asbestos before 2017. Between 1940 and 2018, approximately 8.8 million tonnes of asbestos fibres were industrialised, producing more than 100 million tonnes of manufactured products (USGS, 2021).

Fig. 2 shows the countries with significant asbestos mine production in 2020. It can be observed that Russia has the highest production, followed by Kazakhstan and China.

In 2001, the Brazilian National Environment Council (CONAMA) recommended the progressive banning of chrysotile asbestos in the

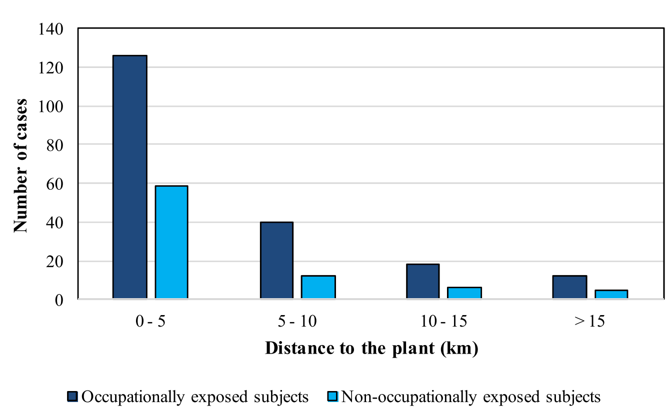


Fig. 1. Mesothelioma cases according to plant distance and exposure in Casale Monferrato, Italy (Based on Airoldi et al., 2021).

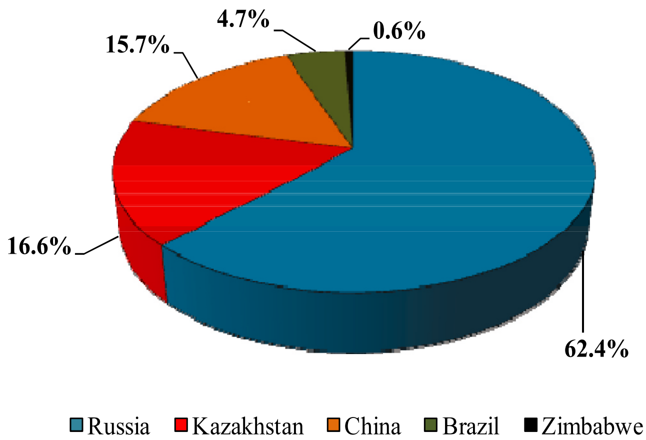


Fig. 2. Countries with significant asbestos mine production in 2020 (Based on USGS, 2021).

country, but the use of such a mineral was allowed until 2010. In 2009, the Ministry of Health, through Ordinance No. 1644, regulated by Ordinance No. 2669 of 2010, prohibited the use of any type of asbestos and products and by-products containing such fibres in Brazil (MS, 2010). However, only in 2017 the Federal Supreme Court banned the production, sale and use of chrysotile asbestos throughout Brazil (INCA, 2017).

Asbestos was banned in around 71 countries, albeit some still allow its use in products under regulations. It is estimated that 140 countries have no ban or restrictions for asbestos use (IBAS, 2021).

In the European Union (EU), a complete ban on every form of asbestos started in 1983 with all state members' expectation of adhesion until 2005 (AS, 2021). Table 3 shows the countries where asbestos was banned.

In 1989, the U.S. Environmental Protection Agency (EPA) issued the Asbestos Ban and Phase-Out Rule (ABPR) to impose a complete ban on asbestos-containing products. Manufacturers of asbestos products filed a lawsuit against the EPA, and in 1991, the Fifth Circuit Court of Appeals overturned the ban. Only spray-applied asbestos and some products (flooring felt, rollboard, commercial paper, corrugated paper and speciality paper) are banned in the United States. All other uses of asbestos, such as automotive brake pads and gaskets, roofing products and fireproof clothing, are legal (UKATA, 2016; Esquire, 2022). Russia, Thailand, Bali, India and Mexico have not banned asbestos yet (UKATA, 2016).

Table 3
Countries where asbestos was banned and the year it came into force (Based on AS, 2021).

Countries	Year
Denmark	1980
Norway, Israel	1984
Sweden	1986
Iceland, Italy	1992
Germany	1993
Kuwait	1995
Bahrain	1996
Saudi Arabia	1998
Djibouti	1999
Chile	2001
Uruguay	2002
Australia	2003
Gabon, Honduras, Mauritius	2004
Argentina, Chile, Egypt	2005
Jordan	2006
New Caledonia	2007
Oman, South Africa	2008
Seychelles, Algeria, South Korea	2009
Qatar, Mozambique, Taiwan, Turkey	2010
Israel, Serbia	2011
Japan	2012
Macedonia (North Macedonia)	2014
Moldova, Iraq, New Zealand	2016
Brazil, Ukraine	2017
Canada	2018

There are concerns about promoting guidelines for conservation purposes for fibre-cement panels used by artists in monumental works in the 1950s and 1960s in Mexico. For this, Pérez et al. (2021) analysed conservation strategies using industrial coating materials to reduce the disintegration of panel surfaces. The coating materials tested were acrylic resin, polyurethane resin and alkyd enamel. As a result, the polymer coatings did not suffer chemical degradation after the accelerated weathering exposure, but the weathering conditions caused physical changes. They concluded that alkyd enamel and acrylic resin affected the panels' colour and water absorption and are not indicated for panel's protection.

In the United States, to protect the worker's exposure, according to the Occupational Safety and Health Administration (OSHA), the Permissible Exposure Limit (PEL) for asbestos is 0.1 fibre per cubic centimetre of air as an 8-h time-weighted average (TWA), with an excursion limit (E.L.) of 1.0 asbestos fibre per cubic centimetre over 30 min (OSHA, 2021).

4. Reducing asbestos in the built environment

Researchers have been developing techniques to carry out on-site identification of asbestos and measurements of exposure of people to asbestos in their households and at work in several countries. Exposure to asbestos fibres is related to many severe lung diseases; hence, fast, accurate and reliable on-site asbestos detection is desirable (Zholobenko et al., 2021).

In Thailand, Phanprasit et al. (2012) evaluated and compared airborne asbestos concentrations that workers were exposed to when cutting asbestos cement roof sheets. The measures were performed in different places, and the roof sheets were cut using either a motor saw (variable speed) or a hand saw. The results showed that for a high-speed motor saw (1200 rpm) in a roof-shaded area and without any building nearby, the concentration was 12.4 fibres/cm^3, while using a hand saw it was 5.0 fibres/cm^3. While asbestos is permitted in Thailand, with easy access and the low cost it will continue to be used extensively. The government must create instruments to facilitate asbestos-substitute policies and strategic plans to reduce the use of asbestos in Thailand (Phanprasit et al., 2012).

Guo et al. (2010) add that asbestos-containing wastes are hazardous and have complex treatment due to the variety and different contents of asbestos in the materials produced with it. Table 4 shows some studies on asbestos waste treatments and recycling reported in the scientific literature. Such treatments and recycling would reduce the amount of asbestos in the built environment.

Currently, the dismantlement and removal have been prioritised in Korea asbestos management. Jung et al. (2021) consider it important to manage such a waste in public facilities and rural dwellings as well. Eight stabilisation treatments were compared through weathered corrugated asbestos cement sheets, and the potential in reducing asbestos fibre dispersion under different wind conditions was evaluated. The asbestos stabilisers used in the study were an inorganic stabiliser from Korea, three inorganic stabilisers from Australia and Japan, and four organic/synthetic stabilisers from Japan. The corrugated asbestos cement sheets were cut in samples of 200 × 200 mm, coated with a stabiliser and then tested. The wind tests were conducted in air erosion test equipment, applying 5 and 10 m/s wind speeds (average data from Korea Meteorological Administration). Airborne asbestos samples were collected from each specimen at a flow rate of 10 L/min for 1 h (Jung et al., 2021). As a result, the authors found that for wind speeds of 5 and

Table 4
Studies on asbestos waste treatments and recycling.

Reference	Country	Treatment description
Gualtieri and Tartaglia (2000)	Italy	Asbestos wastes were transformed to a mixture of non-hazardous silicate phases throughout a thermal treatment at 1000–1,250 °C and to a silicate glass at temperature greater than 1,250 °C, in which the recycled were used to produce ceramics.
Leonelli et al. (2006)	Italy	Through microwave thermal treatment, asbestos was transformed into non-hazardous silicate phases. The microwave process promoted the asbestos-containing waste inerting, and the recycled was introduced to produce porcelain stoneware tiles, porous single-fired wall tiles and ceramic bricks.
Zaremba and Peszko (2008)	Poland	The tubular structure was destroyed from thermal modification of chrysotile asbestos by calcination at 1000 °C. The potential of a mix of calcined asbestos with phosphate binder can be used in refractory materials (ceramics) production.
Guo et al. (2010)	China	A comprehensive literature review about the mechanochemistry applications in asbestos-containing waste management was provided.
Kusiorowski et al. (2012)	Poland	A method was applied to destroy the fibres of asbestos minerals by thermal treatment (temperatures 700-800 °C. The resulted materials presented high-grinding ability milled to pulverulent-shaped and can be used as raw materials in the ceramic industry.
Viani and Gualtieri (2014)	Italy	Asbestos-containing wastes were mixed with magnesium carbonate and calcined at 1100 and 1300 °C. Destruction of asbestos minerals was verified, bringing benefits in terms of energy requirements and preservation of natural resources in cement manufacturing.
Valouma et al. (2016)	Greece	The potential detoxification of pure chrysotile asbestos combined with oxalic acid dihydrate with silicates was evaluated. Amorphous silica was produced, and the combination encapsulated the asbestos fibres.
Mezhov et al. (2018)	Russia	Asbestos-containing waste was recycled through mechanochemical activation. The mortars produced with the treated waste was used for cement replacement (10%) and presented an increase of 20% in compressive strength.
Witek et al. (2019)	Poland	The authors investigated the aggregate production of asbestos waste by the fusion process in the electric arc-resistance process. The findings showed that the asbestos fibrous structure was destroyed, and the technology can be used to produce artificial aggregates.
Kieling et al. (2019)	Cuba	Mechanical characterisation of new composite material based on a polymeric matrix reinforced with particles of the bark of the seed of the tucumá tree (Astrocaryum Aculeatum) using asbestos-cement plates.
Łach et al. (2020)	Taiwan	The research was conducted to immobilise asbestos materials using geopolymers (fly ashes) for wastes storage in landfills. Although asbestos fibres do not dissolve during production, geopolymer materials can be an alternative to disposal asbestos-containing materials.
David et al. (2021)	France	Removal of asbestos cement by bioremediation involving the bacteria *Pseudomonas aeruginosa* to release iron from flocking asbestos waste through a siderophore-driven mechanism was studied.
Carneiro et al. (2021)	Brazil	The thermal treatment of asbestos cement waste to make it suitable as an alternative binder was optimised. The treatment was performed by calcining asbestos cement waste at 800 °C, completely removing chrysotile. The residue presented 40.42% of belite, providing its binding capacity.
Borges et al. (2022)	Brazil	An alternative mechanochemical method to treat asbestos-cement materials by loading them with potassium and phosphorus during the milling process to obtain a product used as liming and soil conditioner was investigated.

10 m/s, the concentrations of fibres dispersed in the samples coated with the stabilisers were significantly lower than the untreated ones (Fig. 3). For the wind speed of 5 m/s, the samples treated with an inorganic stabiliser presented low fibre concentration (0.44 μm). On the other hand, for the wind speed of 10 m/s, the lowest concentration was obtained for organic/synthetic stabiliser (22.6 μm). Therefore, the use of stabilisers would reduce asbestos fibre dispersion into the environment.

For Zhang et al. (2021), the liberation of asbestos fibres in old buildings during demolition or remodelling represents a concern due to health risks to building users and workers. In South Korea, there are initiatives to revitalise areas contaminated by asbestos-containing materials; however, the remained health risks in such areas must be identified.

In a research performed in Busan (South Korea), samples from 790 buildings were collected, and asbestos (chrysotile and amosite) was detected in 271 buildings (34.3%) (Zhang et al., 2021). The asbestos-containing materials identified in the 271 buildings are shown in Fig. 4.

In Italy, there are millions of square meters of asbestos cement roofing. The extensive use of asbestos due to its good thermal insulation properties, however, affects people's health. In order to contribute to meeting the Paris Agreement climate goals, Angelini and Silvestri (2022) performed a study and demonstrated that the cement binding in asbestos cement roofing cancels the asbestos insulation function. The proposal was to replace asbestos cement roofing with roofs made with alternative materials with better thermal transmission coefficients. Such a strategy would reduce the use of asbestos in Italy.

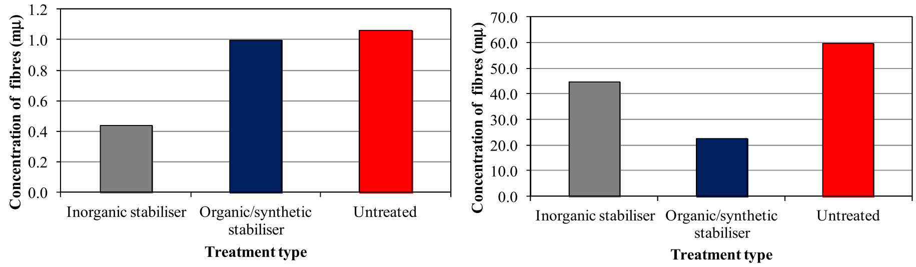
In Iran, asbestos is still used in brakes of cars. So, the hazardous material is dispersed in the air when the car is braked. In this scenario, Nasirzadeh et al. (2021) observed that workers in enclosed parking lots are exposed to asbestos. The authors collected and evaluated 35 air samples from six enclosed parking lots in Tabriz City (Iraq). The samples were analysed by phase-contrast microscopy, showing that the average asbestos fibre concentrations were 0.155 ± 0.069 fibres/cm^3, i.e. higher than the limit allowed in Iraq (0.1 fibres/cm^3). By using a scanning electron microscope and performing an energy-dispersive X-ray analysis it was possible to evaluate the fibre composition of 69.57% synthetic and 30.43% asbestos. Therefore, it is necessary to reduce the concentration of asbestos in such parking lots.

5. Environmental impact due to use and disposal of asbestos

Asbestos production, commercialisation and use are banned in many countries worldwide. However, there is still concern about disposing of the asbestos-containing waste. In general, the wastes come from products, demolitions, or old buildings where there is asbestos.

Hellawell and Hughes (2021) showed concern and alerted that asbestos still represents a hidden threat on many landfill sites. In the United Kingdom, prior to 2000, asbestos was used as a building material and insulator. However, asbestos wastes are still found in urban soil under demolition buildings and waste disposal sites, which leads to environmental impacts.

Proper asbestos waste management is required to avoid harmful effects on the workers, population, and environment. Nevertheless, asbestos waste management is not an easy assignment, comprising a series of steps, such as removal or reduction, packaging in containers, transport and inertisation treatment, or final disposal in hazardous waste landfills. Also, multiple inertisation treatments are necessary to shatter the asbestos fibrous structure. In general, final disposal occurs in



(a) Wind speed equal to 5 m/s (b) Wind speed equal to 10 m/s

Fig. 3. Fibres concentration according to treatment type and wind speed (Based on Jung et al., 2021).

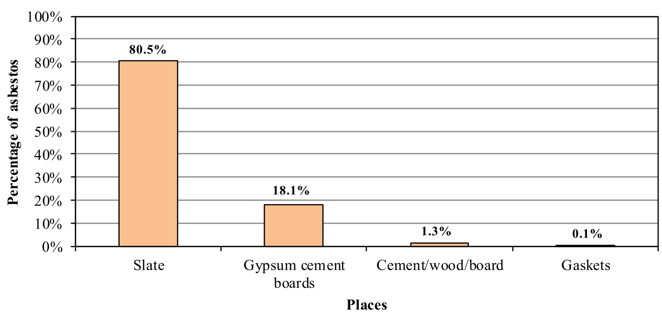


Fig. 4. Asbestos-containing materials in buildings in Busan, South Korea (Based on Zhang et al., 2021).

hazardous waste landfills (Mercadante et al., 2021).

The European Economic and Social Committee (EESC, 2015) warns that hazardous asbestos waste landfills is only a temporary solution, since over time, asbestos fibres are practically indestructible.

Mercadante et al. (2021) compared the environmental impacts of applying thermal vitrification, recycling in a clinker furnace, or final disposal of asbestos in a hazardous waste landfill in Argentina. The study was performed using Life Cycle Analysis (LCA), in which three different management scenarios of asbestos-containing waste management were evaluated:

- The asbestos-containing waste is transported and disposed of in a landfill, representing the current management system;
- Asbestos-containing waste undergoes thermal treatment using an electric kiln. The resulting by-product is a siliceous material disposed of in an inert landfill;
- Asbestos-containing waste is transported to a cement production plant, and part of it is incorporated into clinker production.

Asbestos-containing waste reused in cement plants proved to be the most convenient alternative from an environmental point of view. Beneficial effects of the circular economy were highlighted from the replacement of virgin materials with recycled ones; however, the alternative requires acceptance of cement manufacturing companies (Mercadante et al., 2021). The authors also recommended that the risk assessments be conducted using Life Cycle Cost (LCC) and Life Cycle Assessment (LCA) to have a complete outlook of management alternatives.

Asbestos levels and the risks associated with this contaminant in urban soil were evaluated by Hellawell and Hughes (2021). The research was conducted in Elmbridge (UK), where soil samples were tested to determine the asbestos presence and then the asbestos was quantified and evaluated. Fig. 5 shows the percentages of asbestos types found in the Elmbridge soil; the highest percentage was found for chrysotile asbestos. The authors also measured the form of the asbestos matrix, as shown in Fig. 6, where 71.5% were fibres.

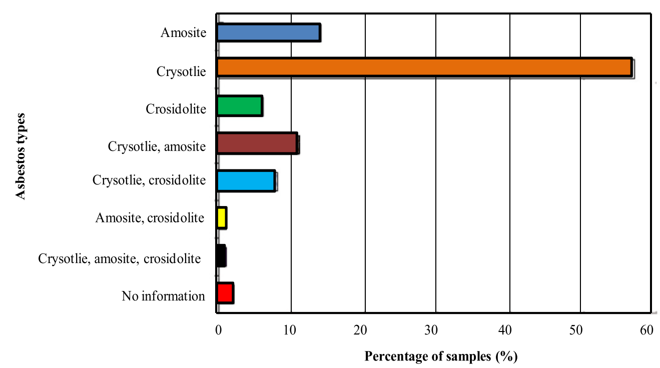


Fig. 5. Percentages of asbestos types found in the soil in Elmbridge (Based on Hellawell and Hughes, 2021).

Hellawell and Hughes (2021) stated that it is vital to identify urban soil contaminated by asbestos due to the health impacts of site workers and population. To afford adequate methods to treat and remediate the contaminated hazardous sites is an alternative to minimise the asbestos damage. The contaminated soil may be evaluated through site history, survey date, soil depth and asbestos type, form and concentration.

Once removed from buildings, asbestos and asbestos-containing materials are buried in hazardous-waste landfill sites. Then, the soil is extracted for a new building, and the people are exposed. However, this practice does not reduce the potential asbestos toxicity and will remain safe only as long as the deposits remain intact (Litvintseva, 2019).

Ajeel et al. (2021) measured the levels of asbestos fibres in the dense air sites of Baghdad (Iraq). Samples were collected using a filter, then the levels of asbestos fibres were analysed using a scanning electron microscope and an energy dispersive X-ray system. The results showed that

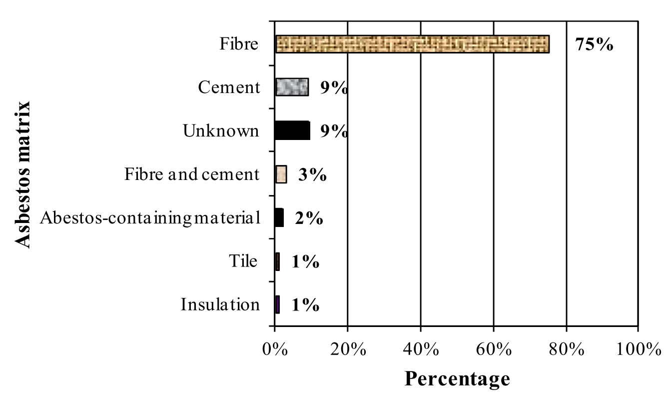


Fig. 6. Percentage of form of the asbestos matrix found in the soil in Elmbridge (Based on Hellawell and Hughes, 2021).

the concentration levels varied from 0.0352 fibre/ml to 0.156 fibre/ml. The average asbestos concentration in the ambient air was 0.0718 fibre/ml, exceeding the World Health Organization standards of 0.0022 fibre/ml.

Campopiano et al. (2021) estimated the number of schools in Rome (Italy) that have asbestos-containing materials and the level of risk for students' health. The schools were built between 1950 and 1980, a time when asbestos was added to every building material to increase durability and fire resistance in Italy. Out of 3672 schools, 1451 participated in the survey, in which 692 samples were collected and then evaluated using optical and electron microscope. Around 16% of the 1451 schools had asbestos-containing materials, but most of them were not accessible to students (water tanks, boiler thermal insulation). On the other hand, asbestos-containing materials were also found in vinyl floor tiles, equipment insulation linings and Bunsen burner gauze mats at science laboratories. Fig. 7 shows the percentage of school components that contain asbestos.

The Health and Safety Executive (HSE) in the UK provides asbestos disposal and management guidelines and considers that asbestos waste is hazardous when it contains more than 0.1% of the total material to be discarded. In order to avoid environmental impacts, there is proper packaging to dispose of asbestos-containing products in the UK (HSE, 2012).

The guideline EPA-414 sets out the minimum requirements for managing, safe handling and disposal of asbestos waste and asbestos-containing materials. Besides, EPA conceptualises asbestos-containing material as any material, object, product or debris that contains asbestos. Asbestos are also present in materials such as plastic sheeting used to cover surfaces in the asbestos work area, disposable coveralls, disposable respirators, rags used for cleaning. After the use, such material becomes asbestos wastes. EPA provides a list of non-friable asbestos disposal sites and waste depots (EPA, 2017).

Wallis et al. (2020) performed a literature review of three case studies about asbestos removal and disposal. Then, they introduced some treatment options. In the first case, "Mr Fluffy Asbestos Insulation in Australia", the authors report the studies from a project developed at the University of Canberra, Australia. They found that despite an excellent decontamination programme, large quantities of asbestos-contaminated soil remain, which need to be stored in hazardous landfills for the long term. The second case, "Asbestos-Contaminated Land in the Cook Islands", was performed in New Zealand through the UNITEC (Institute of Technology) project. The authors assert that this case study provided an example of an island nation without local hazardous landfill capacity and is highly restricted in its capability to export wastes. Also, high amounts of asbestos-contaminated material and soils cannot be addressed appropriately with the current options available. The University of Pennsylvania carried out the third case, "Asbestos Waste in Ambler, Pennsylvania (United States)". This case showed that industrial land contamination could lead to large areas that cannot be decontaminated, requiring unending management to prevent release due to erosion or human interference. In all cases, asbestos waste treatment was performed using expensive physical and chemical processes and evidenced that asbestos-contaminated soils remain an unresolved question (Wallis et al., 2020).

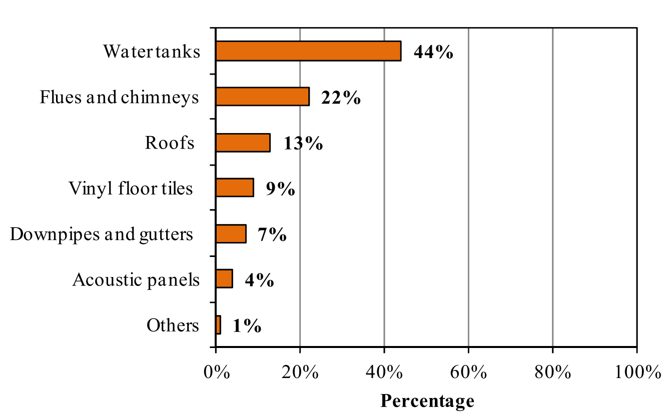


Fig. 7. Percentage of school components containing asbestos in Rome, Italy (Based on Campopiano et al., 2021).

Kameda et al. (2014) assert that the most efficient way to eliminate asbestos-related diseases is to stop using asbestos. The Brazilian National Cancer Institute suggests the following strategies to eliminate the use of asbestos (INCA, 2021):

- Recognise the need to stop using all types of asbestos;
- Provide solutions to replace asbestos with safer agents and develop economic and technological resources to stimulate such a replacement;
- Take necessary actions to avoid exposure to asbestos on-site and during the removal of contaminated waste;
- Improve early diagnosis, treatment and rehabilitation services for asbestos-related illnesses and implement registries for people with a history of asbestos exposure.

Nowadays, ACMs still contaminate the environment and affect people's health. The asbestos ban and ACMs management could avoid illnesses and deaths (LaDou et al., 2010).

Çorapçioğlu and Oymael (2021) state that there are many types of research related to asbestos, such as mitigation use, harmful environmental effects of building demolition, waste sorting and recycling, waste management and improvements to air quality.

After the asbestos ban and the irreversible problems arising from its use, the actions that could assure a future habitable and sustainable environment are as follows (Çorapçioğlu and Oymael, 2021):

- Create environmental awareness through education and joint actions by society, governmental and non-governmental organisations;
- Ensure compliance with legislation and improvement of mechanisms for practical oversight;
- Improve recycling and disposal processes;
- Consider the asbestos factor in air-quality measurements;
- Measure asbestos concentrations in places where workers are exposed, complying with the limits allowed;
- Promote interdisciplinary researches to identify the impact of demolitions and diseases caused by asbestos;
- Promote the mapping of asbestos sources.

6. Conclusions

This work presented a current literature review about asbestos. Different research data developed globally allows to assert that asbestos is responsible for several types of cancer and represents a risk to public health. However, many countries still use asbestos, including the United States of America and Russia. On the other hand, there are several alternatives to reduce the environmental impact generated by the use of asbestos.

There are also three significant challenges the world has to face regarding asbestos. First, asbestos is still present in the existing buildings constructed or renovated before asbestos-bans. Second, the development of methods to recover soil contaminated by asbestos-containing products. Last, the asbestos disposal and its impact on the environment. Asbestos mining is still present in developing countries, where asbestos-bans underpinned by coordinated asbestos hazardous waste management strategies will be critical to prevent public health risks. Therefore, asbestos is still a problem in the world, particularly in developing countries and where asbestos-bans as coordinated management plans have not been implemented.

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.

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