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A systematic review of outdoor airborne asbestos concentrations in urban and rural areas

Marcus Kjær Sørensen [a,c,*], Laura Deen [a], Georges Khoury [a,c], Jonathan Aavang Petersen [a,b], Jane Frølund Thomsen [a,b], Torunn Kringlen Ervik [d], Peter Møller [b], Sandra Søgaard Tøttenborg [a,b], Harald William Meyer [a], Kajsa Ugelvig Petersen [a], Luise Mølenberg Begtrup [a,b], Esben Meulengracht Flachs [a], Ingrid Sivesind Mehlum [a,b,d], Regitze Sølling Wils [a]

[a] Department of Occupational and Environmental Medicine, Copenhagen University Hospital - Bispebjerg and Frederiksberg Hospital, Copenhagen NV 2400, Denmark
[b] Department of Public Health, Section of Environmental Health, University of Copenhagen, Copenhagen K 1014, Denmark
[c] Department of Public Health, University of Copenhagen, Copenhagen K 1353, Denmark
[d] The National Institute of Occupational Health (STAMI), Oslo 0304, Norway

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ABSTRACT

Asbestos is a group of minerals that, due to their distinctive physical properties, has been widely used across numerous industries. The extensive historical global use together with the persistence of the fibers, have led to their widespread presence in various environments. The degradation of asbestos-containing materials, such as asbestos-cement sheets for roofing, may contribute to the dispersion of asbestos fibers into the ambient air. Asbestos is carcinogenic, and low levels of exposure in the environment have been linked to cancer.

The objective of this review is to investigate to what extent populations may be exposed to outdoor airborne asbestos in urban and rural areas, where asbestos-containing materials in buildings or asbestos-containing automobile parts are the main sources. We identified relevant studies by searching in three databases: PubMed, EMBASE, and Web of Science. Included studies were required to provide a predefined set of details regarding the sampling procedures and analytical methods employed. Studies were excluded if measurements had been conducted in areas with nearby asbestos-related industries or high levels of natural occurrence of asbestos.

We identified 22 articles about airborne asbestos concentration in the outdoor environment, of which nine presumed asbestos-containing materials from buildings to be the main source. Our review indicates that low, but non-negligible, levels of airborne asbestos fibers may be present in the outdoor environment. The review highlights the need for further research into the levels of airborne asbestos in rural and urban areas, as well as the need for standardized methods to measure environmental exposure.

1. Introduction

Asbestos refers to a group of six naturally occurring fibrous silicate minerals, that are classified into either serpentine or amphibole fibers according to the chemical composition and morphology (Ross *et al.*, 2008; Pira *et al.*, 2018; Sahin and Koksal, 2023). Chrysotile, commonly known as white asbestos, belongs to the serpentine family. The chrysotile fibers crystallize as rolled-up sheets, resulting in curved and flexible fibers (Ross *et al.*, 2008; Sahin and Koksal, 2023). Amphiboles comprise five types of asbestos: Crocidolite, amosite, actinolite, tremolite, and anthophyllite. Amphibole fibers have a more rigid structure, and their growth is restricted to a single direction, causing them to form long chains or needle-like fibers (Ross *et al.*, 2008; Sahin and Koksal, 2023). Amphibole fibers are chemically more stable and considered more hazardous than chrysotile fibers (Ross *et al.*, 2008; Sahin and Koksal, 2023). The most common type of asbestos used commercially is chrysotile, accounting for 90-95%, followed by amosite and crocidolite (World Health Organization et al., 2014; Pira et al., 2018; Sahin and

* Corresponding author.
E-mail address: marcus.kjaer.soerensen@regionh.dk (M.K. Sørensen).

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Koksal, 2023).

Asbestos fibers have extraordinary tensile strength, durability, and resistance to heat (Ross et al., 2008; Pira et al., 2018; Sahin and Koksal, 2023). Due to these unique physical properties, asbestos has been widely used in various industries worldwide (Virta, 2006). Asbestos has been used predominantly in construction materials, including thermal insulation, as well as in cement products to enhance durability and fire resistance. Some of the widely used asbestos-cement products include roofing sheets, wall panels, floor tiles, ventilation ducts, and pipes (WHO and Chemical Safety and Health Unit, 2014; Pira et al., 2018; Sahin and Koksal, 2023). The content of asbestos may vary in these products depending on different production practices and use of additives across countries (Kusiorowski *et al.*, 2024; Macher *et al.*, 2024). Furthermore, asbestos has been widely used in abrasive products such as automotive brake pads and clutches (WHO and Chemical Safety and Health Unit, 2014; Pira et al., 2018; Sahin and Koksal, 2023). During the 20th century, the global production and consumption of asbestos gradually increased and peaked in the 1970's with an estimated annual production of more than 4.5 million tons asbestos worldwide (Virta, 2006). This extensive global use together with the persistence of the fibers, has led to their widespread presence in urban and rural environments (Krówczyńska and Wilk, 2018a; Peña-Castro, Montero-Acosta and Saba, 2023).

The International Agency for Research on Cancer (IARC) has evaluated the scientific evidence and classified asbestos exposure as carcinogenic to humans (i.e., Group 1) (IARC, 2012). According to the IARC evaluation, there is sufficient scientific evidence to conclude that exposure to all forms of asbestos can cause malignant mesothelioma and cancer of the lung, larynx, and ovary (IARC, 2012). Moreover, exposure to asbestos may cause lung fibrosis (asbestosis) and other pleural diseases, including pleural plaques and thickening (Jamrozik, de Klerk and Musk, 2011). According to the WHO, exposure to asbestos causes more than 200,000 deaths globally each year (WHO, 2024). There is a long latency period between asbestos exposure and disease development, often decades, which means asbestos-related diseases may continue to emerge, even in countries that have banned its use decades ago (WHO, 2024). Notably, the global incidence of new mesothelioma cases increased from 1990-2017, with 34,615 cases identified in 2017 in the Global Burden of Disease 2017 database (Zhai *et al.*, 2021).

The WHO distinguishes between occupational and non-occupational asbestos exposure (WHO, 2000). Occupational exposure may occur in any workplace involving the direct or indirect handling of asbestos such as the extraction/processing in mining areas as well as manufacturing, maintaining, or repairing and removing asbestos-containing products (WHO, 2014; Krówczyńska and Wilk, 2018a; Peña-Castro, Montero-Acosta and Saba, 2023). Non-occupational exposure is a broad term that encompasses several types of exposures outside of work including environmental exposure (Peña-Castro, Montero-Acosta and Saba, 2023). Environmental exposure is often subdivided based on source: exposure from 'Naturally Occurring Asbestos' (NOA), exposure due to proximity to asbestos-related industries (e.g., asbestos-cement manufacturing plants) or exposure through the use of commercial products containing asbestos (WHO, 2014; Krówczyńska and Wilk, 2018a; Peña-Castro, Montero-Acosta and Saba, 2023). NOA refers to asbestos found locally in soil and natural rock formations, where asbestos fibers may be released into the air through natural weathering or human activities (e.g., mining) (Peña-Castro, Montero-Acosta and Saba, 2023; Metintas, Ak and Metintas, 2024). The widespread use of asbestos-containing materials (ACMs) in buildings may be the dominant source of exposure in urban and industrial areas, particularly in countries, where asbestos use is already prohibited or subject to regulations (Krówczyńska and Wilk, 2018a; Kottek and Yuen, 2021). ACMs tend to degrade due to the corrosion process caused by deconstruction, mechanical damages, and natural weathering (Campopiano *et al.*, 2009; Ervik, Eriksen Hammer and Graff, 2021; Kottek and Yuen, 2021). Studies have shown that climatic and environmental exposure, such as rainwater, acidic rain, and atmospheric pollution, lead to the weathering of asbestos-cement products (Spurny, 1989; Ervik, Eriksen Hammer and Graff, 2021). Loosely bound asbestos fibers to weathered asbestos-cement roofing can be carried away by the wind into the ambient air, where they are inhaled, or the fibers are washed off by rainwater, thereby being transported into the surrounding soil and environment (Ervik, Eriksen Hammer and Graff, 2021). The degradation of especially asbestos-cement sheets for roofing contributes to low emissions of asbestos fibers into the ambient air (Spurny, 1989; Krówczyńska and Wilk, 2018a; Lee and Kim, 2021). The dispersion of asbestos fibers into the environment impact therefore more than just human health; contamination of irrigation water and soil can induce toxic stress in plants and negatively affect their growth (Trivedi and Ahmad, 2011; Macher, Torma and Beke, 2025).

Long-term non-occupational exposure to low concentrations of asbestos in the outdoor environment may cause negative health effects (Goldberg and Luce, 2009; WHO and Chemical Safety and Health Unit, 2014). Several epidemiological studies have shown that environmental exposure to asbestos is associated with increased incidence and mortality rates of mesothelioma (Krówczyńska and Wilk, 2018a; Dalsgaard et al., 2019, 2021). Among these, two Danish studies showed an excess risk of mesothelioma in children who attended school in neighborhoods near an asbestos-cement manufacturing plant (Dalsgaard *et al.*, 2019, 2021). In 2014, the WHO stated that even low levels of exposure have been linked to cancer, and there is no evidence of a safe threshold for the carcinogenic effects of asbestos (WHO and Chemical Safety and Health Unit, 2014). Hence, it is imperative to investigate to what extent populations are exposed to asbestos in the environment.

1.1. Analytical methods of air samples

There are various analytical and sampling methods with different standard criteria to measure airborne asbestos concentrations. This can introduce bias and make results across studies difficult to compare. The WHO defines respirable asbestos fibers as particles with a length greater than 5 μm, a diameter (D) smaller than 3 μm, and a length-to-diameter ratio of 3:1 or higher (WHO, 1997).

There are three main microscopic techniques used for quantifying airborne asbestos concentrations: phase-contrast microscopy (PCM), transmission electron microscopy (TEM), and scanning electron microscopy (SEM) (Andrews and Fey O'connor, 2020; Health and Safety Executive [HSE], 2021). With PCM, samples are analyzed by standard optical microscopy, while the other methods rely on electron microscopy. SEM and TEM are often combined with energy dispersive X-ray spectroscopy ('TEM-EDX' or 'SEM-EDX'), which can determine the chemical composition of the fibers and thereby separate asbestos fibers from non-asbestos fibers. With PCM it is not possible to obtain chemical information on fibers on its own, and as a result, the method is not specific to asbestos fibers. However, it is possible to combine PCM with polarized light microscopy (PCM-PLM) to distinguish between asbestos and non-asbestos fibers and quantify the type of asbestos fibers. Electron microscopy offers the advantage of higher resolution than PCM, making it possible to identify fibers with $D<0.2$ μm. PCM is a less expensive method compared to electron microscopy, standardized with many years of experience. Contrarily, TEM and SEM are rather expensive, more time-consuming, and require higher level of training for operators (Andrews and Fey O'connor, 2020; HSE, 2021).

1.2. Aim and scope of the review

The aim of this systematic review is to synthesize and evaluate existing literature on airborne asbestos levels measured in outdoor environments without asbestos-related industries nearby or the presence of high levels of NOA. It is important to investigate to what extent the population may be exposed to asbestos in environments, where the source of asbestos fibers is diffuse, such as ACMs in buildings or asbestos-containing automobile parts. The main research question is: What does the existing literature indicate about outdoor airborne asbestos levels in rural and urban areas within these environmental settings? In this review, we also provide a critical evaluation of the analytical methods employed in the monitoring studies, along with suggestions for future research for measuring the levels of airborne asbestos in the environment. Furthermore, the levels of airborne asbestos fibers in relation to health issues will be discussed.

2. Methods

This is a systematic review and narrative synthesis of airborne asbestos in rural and urban areas. We conducted a comprehensive search of relevant databases to identify studies that addressed the aim. We then screened the yielded studies and included those that met the pre-defined eligibility criteria. Data deemed relevant from the included studies were then extracted and used to create a systematic overview to provide a critical review. The systematic review follows the Preferred Reporting Items for Systematic Review and Meta-analysis (PRISMA) guidelines (Supplementary Table 1).

2.1. Literature search

Relevant studies were identified and retrieved by conducting systematic searches in three databases: PubMed, EMBASE, and Web of Science. In addition, reference list from previous literature reviews were reviewed and added to the overall pool of articles via Google Scholar. We used three aspects of searching in all the databases: Exposure, type of measurement, and identification methods. The three aspects were combined in the final search string (see Fig. 1).

2.2. Eligibility criteria

The inclusion and exclusion criteria were predefined according to the aim of the review and shown in detail in the Supplementary Table 2. In short, we included peer-reviewed and published monitoring studies involving primary or secondary data collection and analysis with airborne asbestos quantification in the outdoor environment. Secondary data refers to existing data that was originally collected for other purposes. The review only included studies in English. At a minimum, included studies should have measurements in either urban, residential, industrial, or rural areas. Studies were excluded if all measurements had been conducted in areas with a known nearby asbestos-related industrial source or high levels of NOA as the primary source of airborne asbestos. In addition, studies were excluded if all measurements had been conducted in a context of a disastrous event (e.g., an earthquake or the collapse of the World Trade Center). Only studies that counted fibers according to the WHO size criteria were included (WHO, 1997). At a minimum, included studies were required to provide information on fiber size, number of samples, analytical method employed (e.g., SEM), and the standards applied for sampling and identification of asbestos fibers (e.g., NIOSH 7400).

2.3. Selection process

We used the web-based tool, Covidence, to manage and conduct systematic reviews for screening and data extraction (Veritas Health Innovation, 2024). The selection process involved two steps; title and abstract screening and full-text screening. The screening procedure was tested and modified prior to each step. The articles were screened independently by two reviewers in both steps. Two of the authors conducted the title and abstract screening and met after finishing the screening process to discuss disagreements. If required, a third reviewer was consulted to solve disagreements. Full-text screening was then conducted by two authors, and a third coder reviewed the disagreements between the two reviewers and made the final decision on whether to include or exclude the articles for data extraction. Fig. 2 shows the PRISMA flow diagram.

2.4. Data extraction

We developed a standardized template for data extraction, ensuring consistent and systematic collection of relevant information across all studies. Data were extracted on the number of samples and sampling sites and location of sampling including type of environment (urban, residential, industrial, rural, or other). Extracted information on

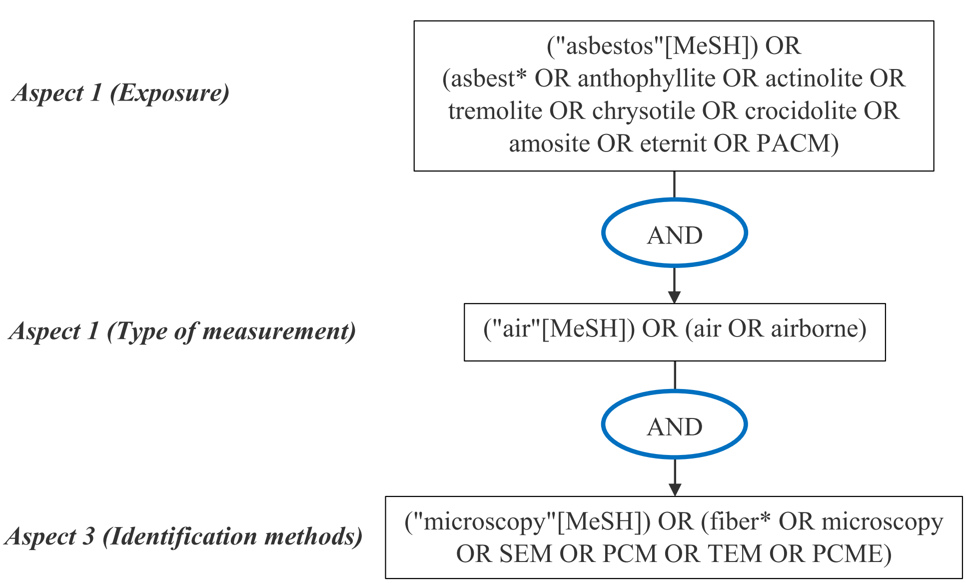

Fig. 1. Search string in PubMed
The figure illustrates the search string used to identify and retrieve relevant studies for the systematic review. PubMed was searched with 'MeSH' and 'free text words' within the three different aspects as presented in fig. 1, whereas Embase was searched with 'subject headings' and 'all fields'. Web of science was searched only with "all fields". The studies yielded from the final search string were imported to the web-based tool, Covidence, 19 June 2024.
*PACM, presumed asbestos-containing material; SEM, scanning electron microscopy; PCM, phase-contrast microscopy; TEM, transmission electron microscopy; PCME, phased contrast microscopy equivalent.

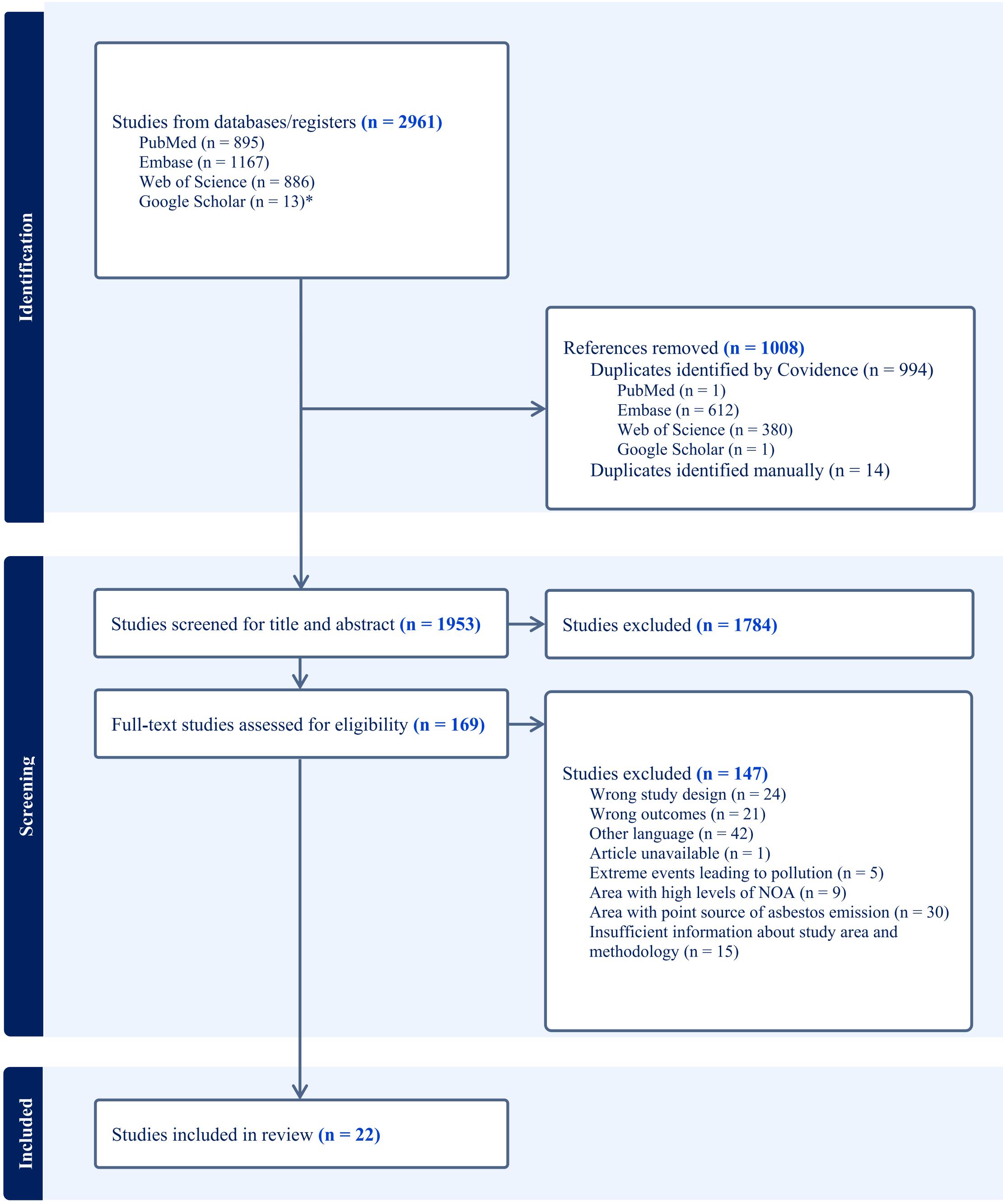

Fig. 2. Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) Flow Diagram
NOA, Natural occurring asbestos, *Only one of the studies from Google Scholar was included in the review.
The PRISMA Flow Diagram was automatically generated by the web-based tool, Covidence, after the screening process was completed (Veritas Health Innovation, 2024). The diagram provides an overview of the screening process in the systematic review. .

asbestos concentrations included mean and range of airborne asbestos concentration, and whether fibers below 0.2 µm in diameter were measured. Data were also extracted on analysis method (e.g., PCM), height of measurements above floor level, and the limit of detection (LOD). Details on weather, season, time interval and the correlation with airborne asbestos concentration were noted, but they were addressed only briefly and descriptively in the results. Additionally, it was recorded if the authors mentioned that the use of asbestos-containing brake pads and clutches was still in use in the study area. When available, the authors' hypotheses on what sources that might have contributed to asbestos pollution were reported.

2.5. Data presentation

The findings from the included studies are presented descriptively. Studies conducted in regions, where asbestos emissions are mainly attributed to the presence of buildings with ACMs, are described in greater details. This includes presenting the characteristics of the study area, the methods employed, the airborne asbestos concentrations including other major findings, as well as the potential source of pollution. There are no well-established standardized guidelines for systematically evaluating the quality of studies monitoring airborne asbestos fibers in the outdoor environment. To ensure a certain level of quality of the studies, we established criteria on minimum information available (see section 2.2.).

3. Results

3.1. Study selection

The database searches yielded 2,948 records and 13 records were added via Google Scholar (n = 2,961) (Fig. 2). After removing duplicates, 1,953 studies underwent title and abstract screening. Out of 169 full-text studies, which were assessed for eligibility, a total of 22 studies were included for data extraction.

The included studies were categorized into two groups according to the primary sources of asbestos emission in the study area. In the main group, comprising nine studies, asbestos emissions were primarily attributed to buildings with ACMs either due to renovation, demolition, or corrosion (Table 1 and Fig. 3). The remaining 13 studies comprised a secondary group of studies conducted in areas, where asbestos-containing brake pads and clutches were still in use (Table 2 and Fig. 4). Therefore, emissions from vehicular traffic were assumed to have contributed significantly to the airborne asbestos concentrations in these studies.

3.2. Studies measuring asbestos concentration in outdoor air samples

In the main group, four out of the nine studies were conducted in rural and urban environments in Poland, where asbestos has been widely used in construction materials such as corrugated roofing and cladding panels on buildings. According to Krakowiak et al. (2009), the total amount of asbestos products in Poland is approximately 15 million tons, of which 96% occurs in the form of asbestos-cement sheets. Below are the main findings in each study briefly summarized.

Krakowiak et al. (2009) investigated the concentration of airborne asbestos in Sosnowiec (Poland), a city with approximately 190,000 inhabitants. It was estimated that about 98% of building materials (roof and elevation covers) from single-family homes, residential blocks, and public and manufacturing sector buildings contained asbestos. Sampling sites were chosen based on proximity to ACMs with various degrees of corrosion. However, the height of measurements was unknown. The concentration was determined by PCM and additionally proved by SEM-EDX analysis. In 51 out of 100 air samples, the asbestos concentration was below the LOD of 1,000 f/m^3. For the rest of the samples, the concentrations varied from 1,000-9,000 f/m^3. These respirable fibers were identified as crocidolite and chrysotile. The highest concentration was observed in the immediate vicinity of buildings with ACMs with an average of 1,800 f/m^3 (<LOD-9,000 f/m^3). The average concentration was below the LOD at sites located 100-500 meters from buildings with ACMs or sites assumed to be free of ACMs. Data showed that high wind velocity significantly increased the levels of airborne asbestos fibers only at sites located at the distance of 100-500 m from the buildings with ACMs.

Szeszenia-Dąbrowska et al. (2012) analyzed a larger number of air samples in residential and urban areas in all provinces of Poland as part of the government's program for eliminating asbestos. A minor proportion of these samples (n = 380) were collected in areas with a former asbestos-cement plant nearby and areas that had recently been afflicted by a hurricane. Results from these sample sites were excluded in this review according to our eligibility criteria. The other 5,582 samples from 1,511 sample sites were collected at a height of 1.5 meter above floor level and analyzed by PCM-PLM. The mean asbestos fiber concentration all over Poland was 472 f/m^3. In 120 out of the total sampling sites (7.9%), the concentration was below the LOD of 180 f/m^3. Based on data regarding the import and consumption of asbestos, results indicated that an increase in asbestos consumption by 1 ton/km^2 in each province resulted in mean asbestos fiber concentration increase of 50 f/m^3. However, this was based on all air samples. The authors reported that the environmental pollution with asbestos was mostly due to release of asbestos fibers from asbestos-containing construction elements in buildings.

In the remaining two Polish studies, Pawełczyk and Božek (2015) and Buczaj et al. (2014), all measurements were performed using PCM. The height of measurements above floor level was unknown. Pawełczyk and Božek (2015) collected 60 air samples in 20 towns of southwest Poland. In each city, one sampling site was located in a neighborhood of busy crossroads in the town center. In this study, airborne fibers were measured three times during a day. The fiber concentration ranged from 141 f/m^3 to almost 1,700 f/m^3. The lowest concentration was observed in small cities and the highest in large cities. Generally, the highest concentrations were found during rush hours. In 21 out of 60 air samples the fiber concentration was below 200 f/m^3, and only in three spots did it exceed 1,000 f/m^3.

Buczaj et al. (2014) investigated the concentrations of airborne asbestos in the rural environment of the Lublin Region in south-east Poland at three different types of farms. The roofing of each farm was rated according to the technical condition of the ACMs, which mainly depended on degree of wastage and lack of protective layers. At each farm, the researchers collected 72 samples at three different sites within a few meters from the buildings during 2009-2011. The lowest mean of fiber concentration (30 f/m^3) was obtained on farm C, where there were no asbestos products. Farm A had good technical condition of asbestos-cement used for roofing, where the average concentration was 328 f/m^3. The highest average concentration (529 f/m^3) was noted on Farm B, which had poor technical condition of asbestos-roof. No asbestos fibers were found in 24% of the samples at Farm A, 10% of the samples at Farm B, and 71% of the samples at Farm C.

The remaining studies in the main group consisted of two studies from Italy, one study from South Korea, and two studies from China. Capella et al. (2020) investigated the airborne asbestos concentration in urban areas of Turin in Italy during two campaigns in 2014 and 2016. Turin does not house any asbestos-producing factories, but asbestos containing roofs and other ACMs are abundant. Natural sources (i.e., rocks) containing NOA surround the city. In total, 48 air samples were collected at a height of 1.5 meter above floor level in 24 districts of Turin city. All samples were analyzed with SEM-EDX. Crocidolite and anthophyllite asbestos, which are common in many ACMs, were not detected in any samples. The average concentration of chrysotile asbestos was 7, 500 f/m^3 and 2,700 f/m^3 in 2014 and 2016, respectively. Their presence was attributed to dispersion both from natural and anthropogenic sources (i.e., ACMs). However, it was uncertain which of the two types of sources contributed most to the airborne asbestos levels. The average concentration of tremolite/actinolite asbestos was 600 f/m^3. Since these asbestos fibers have not been industrially and commercially used in Italy, their presence in air is related to the dispersion from natural sources. The presence of tremolite/actinolite in air also correlated with wind direction that transports the mineral fibers dispersed from the outcropping rocks containing them.

Gualtieri et al. (2009) investigated the airborne asbestos concentration in urban and industrial areas of the region Emilia-Romagna in Italy. The authors collected air samples in different types of environments including industrial areas with roofing made from ACM, but also included clean zones to establish a background level of airborne asbestos. In this review, we have exclusively reviewed the samples collected in areas without NOA or potential major industrial sources of asbestos emission (e.g., storage center for special waste). At each site, a high flow sampling system collected at six locations continuously for one week in each season, and the concentration was then determined by SEM and TEM. The measurement heights were unknown. Asbestos fibers were not detected in four of the sample sites. Three of these sites where clean areas and the fourth site was located nearby a large bowling ground with asbestos roofing. At two other sites, the average concentration ranged from 7-13 f/m^3. These sites were located within 1-50 meters from two ceramic tile production plants with large buildings with up to around 50,000 m^2 of roofing in cement-asbestos.

Table 1
Studies in outdoor environments on airborne asbestos levels primarily attributed to buildings with asbestos-containing materials.

Ref.	Sample Year	Method (s)	Country	City/ Region	Study Area	Samples N.	Sample Sites N.	Quantity of Fibers (f/ m^3)[a] (min-max)	LOD (f/m^3)	Additional analyses	Potential Source of Pollution
Krakowiak, 2009	Unreported	PCM SEM-EDX[e]	Poland	Sosnowiec	Urban area - In the immediate vicinity of asbestos-containing buildings	41	27	1,800 (<1,000-9,000)	1,000	Asbestos concentration was below LOD in 51/100 samples (= 51%)	Asbestos-containing materials (roof and elevation covers) from buildings.
					Urban area - At a distance of 100-500 m from asbestos-containing buildings	42	24	<1,000 (<1,000-2,000)	1,000		
					Urban area - In the immediate vicinity of buildings without asbestos-containing materials	17	11	<1,000 (<1,000-1,000)	1,000		
Szeszenia-Dąbrowska, 2012	2004-2010	PCM-PLM	Poland	All provinces of Poland	Residential area	5,582	1,511	472	180	Asbestos concentration was below LOD in 120/ 5,582 sample sites (= 7.9%)	Mechanical damage and weathering of asbestos-containing tiles or boards.
Pawelczyk, 2015	Unreported	PCM	Poland	20 towns in Southwest Poland	Urban- and residential area	60	20	141-≈1,700[b]	Unreported	Fiber concentration was below 200 f/m^3 in 21/60 samples (= 35%)	Erosion of used asbestos-containing materials in buildings and vehicular traffic.
Buczaj, 2014	2009-2011	PCM	Poland	Lublin Region	Rural area - Farm A: Asbestos roof in good condition	72	3	328	220	Fibers was not detected in 24% of the samples.	Natural weathering of asbestos-roof.
					Rural area - Farm B: Asbestos roof in poor condition	72	3	529		Fibers was not detected in 10% of the samples.	Natural weathering of asbestos-roof.
					Rural area - Farm C: No asbestos roof	72	3	30		Fibers was not detected in 71% of the samples.	Unreported.
Capella, 2020	2014-2016	SEM-EDX[e]	Italy	Turin	Urban area	48	24	2014: - Tremolite/ actinolite: 600 - Chrysotile: 7,500 2016: - Tremolite/ actinolite: 600 - Chrysotile: 2,700	Unreported	Crocidolite and anthophyllite were not detected.	Dispersion of natural sources (i.e., rocks) and asbestos-containing materials.
Gualtieri, 2009	2005-2006	SEM[e] TEM[e]	Italy	Reggio Emilia, Modena,	Residential and	See footnote[d]	6	7-13[c]	SEM: 1,000 TEM: 100	Asbestos was not detected at	Asbestos-cement roofs of large buildings

(continued on next page)

Table 1 (*continued*)

Ref.	Sample Year	Method (s)	Country	City/ Region	Study Area	Samples N.	Sample Sites N.	Quantity of Fibers (f/ m^3)[a] (min-max)	LOD (f/m^3)	Additional analyses	Potential Source of Pollution
				and Bologna	industrial area					4/6 sample sites.	and warehouses.
Jung, 2021	Unreported	PCM TEM-EDX[e]	South Korea	Seoul, Busan, Incheon, Daegu, Ulsan, Gwangju and Daejeon	Urban area	28	28	PCM: 320 (100-2,800) TEM: 460 (<900-900)	PCM: 100 TEM: 900	Asbestos (tremolite) was only detected in 1/ 28 samples (= 3.6%) by TEM.	Demolition of asbestos-containing buildings, however, this was not present in the area where tremolite was detected.
				Several provinces across South Korea	Rural area	20	20	PCM: 560 (200-1,500) TEM: 450 (<900)		Asbestos was not detected by TEM.	Unreported.
				Unreported	Residential area	39	7	PCM: 1,610 (100-5,000) TEM: 460 (<900-900)		Asbestos (tremolite) was only detected in 1/ 39 (= 2.6%) by TEM.	Artificial rivers constructed with asbestos-containing landscape stones.
Wei, 2012	2011	PCM SEM-EDX	China	Dayao county (Yunnan Province)	Rural area	9	9	PCM: 2,400 (1,700-4,700) SEM-EDX: Unreported	Unreported		Natural weathering of crocidolite asbestos in soils in neighboring areas due to human activities (i.e., excavations, road construction, and urban development).
Li, 2020	2018	SEM-EDX[e]	China	Beijing	Urban area - In vicinity of a campus	4	2	Roof: 900 (600-1,500) Ground: 1,400 (1,100-1,700)	100		Cement-prefabricated parts containing asbestos at a construction site nearby the campus.

LOD, limit of detection; PCM, phase contrast microscopy; PCM-PLM, phase contrast microscopy with polarized light microscopy; TEM, transmission electron microscopy; TEM-EDX, transmission electron microscopy combined with dispersive x-ray spectroscopy; SEM, scanning electron microscopy; SEM-EDX, scanning electron microscopy combined with dispersive x-ray spectroscopy.
a) The results are presented as an overall mean and (if data available) a range of minimum and maximum values for all samples (unless otherwise specified).
b) The results are presented as a range of means in 20 different towns in Poland.
c) The results are presented as a range of means at the two sample sites, where asbestos was detected.
d) High flow sampling system conducted continuously for one week in each season at each sample site.
e) It was not specified whether fibers with diameters below 0.2 μm were analyzed using SEM-EDX or TEM-EDX in these studies.

Jung et al. (2021) evaluated respirable asbestos concentration in urban, residential, and rural areas in several regions and cities in South Korea. Measurements were also conducted at other sites (e.g., mining areas and baseball fields) with a potentially high presence of naturally occurring asbestos in the soil. These results are not included in our review. For residential environments, they selected seven artificial rivers constructed using asbestos-containing landscape stones. All samples were collected at a height of 1.5 meter above floor level and analyzed by PCM and TEM. The average fiber concentrations were 320 f/m^3 (PCM) and 460 f/m^3 (TEM) in urban areas, 560 f/m^3 (PCM) and 450 f/m^3 (TEM) in rural areas, and 1,610 f/m^3 (PCM) and 460 f/m^3 (TEM) in residential areas. The only type of asbestos fibers detected was tremolite, and it was only detected in 1/39 samples in residential areas (900 f/m^3 (TEM)) and in 1/28 samples (900 f/m^3(TEM)) in urban areas. In rural areas, the type of asbestos fibers was not determined.

Wei et al. (2012) conducted both outdoor and indoor air samples in rural areas of Dayao county, which is situated in the northwest of Yunnan province in China. Approximately 5% of the surface area of Dayao contains a thin layer of outcrop crocidolite ore. To comply with the eligibility criteria in this review, only results from outdoor measurements in areas without outcrop asbestos were included. All samples were collected at a height of 1.5 meter above floor level. The fiber concentrations were determined by PCM and SEM-EDX analysis, but the authors only report the PCM results in the article. A total of nine outdoor samples were collected in areas without outcrop crocidolite asbestos in the soil, and the mean fiber concentration by PCM was 2,400 f/m^3 (1,700-4,700 f/m^3). The authors argue that this might be influenced by asbestos fibers blowing from neighboring areas in which outcrop

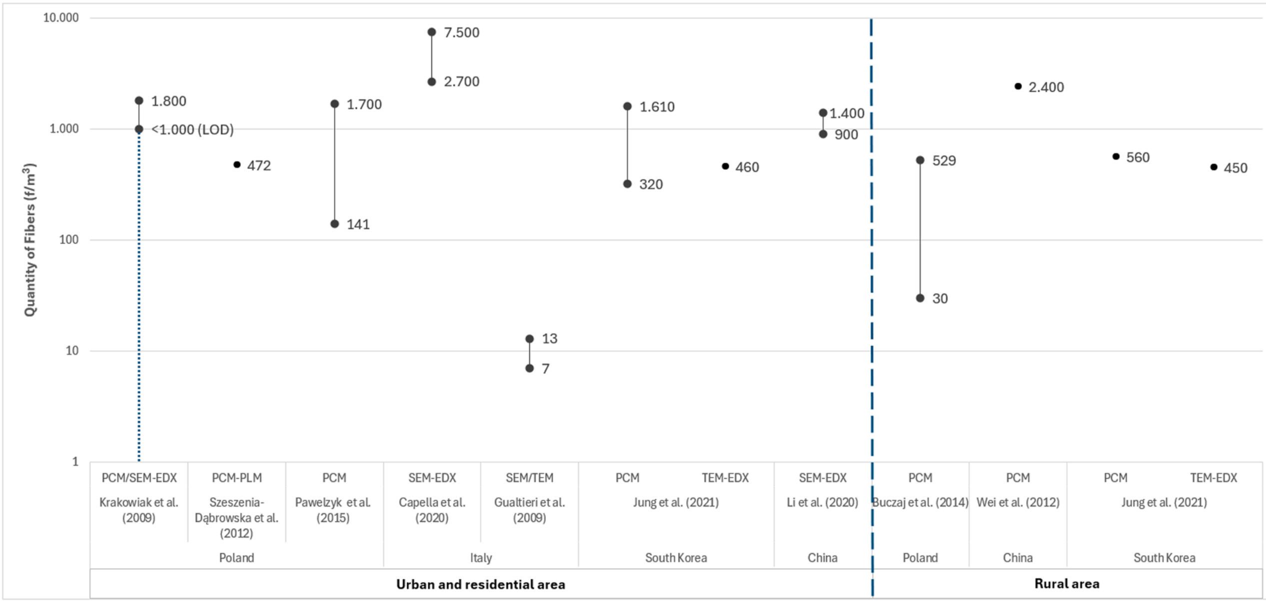

Fig. 3. Overview of airborne asbestos concentrations observed in studies in the main group
The figure illustrates the airborne asbestos concentrations observed in the main group of studies where asbestos emissions were primarily attributed to buildings with ACMs either due to renovation, demolition, or corrosion. The concentrations are presented as an overall mean or range of mean values. In Krakowiak et al. (2009), the lowest mean concentration observed was below the LOD of 1000 f/m^3, and this is represented by a dotted line below this value. For Capella et al. (2020), the results are presented as a range of means of the chrysotile concentration observed in 2014 and 2016. For Gualtieri et al. (2009), the results are presented as a range of means at two sample sites, where asbestos was detected. For Jung et al. (2021), the results are presented as a range of mean concentrations observed in both urban and residential areas. For Li et al. (2020), the results are presented as a range of means observed at the rooftop and ground levels of the campus. For Buczaj et al. (2014), the results are presented as a range of means observed at the three types of farms featuring varying roof conditions. LOD, limit of detection; PCM, phase contrast microscopy; PCM-PLM, phase contrast microscopy with polarized light microscopy; TEM, transmission electron microscopy; TEM-EDX, transmission electron microscopy combined with dispersive x-ray spectroscopy; SEM, scanning electron microscopy; SEM-EDX, scanning electron microscopy combined with dispersive x-ray spectroscopy; ACM, asbestos-containing materials.

crocidolite asbestos is present through natural weathering and other human activities such as excavation, road, or house construction. However, the distance between the sampling sites and the neighboring areas with NOA is unreported.

Li et al. (2020) examined several types of airborne fiber materials including asbestos fiber in the northwestern urban area of Beijing in the vicinity of a university campus. Asbestos fiber concentration was determined by SEM-EDX analysis. Only two air samples were collected from the roof and the ground of the campus at a height of 1.5 meter above floor level, respectively. The average asbestos fiber concentration was 900 f/m^3 at the roof and 1,400 f/m^3 at the ground. The authors considered building materials to be the source of asbestos fibers, yet not further specified.

3.3. *Studies on airborne asbestos in areas with active use of asbestos-containing brake pads and clutches*

The secondary group contained 13 studies, 11 from Iran and two from Iraq (Table 2 and Fig. 4). Common for all was the assumption, that release of asbestos fibers from automobile brakes and clutches containing asbestos contributed significantly to the airborne asbestos pollution. A potential contribution from used ACMs in buildings was also described in several studies, although not as the main contributor. In addition, asbestos emissions from industrial activities cannot not be excluded in most of the studies, and particularly in the Iranian studies. In 2011, The Department of Environment in Iran enacted a ban on the use of asbestos in industrial applications (Ghorbani *et al.*, 2022; Dehhaghi and Hasankhnani, 2024), however, the prohibition was not enforced according to several studies (Kakooei, Meshkani and Azam, 2013; Mokhtari *et al.*, 2019; Moteallemi *et al.*, 2020; Kermani, A, *et al.*, 2021; Kermani, Asadgol, *et al.*, 2021; Dehhaghi and Hasankhnani, 2024). For instance, asbestos-containing brake pads in automobiles are still widely used (Kermani, Asadgol, *et al.*, 2021; Ghorbani *et al.*, 2022; Maleki *et al.*, 2022) and 11 large factories producing asbestos-cement sheets and pipes are presumably still in operation (Kakooei, Meshkani and Azam, 2013; Kermani, A, *et al.*, 2021). PCM measurements conducted by the Tehran Air Quality Control Company (TAQCC), suggest a steep decline of airborne asbestos in Tehran from 2011-2014 (Dehhaghi and Hasankhnani, 2024), that coincided with the implementation of the asbestos ban. Only one of the included studies measured the airborne asbestos concentration before the ban of asbestos. In this study, the urban areas of Tehran had average concentrations as high as 200,000 f/m^3 (SEM) (Kakooei *et al.*, 2009). The remaining Iranian studies did measurements in several different regions and cities in the years after the ban. The studies reported an average airborne concentration in urban and industrial areas in the range of 1,040-2,840 f/m^3 (PCM) and <100-18,160 f/m^3 (SEM) (Kakooei *et al.*, 2009; Kakooei, Meshkani and Azam, 2013; K *et al.*, 2017; Khadem *et al.*, 2018; Mokhtari *et al.*, 2019; Kermani, A, *et al.*, 2021; Ghorbani *et al.*, 2022; Kermani *et al.*, 2022; Maleki *et al.*, 2022; Dehhaghi and Hasankhnani, 2024; Zarezadeh *et al.*, 2024). Noteworthy, in four out of six studies analyzing asbestos concentrations with both PCM and SEM-EDX, SEM-EDX showed the highest average concentrations (Kakooei *et al.*, 2009; Kakooei, Meshkani and Azam, 2013; K *et al.*, 2017; Kermani, A, *et al.*, 2021). In the urban and industrial areas of Bagdad in Iraq, the average concentration was in the range of 78, 000-121,000 f/m^3 (SEM) (Ajeel, Fleeh and Sultan, 2021, 2022).

3.4. *Correlation between airborne asbestos fiber concentrations and meteorological data*

Seasonal variation was only investigated in the Iranian and Iraqi studies. The total mean concentration was generally highest during winter or autumn (Kakooei *et al.*, 2009; Kakooei, Meshkani and Azam, 2013; K *et al.*, 2017; Mokhtari *et al.*, 2019; Kermani, A, *et al.*, 2021;

Table 2
Studies on airborne asbestos levels in outdoor environments with active use of asbestos-containing brake pads and clutches.

Ref.	Sample year	Methodology	Country	City/ region	Study Area	Samples N.	Sample Sites N.	Quantity of Fibers (f/ m3)[a] (min-max)	LOD (f/m^3)	Potential Source of Pollution
Kakooei, 2009	2006-2007	PCM SEM-EDX	Iran	Tehran	Urban area	80	40	PCM: 3,400 SEM-EDX: 200,000	PCM: 10,000 SEM-EDX: 400	Heavy traffic with vehicles using asbestos-containing brake pads. Industrial consumption of asbestos.
Kakooei, 2013	2012	PCM SEM-EDX[e]	Iran	Tehran	Urban area	110	15	PCM: 1,100 (900-1,300) SEM-EDX: 16,000 (13,700-186,000)	PCM: 10,000 SEM-EDX: 100	Heavy traffic with vehicles using asbestos-containing brake pads.
FathiFathabadi, 2017	2014	PCM SEM-EDX[f]	Iran	Shiraz	Urban and industrial area	64	8	PCM: 1,110 SEM-EDX: 12,210	PCM: 100,000 SEM-EDX: 100	Heavy traffic with vehicles using asbestos-containing brake pads. Industrial activities (e. g., production of fireproofing clothes and brake pads containing asbestos).
Khadem, 2018	2017	PCM SEM-EDX	Iran	Tehran	Urban- and residential area	6	2	PCM: 1,200-2,100[b] SEM-EDX: <1,000	PCM: Unreported SEM: 1,000	Heavy traffic with vehicles using asbestos-containing brake pads.
Mokhtari, 2019	2015	SEM-EDX[e]	Iran	Yazd City	Urban- and industrial area	60	15	Overall: 9,510 (1,170-23,220) Summer: 8,130 Winter: 10,890	100	Heavy traffic with vehicles using asbestos-containing brake pads. Industrial workshops. Repair and construction of old houses.
Ajeel, 2021	2019	SEM-EDX[f]	Iraq	Baghdad	Urban-, commercial-, and industrial area	16	4	78,000 (35,000-156,000)[c]	100	Heavy traffic with vehicles using asbestos-containing brake pads. Activities of repairing and construction of streets. Heavily crowded bus garages located near one sampling site. Industrial origin.
Kermani, 2021	2018-2019	PCM SEM-EDX[e]	Iran	Karaj	Urban and industrial area	68	17	PCM: 1,840 (1,060-3,310) SEM-EDX: 18,160 (8,710-29,600)	PCM: Unreported SEM-EDX: 100	Heavy traffic with vehicles using asbestos-containing brake pads. ACM-containing buildings. Factories, such as glassmaking, concrete and polyethylene pipes.
Ajeel, 2022	2020	SEM-EDX[f]	Iraq	Baghdad	Urban-, commercial- and industrial area	Unreported	5	18,000-121,000[d]	100	Heavy traffic with vehicles using asbestos-containing. Asbestos attributed to commercial and industrial nature. Process of demolition of older houses.
Ghorbani, 2022	2015	SEM-EDX[f]	Iran	Isfahan	Urban- and industrial area	66	11	Summer: 9,340 Winter: 14,480	Unreported	Heavy traffic with vehicles using asbestos-containing brake pads. Construction of buildings and roads.
Kermani, 2022	2018-2019	PCM	Iran	Veramin and Pakdasht	Urban- and industrial area	24	6	2,840	Unreported	Heavy traffic with vehicles using asbestos-containing brake pads. Industrial factories.
Maleki, 2022	2018-2019	PCM	Iran	Tehran	Urban- and industrial area	60	15	Warm season: 1,460 (200-3,400) Cold season:	Unreported	Heavy traffic with vehicles using asbestos-containing brake pads. Natural origin or different sources such as

(continued on next page)

Table 2 (*continued*)

Ref.	Sample year	Methodology	Country	City/ region	Study Area	Samples N.	Sample Sites N.	Quantity of Fibers (f/ m3)[a] (min-max)	LOD (f/m^3)	Potential Source of Pollution
								2,310 (700-5,700)		roofing sheets, heat insulators, and cement pipes.
Dehhaghi, 2024	2019-2020	PCM SEM-EDX	Iran	Tehran	Urban area - Sample site at a traffic station in the city center	PCM: 24 SEM: Unreported	1	PCM: 2019: 2,380 (1,100-5,600) 2020: 2,100 (1,000-3,800) SEM: March-May 2020: <100 (actinolite)	PCM: Unreported SEM-EDX: 100	Heavy traffic with vehicles using asbestos-containing brake pads.
Zarezadeh, 2024	2020-2021	PCM SEM-EDX	Iran	Tabriz	Urban- and industrial area	64	16	PCM: 1,940 (670-3,810)[c] SEM: Not reported.	PCM: Unreported SEM-EDX: 100	Heavy traffic with vehicles using asbestos-containing brake pads. Industrial factories and enterprises.

LOD, limit of detection; PCM, phase contrast microscopy; ATEM, analytical transmission electron microscopy; SEM, scanning electron microscopy; SEM-EDX, scanning electron microscopy combined with dispersive x-ray spectroscopy.

a) The results are presented as an overall mean and (if data available) a range of minimum and maximum values for all samples (unless otherwise specified)

b) The results are presented as a range derived from measurements of two samples.

c) The results are presented as an overall mean along with a range of means observed across the different sampling sites.

d) The results are presented as a range of means observed across the different sampling sites.

e) It was specified that fibers with diameters below 0.2 μm were analyzed using SEM-EDX in these studies.

f) It was not specified whether fibers with diameters below 0.2 μm were analyzed using SEM-EDX in these studies.

Ghorbani *et al.*, 2022; Kermani *et al.*, 2022; Maleki *et al.*, 2022; Zarezadeh *et al.*, 2024), with two studies reporting a 1.5-fold greater exposure in the cold seasons (Ghorbani *et al.*, 2022; Maleki *et al.*, 2022). Most authors argued that these observations were due to higher traffic volume and the use of insulation materials to keep houses warm during cold seasons. The majority of studies included in this review, which examined the association between meteorological parameters and asbestos concentrations, found no significant relationship (Kakooei, Meshkani and Azam, 2013; K *et al.*, 2017; Mokhtari *et al.*, 2019; Ajeel, Fleeh and Sultan, 2021; Maleki *et al.*, 2022; Dehhaghi and Hasankhnani, 2024). However, among the studies that reported a significant correlation, the findings were inconsistent. Two studies found that wind speed significantly increased the levels of airborne asbestos fibers (Krakowiak *et al.*, 2009; Kermani, A, *et al.*, 2021), while two other studies found a negative correlation (Ajeel, Fleeh and Sultan, 2022; Ghorbani *et al.*, 2022). Gualtieri et al. (2009) found a positive correlation between the precipitation level and the concentration of asbestos fibers.

4. Discussion

This study reviewed 22 articles assessing airborne asbestos concentration in the outdoor environment of which nine studies presumed ACMs from buildings to be the main source. Overall, these studies suggest that airborne asbestos persists in the outdoor environment even in the absence of NOA or adjacent asbestos-related industries. The asbestos levels in the studies of the main group were relatively low yet non-negligible, with airborne concentrations ranging from below LOD to 9,000 f/m^3 (Table 1 and Figure 3). Asbestos levels were generally observed to be higher in the immediate vicinity of asbestos-containing buildings (Krakowiak *et al.*, 2009; Buczaj *et al.*, 2014). Noteworthy, asbestos fibers were below the LOD in 3.6% to 51% of the samples across the studies. The highest mean concentrations in urban and rural areas were recorded in Turin (Italy) and Dayao county (China), respectively (Wei *et al.*, 2012; Capella *et al.*, 2020). It should be noted that these studies collected samples at locations nearby areas with soils and rocks containing NOA, where the presence of airborne asbestos could be attributed to dispersion originating from both natural and anthropogenic sources. However, it remains uncertain to what extent these sources contributed to the observed asbestos levels.

In the secondary group, comprising 13 studies, the asbestos pollution was primarily attributed to the release of fibers from asbestos-containing automobile brakes and clutches. The asbestos levels appeared substantially higher across almost all studies in the secondary group compared to those observed in the studies of the main group, with airborne concentration reaching up to 200,000 f/m^3 (Table 2 and Fig. 4). The highest airborne asbestos concentrations were consistently observed in areas with high vehicular traffic across the studies, indicating that asbestos-containing brakes and clutches were the main contributors. It should be emphasized that asbestos emissions from industrial activities cannot be completely dismissed, as several studies indicated that prohibition of asbestos use was not enforced.

4.1. Evaluation of the generalizability of the findings and methodological differences across studies

Based on the studies in the review, it is not possible to establish a mean background level of asbestos fibers in the outdoor air. While the included studies in this review offer valuable insights into airborne asbestos concentrations in various rural and urban areas, their findings are challenging to apply to other settings. The density of buildings and prevalence of asbestos-cement roofing and other ACMs, as well as variation in construction periods and extend of natural weathering, may differ across cities and locations. Kameda et al. (2014) provides an overview, illustrating that even among countries within the European Region, there are substantial differences in average per capita asbestos use over different time periods, as well as in the timing of the introduction of asbestos bans. Current legislation and asbestos abatement programs vary between countries, which may influence the number of buildings with ACMs across different regions (Peña-Castro, Montero-Acosta and Saba, 2023). Across all studies in both the primary and secondary groups, the sample year ranged from 2004 to 2021, but it was unreported in several of the studies. In addition, the levels of

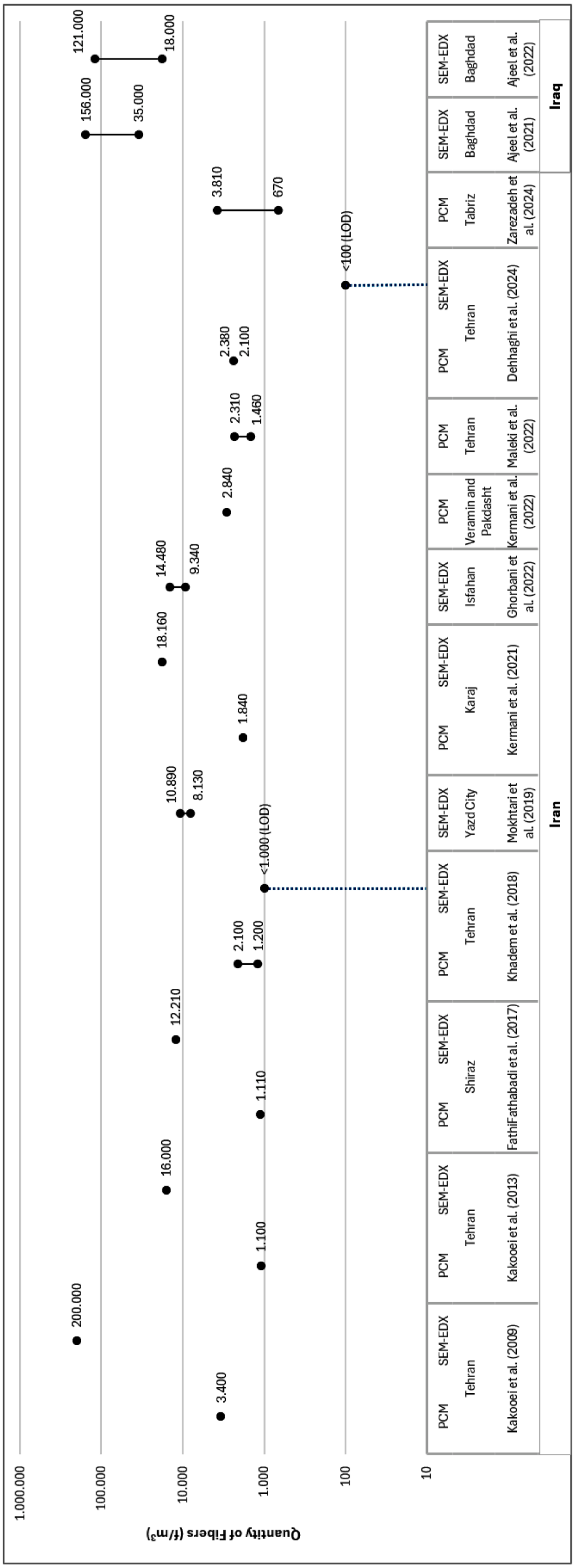

Fig. 4. Overview of airborne asbestos concentrations observed in studies in the secondary group.

airborne asbestos fibers may also vary depending on seasonal variations and climatic conditions. In general, the local area, weather conditions, and asbestos usage were not well-described in the included studies. Wei et al. (2012) and Jung et al. (2021) conducted measurements in rural areas; however, it remains unknown whether the sample sites were situated in rural villages, in proximity to houses containing ACMs, within forested areas, or other locations. If the sampling is not pre-defined based on objective criteria such as proximity to ACM, building ratio, and weather conditions, there is a risk of bias in the placement of measurement equipment. Consequently, in most studies, it remains uncertain whether the results reflect exposures in the vicinity of ACMs or reflect a more general environmental exposure at a greater distance from ACMs in the specific environment studied. Repeated measurements and variation in sample sites provide a more robust results, yet Li et al. (2020) and Wei et al. (2012) only had sample sizes of four and nine, respectively.

Major methodological differences affect the generalizability of the results. First, only one study (Szeszenia-Dąbrowska *et al.*, 2012), explicitly stated being accredited to employ the analytical procedures used to determine asbestos concentrations in air samples. In the remaining studies, it is unknown whether the laboratories were accredited to conduct the analyses, since this was not explicitly stated. Three studies analyzed asbestos concentration using only PCM (Wei *et al.*, 2012; Buczaj *et al.*, 2014; Pawełczyk and Božek, 2015). As this method cannot distinguish between asbestos fibers and non-asbestos fibers, this method may overestimate the actual asbestos fiber concentration (Abelmann *et al.*, 2015; Andrews and Fey O'connor, 2020). Conversely, it is not possible to identify the thinnest fibers with PCM, potentially leading to an underestimation of the total fiber count. The latter limitation may help explain why asbestos concentrations determined by PCM were sometimes lower than concentrations determined by SEM-EDX in the secondary group. Notably, in all studies from the main group and in three of the 10 studies from the secondary group that reported concentrations using electron microscopy, it was unclear whether fibers with a diameter of less than 0.2 μm were counted. Other methodological discrepancies include differences in LOD and how to report samples below the LOD. The LOD was unreported in three studies, while it ranged from 100 f/m^3 to 1,000 f/m^3 in the other studies. In Jung et al. (2021), concentrations below the LOD were substituted with half of the analytical sensitivity, which is a common approach. However, one study has shown that using LOD/2 may lead to considerable uncertainty when the percentage of censored values is high (Gillespie *et al.*, 2010; Neitzel *et al.*, 2020). Considering that asbestos fibers were detected in a very limited proportion of samples (e.g., 1/39 samples) in Jung et al. (2021), the findings should be interpreted with caution, as they are subject to uncertainties. Gualtieri et al. (2009) also calculated asbestos concentrations below the LOD; however, the methodological approach was not described.

4.2. Strengths and limitations of the systematic review

This review applied a strict systematic approach with multiple reviewers and pre-defined eligibility criteria regarding the methodology of counting asbestos fibers to ensure as much comparability as possible between the studies. We developed a standardized template for data extraction, ensuring consistent and systematic collection of relevant information across all studies. Additionally, we established a list of information considered essential to assess the quality of each study, that at a minimum should be described in each paper. Consequently, only a limited number of studies were included in this review. The studies have also been conducted in a limited number of countries, which restricts the generalizability of the findings. The main group only included studies in which the release of asbestos fibers from ACMs in buildings was the primary source; however, as previously mentioned, it still cannot be ruled out that the presence of NOA contributed significantly to the observed asbestos levels in two of the studies within this group.

A high number of studies were excluded due to the absence of an English-language publication (see Figure 2), despite their potential relevance. Most of these studies were from Italy, Germany, Poland, and Russia. However, most of these studies were conducted between the 1970s and the 1990s. Based on experience with screening full-text English articles, studies from this period rarely provide sufficient methodological details and often employ analytical approaches differing from those used today, and thus, would probably not align with our eligibility requirements.

Only a limited number of studies reported the concentrations of the different types of asbestos fibers or reported details regarding the distribution of fibers within aspect ratios, which are important for understanding the potential health implications.

4.3. Standardization of methods for sampling and analyzing asbestos fibers

Standardization of methods for sampling and analyzing airborne asbestos fibers in the environment is crucial to ensure consistency and comparability across studies. To establish a broader basis for comparison, we recommend that future studies provide more details of both methodologies employed and the characteristics of the study area. Essential methodological details include information on the height of measurements above floor level, the number and spatial distribution of samples and sampling sites, the analytical method employed, the estimated LOD, the standards applied for sampling and identification of asbestos fibers, and specifically whether the thinnest fibers, with a diameter of less than 0.2 μm, are counted. Future research should also include a detailed characterization of the sample site locations, specifying the distance between the sample sites and potential sources of asbestos emissions (e.g., ACMs). Studies in this review indicate that the release of asbestos fibers increases with the degree of material deterioration in ACMs (Krakowiak *et al.*, 2009; Buczaj *et al.*, 2014). Therefore, it would be valuable to include an assessment of the condition of these materials, as exemplified by Campopiano et al. (2009). In this context, it would also be necessary to incorporate meteorological data, particularly wind speed and direction, as studies suggest these factors may significantly influence asbestos fiber dispersion. Therefore, future studies are encouraged to conduct measurements in different seasons to facilitate a comparative analysis of the results.

Future studies should use electron microscopy rather than PCM, as it represents the most sensitive method for detecting and measuring asbestos fibers. This recommendation aligns with the amending Directive 2023/2668/EU, which mandates the implementation of electron microscopy for measuring asbestos fibers in occupational settings by December 21, 2029 (European Agency for Safety and Health at Work, 2023). There is a lack of standardized guidelines regarding the number of samples to be collected at a given site to ensure the results are representative. One review on asbestos recommended that stationary monitoring stations should sample air over a minimum of 15 consecutive days to ensure the representativeness of the data (Peña-Castro, Montero-Acosta and Saba, 2023). However, this remains an ongoing discussion.

The use of artificial intelligence (AI) models for the analysis of fibers should also be considered in future studies (Iida *et al.*, 2021; Rabiee *et al.*, 2023). A recent study on SEM image analysis using AI, demonstrated that the method detected thin airborne fibers with greater accuracy and 50 times faster than conventional methods by PCM and SEM (Iida *et al.*, 2021). The new methods may offer monitoring of airborne asbestos concentrations at lower costs, while also avoiding delay in asbestos abatement due to more rapid analyses.

4.4. Health implications

Epidemiological studies have shown that environmental exposure to asbestos can increase the incidence and mortality rates of mesothelioma (Krówczyńska and Wilk, 2018; Dalsgaard *et al.*, 2019, 2021). This is mainly observed in environments located nearby asbestos-related industries (Chang, Chen and Wang, 1999; Kang *et al.*, 2018). Krówczyńska and Wilk (2018a) found that the amount of asbestos-cement roofing in use in different districts of Poland correlated with asbestos concentrations in the ambient air. However, they found no correlations between the number of asbestos-cement products in use and the number of mesothelioma cases.

The WHO has estimated the probability of an individual's risk of developing mesothelioma from breathing air containing asbestos, based on a considerable number of epidemiological studies of occupational exposure (WHO, 2000). The WHO conservatively extrapolated these data to account for the significantly lower levels of asbestos that are typically found in the general environment. Evidence indicates that chrysotile is less potent than amphiboles; however, as a precaution, the WHO assigned chrysotile the same risk in the estimates. The WHO estimated that, with a lifetime exposure to 1,000 f/m^3 (500 f/m^3, optically measured), the excess risk due to mesothelioma would be in the range of 1:10,000 to 1:100,000 in the general population (WHO, 2000). These risk estimates are associated with considerable uncertainties. First, the risk estimates are based on fiber obtained using PCM and should not be directly applied to measurements obtained through SEM/TEM. Second, the risk estimates derive from several cohort studies that lack reliable exposure data including information on past exposure. Third, the long latency period between exposure and disease onset may cause cohort studies to underestimate the number of cases. Fourth, it is uncertain whether it is possible to generalize the risks associated with occupational exposures and between high to low-level environmental exposures.

The United States Environmental Protection Agency (U.S. EPA) suggest that the excess lifetime cancer risk is negligible if it is less than 1:1,000,000, whereas risk levels exceeding 1:10,000 are usually considered unacceptable (U.S. EPA, 2024). However, the definition of acceptable risk remains a subject of ongoing debate (National Research Council, 2004; Pawełczyk and Božek, 2015). Nonetheless, based on the calculated risk estimates by the WHO, the airborne asbestos concentrations in the outdoor environment found in several of the studies included in this review, exceed risk levels usually considered acceptable for lifetime exposure. This applies especially for the studies in the secondary group. Thus, eliminating the use of asbestos-containing brake pads and clutches in countries, where such products are still in use, represents a substantial opportunity to enhance public health.

5. Conclusion

This study reviewed 22 articles assessing airborne asbestos concentration in the outdoor environment, of which nine studies presumed ACMs from buildings to be the main source, while 13 studies attributed the concentrations mainly to the use of asbestos-containing brake lining in vehicles. We applied well-defined eligibility criteria for the methodology to enhance comparability across studies. The review indicates that even in the absence of asbestos-related industries and presence of NOA, and despite asbestos bans being in place for decades in numerous countries, low but non-negligible levels of airborne asbestos fibers may still be present in the outdoor environment. Of particular concern, in countries where asbestos-containing brakes and clutches are still utilized in automobiles, asbestos levels appeared substantially high in several studies.

Only a limited number of studies have investigated levels of airborne asbestos in outdoor environments without asbestos-related industries or the presence of high levels of NOA. This review emphasizes the need for further research into the background levels of airborne asbestos. Especially, more studies should investigate the associations between deterioration of asbestos-cement roofing and the ambient airborne asbestos levels. The screening process of numerous studies in this review also highlights a critical need for standardization of methods used to measure airborne asbestos to ensure consistency and comparability across studies.

The studies reviewed may serve as tentative reference points for future investigation. However, it must be strongly emphasized that several factors, including geographical variations in the historical use of asbestos and differences in current legislations, can result in significant variability in airborne asbestos levels.

Graphical abstract creation

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Disclosure statement

No potential conflict of interest was reported by the authors.

Protocol and data availability statement

Upon request, the protocol and data will be made available.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of the first draft the author, MKS, used ChatGPT 4o, in order to improve the readability and language of some of the sentences in the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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CRediT authorship contribution statement

Marcus Kjær Sørensen: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Laura Deen:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Georges Khoury:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Jonathan Aavang Petersen:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Jane Frølund Thomsen:** Writing – review & editing, Methodology, Conceptualization. **Torunn Kringlen Ervik:** Writing – review & editing, Validation, Methodology, Conceptualization. **Peter Møller:** Writing – review & editing, Methodology, Conceptualization. **Sandra Søgaard Tøttenborg:** Writing – review & editing, Methodology, Conceptualization. **Harald William Meyer:** Writing – review & editing, Methodology, Conceptualization. **Kajsa Ugelvig Petersen:** Writing – review & editing, Methodology, Conceptualization. **Luise Mølenberg Begtrup:** Writing – review & editing, Methodology, Conceptualization. **Esben Meulengracht Flachs:** Writing – review & editing, Methodology, Conceptualization. **Ingrid Sivesind Mehlum:** Writing – review & editing, Methodology, Conceptualization. **Regitze Sølling Wils:** Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hazadv.2025.100926.

Data availability

Data will be made available on request.

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