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Review

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Environmental and occupational exposure to erionite and related health risks: progress and prospects

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Abstract

Objectives: Erionite, a naturally occurring fibrous zeolite classified as a human carcinogen, is believed to be more potent than asbestos in causing mesothelioma. However, unlike asbestos, erionite has rarely been used for commercial purposes and, as a result, knowledge about exposure pathways is limited. This paper provides a narrative review of the current knowledge regarding the associations between erionite exposure, health effects and exposure circumstances.

Methods: Medline/PubMed and Scopus were systematically searched up to the end of 2024 using keywords related to erionite exposure and health outcomes.

Results: We identified 26 peer-reviewed journal articles reporting on the health effects of erionite exposure, specifically mesothelioma and lung cancer, with mesothelioma being the most extensively studied outcome. Of these, 12 studies focussed on erionite-exposed populations in Turkey, 8 examined health effects among Turkish migrants in northern Europe, and 6 investigated erionite-related health risks in North America (3 in the United States and 3 in Mexico). These studies showed a very high incidence of mesothelioma, often in relatively young individuals, from the Cappadocia region of Turkey, with well-documented environmental exposures to erionite, contributing to a high proportion of all deaths (21% to 51%) in affected villages. Evidence of lung cancer associated with erionite exposure was also found. There is also evidence of erionite exposure-associated mesothelioma in Guanajuato, central Mexico. In the United States, erionite exposure-associated health effects (not mesothelioma) have been reported among people occupationally exposed to erionite. Studies on environmental exposures have shown outdoor concentrations ranging from 0.001 f/ml to 0.3 f/ml, while indoor concentrations have ranged from 0.005 to 1.38 f/ml. Occupational exposure to erionite has been less studied, with only one study in forestry workers showing elevated exposures to erionite ranging from non-detectable to 0.36 f/cc. Erionite deposits have also been identified in other countries such as Italy and New Zealand, but exposures and associated health effects have not yet been studied in these regions.

Conclusion: There is clear evidence that environmental exposure to erionite in the Cappadocia region of Turkey, and Guanajuato in central Mexico are causally associated with the high mesothelioma rates observed in these areas. Evidence for other parts of the world where there is naturally occurring erionite is limited. This review has highlighted significant knowledge gaps, and advocates for further research on occupational exposure to erionite fibres and associated health effects.

Keywords: asbestos; environmental exposure; exposure limits; erionite; mesothelioma; occupational exposure

What's Important About This Paper?

Exposure to erionite fibres is a known cause of mesothelioma, occurring at lower exposure levels than those associated with asbestos. With increasing concerns about occupational exposure to erionite, this paper provides the first comprehensive review of exposure scenarios and levels. There is a need to establish regulatory exposure limits for erionite and develop a more robust understanding of occupational exposure risks.

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Introduction

Erionite, first described in 1898 (Eakle 1898) is a naturally occurring fibrous mineral belonging to a group of aluminosilicate minerals called zeolites. Because of its white, fibrous, wool-like appearance, erionite was named after the Greek word "erion" meaning "wool" (Christie 2002). It originates from silica-rich volcanic ash and forms after the glassy ash is dissolved by water and recrystallised as zeolites (Beaucham et al. 2018). Typically, erionite is not found in its pure form, instead, it is associated with other zeolite minerals across a variety of geological settings (IARC 2012). Erionite deposits are identified in all continents, including Russia, Japan, Turkey, Iran, Italy, Germany, Kenya, Mexico, the United States, and New Zealand (Berry et al. 2022).

The disturbance of erionite-containing rock and soil can generate airborne erionite fibres similar in size and shape to those of asbestos, with similar health risks. In fact, the International Agency for Research on Cancer (IARC) has classified erionite as carcinogenic to humans (Group-1 human carcinogen) based on its potential to cause mesothelioma (IARC 1987b, 2012), but with erionite considered to be several orders of magnitude more potent than asbestos (Hill et al. 1990; Carbone and Yang 2012; IARC 2012). In particular, animal studies have shown that its potency maybe 300 to 800 times greater than chrysotile asbestos and 100 to 500 times greater than crocidolite asbestos when exposed through intrapleural routes (Wagner et al. 1985). In addition to mesothelioma, erionite, like asbestos, can also cause other adverse health effects including lung fibrosis (Berry et al. 2022).

Compared to asbestos, the mean age of onset for erionite-related mesothelioma is much earlier, around the mid-50s compared to 70 yr in asbestos-exposed subjects (Emri 2017). Also, the male-to-female ratio is closer to 1 or smaller than 1 (Mousavi et al. 2010; Demirer et al. 2015), which differs from asbestos-associated mesothelioma that is much more common in men. This reflects the very different exposure circumstances with asbestos exposure predominantly occurring through male-dominated occupational activities, whilst erionite exposure may already occur in early childhood (Carbone et al. 2012), often in the home environment (described below).

Despite similar health risks, albeit at lower doses, erionite has received far less attention than asbestos (Dogan and Dogan 2008), likely due to fewer people being at risk from exposure to erionite, as unlike asbestos, it only has limited commercial applications (including being used as a catalyst in the petroleum refining process (Steven and Hill 1988; Mumpton 1999)) and with commercial mining only occurring from 1960 to 1980 (IARC 1987a, 1987b). As a result, exposure is more limited as it typically occurs only when erionite-containing rock or soil is disturbed or laid bare, and it was not until the 1970s that the risks and exposure circumstances of erionite were described. Relatively few studies have been conducted since, most of which were undertaken in the Cappadocia region of Turkey. Although there is now an increased understanding that erionite exposures may not be limited to only Cappadocia, there is relatively little awareness in other countries about the associated risks, particularly in occupational environments where workers may disturb erionite-containing rock and soil.

This narrative review summarizes current knowledge about associations between erionite exposure and associated health effects. It also discusses exposure circumstances and levels, including occupational exposures.

Methods

This narrative review involved a systematic literature search of two databases, Medline/PubMed and Scopus, through the end of 2024, using keywords related to erionite exposure and health outcomes.

Search strategy

The search terms used for the literature review were: (erionite OR zeolite* OR "Zeolite fibre*" OR "soil or rock") AND (cancer* OR neoplasm* OR mesothelioma* OR " pleural disease*" OR "pleural change*") AND (environment* OR soil* OR occupation* OR "zeolite dust" OR "air pollutant*" OR "erionite-Associate*"). The flowchart of the data extraction process and the complete search string are provided in Supplementary Material 1.

Eligibility criteria

Studies were considered eligible if they investigated erionite-exposed populations, provided data on health effects, and detailed exposure circumstances and levels, including environmental and/or occupational exposures. Additionally, studies assessing exposure circumstances and levels in these populations, regardless of whether health outcomes were reported, were also included. Conversely, studies were excluded if the exposure was not related to erionite fibres or if they did not evaluate the relationship between erionite exposure (occupational and/or environmental) and health outcomes.

Data extraction

Screening and assessment of articles were performed by one author (GC), following a process that included an initial evaluation of titles and abstracts, followed by a full-text review. Additionally, references cited within the included articles were examined to identify further relevant studies. Reasons for exclusion during full-text screening were discussed by the authors (GC and AM). To ensure accuracy and reliability, data extraction was conducted systematically by one author (GC) and cross-checked by another author (AM). Extracted data included study characteristics (e.g. publication year, authors, study design, and country), participant characteristics (e.g. sample size, sex, and occupation/job title, if applicable), methods of exposure and outcome assessment, as well as prevalence and mortality estimates. Throughout this process, any unclear information was noted for further clarification.

Results

The systematic literature search initially identified 209 articles from PubMed and 257 articles from Scopus. After excluding 152 duplicates, 314 articles remained for screening. During the title and abstract screening phase, 190 articles were excluded, leaving 124 articles for full-text review. Subsequently, 99 articles were excluded during the full-text review, resulting in 25 included articles. A supplementary search of reference lists identified one additional article. Thus, to date, 26 peer-reviewed journal articles have reported on the health effects of erionite exposure, with mesothelioma being the most extensively studied outcome. Of these, 12 studies focussed on erionite-exposed populations in Turkey, 8 examined health effects among Turkish migrants in northern Europe, and 6 investigated erionite-related health risks in North America (3 in the United States and 3 in Mexico).

Health effects in erionite-exposed populations

Health effects of erionite exposure were first identified in Cappadocia, Turkey in the mid-70s, where in one village (Karain), approximately 50% of all deaths during the period 1970 to 1976 were due to erionite-related mesothelioma (Baris et al. 1978). Erionite exposure in this area was associated with unique ancient rock cave settlements where houses and rooms were hollowed out of volcanic tuff and walls plastered with a greyish-white powdered rock from the surrounding hills (Baris et al. 1978). Although initially considered a local issue, it has become clear, in the past three decades, that there is also potential for erionite exposure in other parts of the world, with reports on erionite-related health effects now also emerging from other countries, including North America. Table 1 presents papers focussed on populations in Turkey and Turkish migrants in northern Europe, while Table 2 summarizes erionite-induced health risks in North America. Full details from these papers can be found in Supplementary Tables 1 and 2.

Studies from Turkey

In Turkey, the erosion of erionite-containing volcanic tuff has led to conical and beehive-shaped landforms, which are extensively quarried for construction. In Karain, these landforms have been extensively excavated for dwellings, animal pens, and storage pens for food and fodder (Rohl et al. 1982). This has resulted in elevated erionite exposures for those living in or near these places.

An epidemic of pleural mesothelioma in Kairan, Turkey was first reported in 1978, with 25 pleural mesothelioma deaths observed in the period 1970 to 1974, and at least 11 of the 18 total deaths in 1974 attributed to mesothelioma (Baris et al. 1978). Another 11 pleural mesotheliomas and 5 fibrosing pleurisy cases were observed in 1975 to 1976 in this village of 600 people. Asbestos in the local soil or rock was not found and deposits of asbestos or processed asbestos material in the area were also not observed; however, volcanic debris was observed in airborne dust. In 1979, a study in Tuzköy, 50 km from Karain, found an annual mesothelioma incidence 942 times higher than that observed in a control village (Artvinli and Bariş 1979). Zeolite minerals, including erionite, were found in both environmental and lung tissue samples.

In 1981, a survey in Karain and the nearby village of Karlik found a higher prevalence of pleural abnormalities in Karain compared to the control village, Karlik. Specifically, mesothelioma was observed in 11 participants in Karain (3.4%; 8 males, 3 females), compared to one male case in Karlik (0.4%) (Baris et al. 1981). Environmental samples revealed that approximately 80% of respirable fibres in Karain had a chemical composition similar to erionite, compared to only 20% in Karlik. Indoor samples of both fibrous and non-fibrous particles from the walls of family caves in Karain showed a composition similar to that of erionite. The following year, environmental and lung tissue samples from five villages in Cappadocia showed that 90% of the fibrous particles in the tissue of mesothelioma patients consisted of sodium-potassium-calcium aluminosilicates, a composition consistent with that of erionite (Rohl et al. 1982). Erionite defined as "major" (with a mean of ≥3% erionite by weight) was found in environmental samples taken in three villages. Several kinds of other asbestos minerals were also observed, but only in "trace" amounts each less than 3%.

A 1987 study conducted between 1979 and 1983 in four villages in the Cappadocia region (Karain, Karlik, Sarihidir, and Tuzköy) found that the three villages with the highest proportion of erionite fibres in outdoor airborne samples (Karain, Sarihidir, and Tuzköy) also had high death rates due to malignant pleural mesothelioma (29 out of 141 deaths), malignant peritoneal mesothelioma (4 out of 141), and lung cancer

Table 1. Environmental exposure to erionite and associated health risks in Turkey and Europe

Author, Year, Country	Study design, Number of participants (n)	Data collection method	Gender	Health outcomes	Main findings
Baris et al. 1978 Turkey	Retrospective health survey Karain (n):575	Mortality data and medical information from the local Health Institute.	Both	Mesothelioma	25 mesothelioma deaths between 1970 and 1974. 11 pleural mesothelioma and 5 fibrosing pleurisy cases in 1975/76.
Artvinli & Bariş 1979 Turkey	Cross-section study Tuzköy (n):312; Control village (n): 95	Questionnaire	Both	Mesothelioma	Annual pleural mesothelioma rate: 6.5 (22/ 10,000) which was 942 times higher than expected for this village.
Baris et al. 1981 Turkey	Health survey Karain (n):554; Karlik (n): 479	Interview and chest X-ray	Both	Mesothelioma	Karain: 11 mesotheliomas. Karlik (control village): 1 mesothelioma.
Rohl et al. 1982 Turkey	Retrospective cases study. lung tissues (n): 22 patients	Lung tissue specimens of patients with mesothelioma.	n/a	Mesothelioma	~ 90% of the fibrous particles in the lung tissues were erionite.
Baris et al. 1987 Turkey	Health survey of four villages (Karain, Karlik, Sarihidir, Tuzköy) (n): 892 participants	Interview and chest x-ray. Mortality data were also obtained.	Both	Mesothelioma lung cancer	29 pleural mesotheliomas, 4 peritoneal mesotheliomas and 17 lung cancers. Annual Mesothelioma rate: 8/1,000 in affected villages.
Simonato et al. 1989 IARC, France	Environmental and epidemiological survey (Follow-up analysis on 4 Turkey villages).	Interview, chest X-ray and physical examinations. Mortality data from the health centre and clinical files.	Both	Mesothelioma Lung cancer	A cumulative dose of l fibre. year/ml could induce pleural mesothelioma with a rate of 996/100,000 person-years in the exposed population.
Bariş et al. 1996 Turkey	Mortality study (n): 824 deaths	Mortality data from Karain (1971-1994), Tuzköy and Sarihidir (1980-1994)	Both	Mesothelioma Lung cancer	Karain: 150 (49.2%) pleural mesotheliomas;7 (2.3%) peritoneal mesothelioma, 4 (1.3%) lung cancer among 305 deaths. Tuzköy and Sarihidir: 120 pleural mesotheliomas, 64 peritoneal mesotheliomas, and 14 lung cancer among 519 deaths.
Karakoca et al. 1997 Turkey	Review of cross-sectional surveys (n):19462 chest x-ray	Data from radiographic (chest X-ray + microfilm) between 1973 and 1996.	Both	Calcified pleural plaques	Calcified pleural plaques were found in 5.4% of adult (asbestos villages), 9.3% (erionite village) and <1% (control villages)
Emri et al. 2002 Turkey	Review	From previous studies in Turkey	n/a	Mesothelioma	>50% of deaths due to mesothelioma in affected villages).
Baris & Grandjean 2006 Turkey	Prospective cohort (n): 891(420 males, 471 females)	Mortality data from hospital records and death certificates.	Both	Mesothelioma	The standardized pleural mesothelioma mortality rate (Karain & Sarihidir, both sexes): 485 (95% CI: 395–590)
Metintas et al. 2010 Turkey	Cohort (n):322 (154 males, 168 females)	Questionnaire, mortality data from village Muhktar, clinic and hospital records.	Both	Mesothelioma	Annual mesothelioma incidence:639/100,000(males), 1266/ 100,000 (females). Mesothelioma accounts for 50.5% of all deaths.

Table 1. Continued

Author, Year, Country	Study design, Number of participants (n)	Data collection method	Gender	Health outcomes	Main findings
Metintas et al. 2019 Turkey	Review 21 cohort studies (8 environmental and 13 occupational)	Studies published in international journals	Both	Mesothelioma	In environmental cohorts, the risk of MM incidence was higher in females (65.23 × 10^{-5}; 95%CI:32.45–98.00 for females, 50.50 × 10^{-5}; 95%CI: 22.10–78.90 for males) and people exposed to erionite.
Boman et al. 1982 Sweden	Health survey (n): 94 participants	Questionnaire and chest radiographic survey from Turkish immigrants	Both	Mesothelioma	3 pleural mesotheliomas were observed in Turkish immigrants from Karain. Tow lung tissue biopsy showed 75% and 64% zeolite fibres.
Ozesmi et al. 1990 Sweden	Health survey (n): 94 participants	Questionnaire and clinical examination among Turkish immigrants.	Both	Mesothelioma	4 mesothelioma (1 male, 3 females) among Turkish immigrants. Mesothelioma incidence rate: 1%/year in this population.
Metintas et al. 1999 Sweden	Cohort (n):162 Karain-born participants (87 males and 75 females)	Personal information was collected from the Cultural Association of Turkish Swedish register. Death and diagnosis data from hospitals and cancer registry.	Both	Mesothelioma	Mesothelioma risk was 135 times higher in males and 1,336 times higher in females vs same-sex/age groups in Sweden. The risk increased with the duration of residence.
Dumortier et al. 2001b Belgium	Retrospective diagnosis/case report (n): 68 Turkish immigrants (51 males, 17 females)	>5,000 BALF samples referred for mineral analysis since 1979 as part of clinical evaluation.	Both	Mesothelioma, asbestosis	Of 68 immigrants, 1 had asbestosis, 1 had mesothelioma and 46 had non-malignant pleural lesions. Two were exposed to erionite in Turkey; others to asbestos.
Hillerdal & Elmberger 2007 Sweden	Case report (n):1 case	Lung biopsy	Male	Sarcomatous mesothelioma	13 years of environmental exposure to erionite in Karain, Turkey with sarcomatous mesothelioma with bone formation.
Gräsel et al. 2008 Germany	Case report (n):1 case	Clinical diagnosis	Female	Pleural plaques	A female Turkish migrant developed pleural plaques decades later after being exposed to erionite in her hometown.
Mousavi et al. 2010 Sweden	Retrospective cohort (n):2316 mesothelioma cases (2128 native Swedish, 188 immigrants)	Swedish Family-Cancer Database and the national census	Both	Mesothelioma	First-generation Turkish immigrants had a mesothelioma risk of 5.29 (95% CI: 3.08–8.47) vs native Swedes; elevated risk was seen only in Turkish immigrants.
Metintas et al. 2021 Sweden	Cohort (Stockholm-Karain cohort) (n):337 (203 were born in Karain, 134 were born in Stockholm)	All deaths and/or mesothelioma diagnoses from January 1965 to October 2019 were investigated.	Both	Mesothelioma	Of 69 deaths, 42 (61%) were from mesothelioma; 2 additional cases were alive. Among 44 total cases, 22 were men. All first-generation immigrants exposed to erionite.

Table 2. Environmental exposure to erionite and associated health risks in North America

Author, Year, Country	Study design, Number of participants (n)	Data collection method	Gender	Health outcomes	Main findings
Casey et al. 1981 USA	Case report (n): 1 case	Lung biopsy	Male	Pleural fibrosis	A lung biopsy revealed fibrous and non-fibrous particles consistent with erionite.
Ilgren et al. 2008 Mexico	Case report (n):12 cases	Death certificate.	Both	Mesothelioma	A cluster of 12 mesothelioma cases (4 females, 8 males) lived in the valley of Jalpa which is located on the zeolitized sedimentary bed within the Sierra Madre Occidental. Exposure to zeolites appears to be the cause of the cluster as no asbestos exposure.
Kliment et al. 2009 USA	Case report (n): 1 case	Lung digest	Male	Mesothelioma	Erionite fibres (greater than 5 microns in length) and erionite ferruginous bodies were found in lung tissues.
Ryan et al. 2011 USA	Cross-section (n):34 participants	Questionnaires, chest radiographs and high-resolution computed tomography scans were used for exam health outcomes.	Both	Interstitial and pleural changes	7 (21%) road/gravel workers had interstitial and/or pleural changes; 2 showed mild bilateral pleural calcification with minimal lower lobe fibrosis—suggesting erionite in gravel is a health risk.
Ortega-Guerrero et al. 2015 Mexico	Mortality study (n):45 deaths	Mortality data between 2000 and 2012 in the Village of Tierra Blanca.	Both	Mesothelioma Lung cancer	Of 45 deaths in Tierra Blanca, 10 were lung cancer and 4 were mesotheliomas. The annual rate of lung cancer was 7.09/1,000 (males) and 4.75/1,000 (females). The annual rate of mesothelioma was 2.48/1,000 (males) and 1.05/1,000 (females). The national incidence rate of lung cancer was 13.2/100,000(males) and 5.4/100,000 (females).
Oczypok et al. 2016 Mexico	Case report (n): 1 case	Lung digest	Male	Epithelial malignant pleural mesothelioma	The morphology and composition of the fibres are consistent with erionite. No asbestos fibres were found.

(17 out of 141). The annual crude mesothelioma mortality rate was approximately 8 deaths per 1,000 inhabitants. No cases of malignancy for the same sites were reported from the control village (Karlik) (Baris et al. 1987). A 1989 re-analysis showed a clear-dose response with cumulative fibre exposure. It also showed that a cumulative dose of 1 fibre/year/ml from birth was associated with a pleural mesothelioma rate of 996/100,000 person-years (Simonato et al. 1989). A subsequent (1996) mortality study showed that mesothelioma accounted for 51.5% of deaths in Karain, 38.2% in Tuzköy, and 21.8% in Sarihidir between 1970 and 1994, with excess cases of lung cancer also attributed to erionite exposure (Bariş et al. 1996).

Two cohort studies were conducted. The first, which followed 891 inhabitants from two exposed (Karain and Sarihidir) and one control village (Karlik) from 1979 to 2003, reported an extremely high mesothelioma incidence in the exposed villages, with 697 and 197 cases per 100,000 annually versus 11/100,00 in the control village (Baris and Grandjean 2006). The second cohort study, which followed 322 inhabitants from Karain from 1990 to 2006, showed annual mesothelioma incidence rates of 639/100,000 in males and 1266/100,000 in females. The higher rates in women are different from international mesothelioma trends, where higher incidence rates are typically observed in males. This, combined with earlier onset, i.e. the mean age of mesothelioma patients linked to erionite exposure is notably lower (53 yr for males and 48 yr for females) compared to cases caused by asbestos exposure (around 60 to 65 yr) (Talcott 1988; Hagemeyer et al. 2006), suggest unique exposure patterns, with exposure likely occurring as early as childhood (Metintas et al. 2019). Environmental samples showed that two (Akkusak stone and Water stone) out of eight types of stone contained erionite within the nodules, with both types of stone commonly used for the walls of houses in the village. Apart from mesothelioma, calcified pleural plaques were also commonly found in erionite-exposed villages (Baris et al. 1987; Karakoca et al. 1997; Emri et al. 2002).

Studies in Europe of Turkish migrants

Mesothelioma cases have been reported among Cappadocian immigrants in Sweden. In particular, three mesothelioma cases among 94 Karain immigrants were reported, with evidence of erionite fibres found in lung tissue (Boman et al. 1982). A few years later, another four mesothelioma cases among the same migrant group were observed (Ozesmi et al. 1990), and a case report was published of a Turkish migrant from Karain who was also diagnosed with mesothelioma (Hillerdal and Elmberger 2007). A subsequent cohort study (Metintas et al. 1999) also from Sweden, which followed 162 Turkish immigrants from Karain from 1965 to 1997, showed a significantly higher mesothelioma incidence when compared with a native Swedish population of the same sex and age—the standardised incidence ratio was 135 times higher for men and 1336 times higher for women. Another Swedish cohort study (Mousavi et al. 2010), following Turkish immigrants from 1958 to 2006, showed elevated mesothelioma mortality rates compared to the native Swedish population, with a standardised incidence ratio for Turkish immigrants of 5.29 (95% confidence interval: 3.08 to 8.47). A 2021 study comparing mesothelioma mortality between first-generation immigrants from Karain, and second-generation immigrants born in Stockholm, found all mesothelioma cases in the first-generation immigrants, thus reinforcing erionite exposure in Turkey as the primary cause (Metintas et al. 2021).

Case reports of erionite-induced pleural plaques, lung cancer, and mesothelioma in Turkish immigrants have also been reported in Germany and Belgium (Dumortier et al. 2001b; Gräsel et al. 2008) with one study reporting erionite fibres in bronchoalveolar lavage fluid and exposure to erionite linked to Tuzköy, Turkey.

Studies from North America

Until recently, erionite was not generally considered a hazard in North America. However, there is now some evidence of erionite exposure-associated health effects in North America (Weissman 2011). In 1981, a Utah road construction worker developed pleural fibrosis, with a subsequent lung biopsy revealing erionite fibres (Rom et al. 1983; Casey et al. 1985). This was the first study suggesting adverse health effects associated with occupational erionite exposure, despite evidence that occupational exposures may be more widespread (see below).

In 2008, a cluster of mesothelioma cases was reported in a Mexican village built on a zeolitized sedimentary bed. Twelve mesothelioma cases (8 males and 4 females) were observed from 1999 to 2006. Although only clinoptilolite (a non-fibrous zeolite) was found in environmental samples, erionite exposure was suspected (Ilgren et al. 2008).

In 2009, the first US case of erionite-associated pleural mesothelioma was reported, involving a 47-yr-old male, originally from Mexico. Lung tissue analysis revealed erionite fibres, most likely related to environmental exposure in his hometown (Kliment et al. 2009). A study comparing mortality rates in Tierra Blanca de Abajo, a rural village in Guanajuato State, central Mexico, where geological formations have high erionite content, with those of the entire Mexican population, revealed elevated rates of mesothelioma and lung cancer among the villagers. The annual age-standardised mortality rates per 1000 inhabitants (aged >20 yr) were 2.48 and 7.09 for males, and 1.05 and 4.75 for females, due to mesothelioma and lung cancer, respectively. Erionite fibres were found in rocks, soils, and building materials, suggesting environmental exposure as the main cause (Ortega-Guerrero et al. 2015).

In 2011, a cross-sectional study in North Dakota identified chest radiographic abnormalities in 21% of residents that were consistent with erionite exposure, potentially from road gravel containing erionite (Ryan et al. 2011). This study also found abnormalities among subjects with occupational exposure to erionite-containing road gravel, although no cases of mesothelioma were detected. The most frequently reported primary exposure was working in gravel pits and/or road maintenance (44%), followed by frequent driving (20.6%), and ranching/farming (17.6%) (Ryan et al. 2011). Furthermore, a 2016 case report documented erionite-associated pleural mesothelioma in a vehicle repairman raised in the Mexican Volcanic Belt region, with erionite fibres found in both the patient's lung tissue and on their family farm (Oczypok et al. 2016). For all these studies, there was no evidence that asbestos played a role.

Erionite exposure

Residential areas adjacent to erionite-rich geological formations, including villages and towns, present potential exposure risks. These risks may arise from the use of erionite-containing building materials in homes, workplaces, roads or recreational facilities, such as those in the Turkish villages discussed above. Additionally, individuals residing or working near areas where erionite-containing rock or soil is being disturbed may also be exposed.

Currently, there are no standardised sampling and analytical methods for measuring airborne erionite fibres, and sampling methods similar to those for asbestos are therefore typically used. Exposure levels are quantified as the number of fibres per cubic centimetre (f/cc) or millilitre (f/ml) of air. Although there is no general consensus, fibres are usually defined as particles that exhibit an aspect ratio (L/w) of ≥3:1, with a length greater than 5 µm, and diameters less than 3 µm (WHO 1996). Identification of erionite in rock materials is achieved through screening procedures which start with polarised light microscopy (PLM), with additional methods like X-ray powder diffraction (XRD), scanning electron microscopy (SEM) with energy dispersive X-ray spectroscopy (EDS), and transmission electron microscopy (TEM) equipped with EDS required to confirm the presence of erionite rather than other similar but assumed less toxic zeolites such as mordenite (Hamilton 2022; Agrawal et al. 2024). For occupational and air samples, TEM and SEM-EDS are the most utilised methods, following established asbestos reference methods (NIOSH 2022).

An overview of studies reporting environmental and occupational airborne erionite exposure levels, using the methods described above, is provided in Tables 3 and 4 and discussed in further detail below.

Exposures related to residential building materials containing erionite

As noted earlier, studies have shown that building materials (stone, caves, walls made of tuff) in the Turkish villages of Tuzkoy, Karain, and Sarihidir contain zeolite fibres, including mordenite, erionite, and chabazite (Artvinli and Bariş 1979; Mumpton 1979; Pooley 1979; Baris et al. 1981, Baris et al. 1987; Simonato et al. 1989; Metintas et al. 2010). Further studies have confirmed that this results in elevated airborne exposures to erionite. In particular, indoor environmental concentrations of erionite fibres during cleaning activities in Karain houses ranged from <0.01 to 1.38 f/ml (Table 1) (Baris et al. 1981, Baris et al. 1987) with levels increasing more than 60 times during the sweeping of walls and floors (from 0.005 to 0.31 f/ml) (Baris et al. 1987). The houses with the highest fibre concentration had walls constructed from friable soft volcanic rock (tuff) containing fibres with a mean length of 20 µm and a mean diameter of 1.3 µm. Elemental analysis confirmed the presence of erionite in this tuff, which was observed in several family caves (Baris et al. 1981).

Outdoor concentrations measured near disturbed erionite-containing rock or soil

Studies from Turkey have shown that those living in villages with high mesothelioma rates, often near erionite-containing soils and rocks, also experienced outdoor exposures (in addition to indoor exposures) with erionite concentrations ranging from 0.001 f/ml to 0.3 f/ml (Baris et al. 1981, Baris et al. 1987; Simonato et al. 1989) (Table 3). In Karian, airborne fibre concentrations on streets were below 0.01 f/ml, but higher concentrations (0.2 to 0.3 f/ml) were observed in and around school playgrounds, work fields and stone-cutting areas (Baris et al. 1981).

In North Dakota, USA, gravel deposits containing erionite are situated in or near the Arikaree, Brule, and Chadron geologic formations corresponding to the Chalky Buttes, Little Badlands, and Killdeer Mountain areas in Slope, Stark, and Dunn counties (DEQ 2006). Over recent decades, gravel pits have been excavated in areas with naturally occurring erionite deposits, with erionite-containing gravel used to surface local roads, parking lots, and other areas, including school bus routes, parking lots, playgrounds, and baseball fields (Carbone et al. 2011; Weissman 2011; Pacella et al. 2018). Airborne erionite was found near roads at school bus stops and inside buses; it was also found in cars driving on erionite-containing gravel roads, thus indicating the potential for exposure for those living or working near these sites (Carbone et al. 2011; Weissman 2011). Further air sampling conducted by the US Geological Survey and the Environmental Protection Agency (EPA) confirmed the presence of erionite (Sheppard 1996), with fibre concentrations ranging from 0.003 to 0.02 s/cc during activity-based personal sampling scenarios (e.g. driving cars and school buses on gravel roads) (Carbone et al. 2011). In addition, stationary air sampling near roads showed concentrations from 0 to 0.001s/cc (Carbone et al. 2011) (Table 3). Full details on environmental erionite exposure levels from these studies are provided in Supplementary Table 3.

Occupational erionite exposure

Occupational environments with potential for exposure to airborne erionite historically include commercial mining and production of erionite. However, since the late 1980s, erionite mining for commercial purposes largely stopped (IARC 2012). Despite this, other zeolites are still commercially mined and quarried, notably in Italy and New Zealand (Brathwaite 2017), for applications in pet litter, soil conditioners, animal feed, wastewater treatment, and gas absorbents.

Table 3. Environmental airborne erionite exposure levels

Location, Activity	Erionite (f/ml, or s/cc)*	Sample duration (minutes)	Exposure measurements / Analytical method#
Turkey			
Baris et al. 1981			
Karain			Fibres were analysed with EDAX in conjunction with TEM.
Outdoor stationary sampling	<0.01–0.3 f/ml	1440–1800	
Indoor activities sampling (swept the walls and floors in the cave home)	<0.01 f/ml–1.38 f/ml	1440–1800	
Karlik			
Outdoor stationary sampling	<0.01 f/ml	1440–1800	
Indoor activities sampling (swept the walls and floors in the cave home)	<0.01 f/ml	1440–1800	
Baris et al. 1987			
Karain			Fibres were analysed with EDAX in conjunction with TEM.
Outdoor stationary sampling	0.002–0.175 f/ml	120–480	
Indoor activities sampling (swept the walls and floors in the cave home)	0.005–0.31 f/ml	120–480	
Sarihidir			
Outdoor stationary sampling	0.001–0.029 f/ml	120–480	
Indoor activities sampling (swept the walls and floors in the cave home)	0.005–1.0 f/ml	120–480	
Tuzköy			
Outdoor stationary sampling	0.005–0.025 f/ml	120–480	
Indoor activities sampling (swept the walls and floors in the cave home)	0.005–0.08 f/ml	120–480	
Karlik			
Outdoor stationary sampling only	0.002–0.006 f/ml	120–480	
Simonato et al. 1989			
Karain	0.002–0.01 f/ml	120–480	Fibres were analysed with EDAX in conjunction with TEM.
Sarihidir	0.001–0.029 f/ml	120–480	
USA			
Carbone et al. 2011			
North Dakota			Fibre concertation was determined by Phase contrast microscopy equivalent (PCME).
Outdoor stationary sampling	0–0.01 s/cc	n/a	
Outdoor activity-based sampling (driving cars and school buses on gravel roads)	0.003–0.02 s/cc	n/a	
Indoor stationary sampling	0–0.001 s/cc	n/a	
Indoor activity-based sampling (during cleaning activities)	0–0.06 s/cc	n/a	

*f/ml: fibres per millilitre; s/cc: structures per cubic centimetre.

If erionite is present as a component in these zeolites, quarrying and processing may pose a risk of occupational exposure to erionite (Giordani et al. 2016), but to date this has not been studied. Quarries and mining activities in the zeolite host rocks of Italy's Lessini Mountains used for construction is another example of where potential exposure may occur given the discovery of fibrous erionite in these areas, but again, to date, this has not been studied (Giordani et al. 2016, 2017a). Likewise, major groundworks and tunnelling projects that may disturb erionite deposits on building sites may also pose risks, such as in Auckland, New Zealand, where the occurrence of erionite in the underlying rock materials has been known for more

Table 4. Occupational airborne erionite exposure levels

Location: Activity (number of employees sampled)	Erionite (f/cc)*	Sample duration (minutes)	Exposure measurements / Analytical method
USA			
Beaucham et al., 2018			
Full-shift task-based personal air sample conducted in July 2013 (these samples were collected while it was dry)			
campground maintenance			Occupational personal breathing zone (PBZ) samples and area air samples for erionite were collected on 25-millimetre (mm) mixed cellulose ester filters at a flow rate of 1.5 L/min. Analysis was done by counting fibres using phase-contrast microscopy (PCM), according to the NIOSH Method 7400.
Felling and bucking (11 employees)	ND#–0.056	155–233	
Mowing (5 employees)	0.012–0.26	54–290	
universal terrain vehicle operation			
Operator and assistant (4 employees)	0.0077–0.015	302–336	
thinning, bucking, felling, mastication			
Chainsaw operation (6 employees)	0.024–0.11	141–225	
Masticator (1 employee)	0.36	213	
Log stacker (1 employee)	0.061	214	
Skid loading (1 employee)	0.078	164	
digging fire line			
Polaski† (2 employees)	0.025 and 0.11	204 and 206	
Combi† (2 employees)	0.081 and 0.026	203 and 321	
Rogue hoe† (2 employees)	0.016 and 0.057	218 and 324	
McCloud† (1 employee)	0.008	320	
Full-shift task-based personal air sample conducted in September 2014 (these samples were collected while it was raining and snowing)			
thinning, bucking, felling, mastication			Occupational personal breathing zone (PBZ) samples and area air samples for erionite were collected on 25-millimetre (mm) mixed cellulose ester filters at a flow rate of 1.5 L/min. Analysis was done by counting fibres using phase-contrast microscopy (PCM), according to the NIOSH Method 7400.
Chainsaw operation (4 employees)	0.012–0.096	516–522	
Masticator (1 employee)	0.015	501	
Driving (1 employee)	0.013	496	
Campground maintenance and pushpit reclamation			
Mowing (3 employees)	0.001–0.002	296–298	
Seeding pushpit (2 employees)	0.005 and 0.006	595 and 597	
Safety at pushpit (2 employees)	0.003 and 0.004	564 and 569	
Bobcat operator (1 employee)	0.009	585	

*f/cc: fibres per cubic centimetre. #ND-non detectable.

than two decades (Davidson 1994). To date, only three studies (all from the United States) have assessed occupational exposure to erionite, with only two providing quantitative data (described in more detail below).

Between 2012 and 2013, the US Health Hazard Evaluation Program studied occupational exposures to erionite and respirable crystalline silica in workers repairing and maintaining dirt roads where erionite was suspected (Beaucham et al. 2014). Personal and area air samples were taken during tasks including culvert replacement, road blading/grading, replacing cattle guards with a backhoe, and replacing aggregate on a parking lot. No erionite was detected in the air or bulk samples, but due to the small number of samples ($n = 14$) and variable geological conditions, potential exposure to erionite cannot be ruled out.

Another study was conducted in Wyoming, South Dakota, and Montana where some of the rock formations are known to contain erionite (Beaucham et al. 2018). In this study, exposure to airborne erionite was measured in forestry workers who performed various tasks including dirt road maintenance, cattle guard replacement, parking lot and campground maintenance, tree thinning and vegetation reduction, digging fire lines, pushpit reclamation, and spraying invasive species. Erionite fibres were detected in full-shift personal air samples from workers involved in dust-generating tasks, with airborne erionite concentrations ranging from non-detectable to 0.36 f/cc (Table 4). The highest airborne erionite concentrations were found in workers operating the masticator (0.36 f/cc), followed by those mowing the campground (0.26 f/cc), digging fire lines with a pulaski axe (0.11 f/cc), and those operating chainsaws (0.11 f/cc) (Table 4). Airborne erionite concentrations were lower in wet weather (maximum 0.096 f/cc, Table 4) compared to dry weather. To date, this is the only study that has shown elevated airborne erionite levels in an occupational environment.

Discussion

Building upon earlier research on erionite exposure, particularly studies from Turkey, the IARC reaffirmed in its 2012 review the carcinogenic potential of erionite based on population studies from both Turkey and Sweden. The review also noted that occupational exposure to erionite could occur during the mining, production, and use of other zeolites, but no studies on occupational erionite exposure had been conducted at that time (IARC 2012). Since then, additional cases of erionite-related mesothelioma and lung cancer have been reported in Mexico (Ortega-Guerrero et al. 2015; Oczypok et al. 2016), and studies in the United States have documented occupational exposure, particularly among forestry workers (Beaucham et al. 2018). These findings not only expand the geographic scope of erionite-related health risks but also highlight the potential for occupational exposure to erionite in diverse settings. Revisiting historical data from Turkey and Turkish migrants alongside emerging findings from North America underscores the urgent need for further research and regulatory measures to mitigate exposure and its associated health risks.

Most epidemiological studies on erionite exposure have focussed on two primary populations: residents of the Cappadocia region in Turkey and a small village in Guanajuato, Mexico. Studies have confirmed the presence of erionite fibres in the environment of these affected villages (Baris et al. 1987; Ortega-Guerrero et al. 2015). Lung tissue samples from affected individuals in these areas have also confirmed the presence of erionite fibres. In particular, of 11 studies examining both asbestos and erionite fibres in either lung tissues (Baris et al. 1978, Baris et al. 1987; Artvinli and Bariş 1979; Casey et al. 1981; Sebastien et al. 1981; Boman et al. 1982; Rohl et al. 1982; Bariş et al. 1996; Karakoca et al. 1997; Kliment et al. 2009) or bronchoalveolar lavage fluid (BALF) (Dumortier et al. 2001a) from mesothelioma patients, seven confirmed the presence of erionite fibres in lung tissue or BALF in the absence of asbestos fibres (Artvinli and Bariş 1979; Casey et al. 1981; Sebastien et al. 1981; Bariş et al. 1996; Karakoca et al. 1997; Dumortier et al. 2001a; Kliment et al. 2009). The remaining four studies found only trace amounts of tremolite or chrysotile asbestos, while over 90% of the fibres identified in lung tissue were erionite (Baris et al. 1978, Baris et al. 1987; Boman et al. 1982; Rohl et al. 1982). Mineralogical studies in these villages also detected erionite fibres and ferruginous bodies in sheep lung tissue (Baris et al. 1987), reinforcing that erionite is the primary cause of mesothelioma in these regions. Both environmental and residential exposures were identified as the main routes of contact in these populations.

Studies from Turkey suggest that erionite-related mesothelioma cases could be underreported due to various factors, including a lack of awareness of the exposure-disease link, misdiagnosis (Baris et al. 1987; Carbone et al. 2007, 2011), and limited diagnostic resources in some regions (Carbone et al. 2007). In fact, in rural areas with restricted healthcare access, mesothelioma was often misdiagnosed as tuberculosis (in the case of malignant pleural mesothelioma) or as ovarian cancer or cirrhosis (in the case of malignant peritoneal mesothelioma) (Bariş et al. 1996; Emri 2017). Additionally, in erionite-exposed regions like rural Cappadocia, efforts to obtain an accurate or biopsy-confirmed diagnosis were often restrained by limited access to specialised diagnostic tools and, in some cases, religious considerations (Baris et al. 1987). Baris et al. also reported misclassifications due to incomplete records in disease registries. For example, nine male cases initially recorded simply as "cancer" were later identified as pleural mesothelioma or lung cancer in Tuzköy (Baris et al. 1987).

Peritoneal mesothelioma, though less common than pleural mesothelioma, has also been reported in erionite-exposed villages in Turkey and among Turkish immigrants in Sweden (Baris et al. 1987; Metintas et al. 1999, 2021; Baris and Grandjean 2006). While mesothelioma is primarily linked to inhaling carcinogenic fibres, the exact mechanism by which erionite fibres reach the peritoneum remains unclear. Ingestion is a possible route, as studies from Turkey have shown airborne erionite fibres in homes, outdoor playgrounds, and recreational areas, where they could settle on food, water, or hands, thus potentially resulting in ingestion. Additionally, inhaled fibres may be swallowed after being coughed up from the lungs (ATSDR 2001b) or migrate via interstitial fluid to the lymph nodes and bloodstream, potentially reaching the abdominal cavity (Miserocchi et al. 2008). These findings emphasise the need for further research on the full impact of erionite exposure on peritoneal mesothelioma.

The latency period for erionite-related mesothelioma has been reported to range from 30 to 50 yr, with most exposures occurring during childhood, often within the home environment (Carbone et al. 2007, 2011; Metintas et al. 2010, 2021). For example, Selcuk et al. documented mesothelioma cases in patients from Cappadocia as young as 26 and 27 yr old (Selçuk et al. 1999). A similar pattern was observed in Wittenoom, Western Australia, where children exposed to mined crocidolite (blue asbestos) developed mesothelioma in their 40s or 50s, with the youngest case diagnosed at age 26 yr (Reid et al. 2018). However, the majority (93.5%) of children in Wittenoom who were exposed to crocidolite left the area by the age of 16, limiting their exposure to asbestos primarily during childhood. In contrast, children in the erionite-exposed village in Turkey were exposed to erionite from childhood into adulthood, resulting in a significantly longer exposure period. Both the experiences in Wittenoom and Cappadocia highlight the urgent need to address environmental exposures to carcinogenic fibres that may result in childhood exposures and long-term health consequences.

While studies in the United States have identified potential occupational exposure to erionite in outdoor maintenance jobs and noted pulmonary changes among individuals working in erionite-rich areas, mesothelioma clusters in naturally occurring erionite areas have not (yet) been documented in the United States. This apparent absence of erionite-associated mesothelioma cases in the United States may be attributed to the transient nature of at-risk populations, such as migrant workers, or the relatively small workforce in quarries, gravel pits, and maintenance jobs (Ilgren et al. 2008). Moreover, as noted above, erionite-related mesothelioma has a latency period of approximately 30 to 50 yr (Carbone et al. 2007, 2011). This prolonged latency, combined with the cross-sectional nature of studies and the limited number of studies conducted, may further explain the absence of observed erionite-associated mesothelioma cases in the United States.

Although studies on airborne erionite concentrations in environmental or occupational settings remain limited, studies from Turkey have shown that outdoor exposure can range from 0.001 to 0.3 f/ml outdoors, surpassing asbestos levels found near the Wittenoom mine (see above; 0.001 f/cc) (Ashton 1986); indoor levels were shown to range from 0.005 to 1.38 f/ml (Table 3). In the United States, occupational exposure levels to erionite fibres range from non-detectable to 0.36 f/cc, with only one sample identified as non-detectable (Beaucham et al. 2018). To provide some further context, asbestos levels in outdoor air in rural areas typically register 0.00001 f/cc, with levels in urban areas potentially being up to 10 times higher, and areas in close proximity to asbestos mines or factories reaching 0.01 f/cc or more (ATSDR 2001a). Therefore, rionite levels may in some cases exceed levels typically found for asbestos. For example, in areas where roads contain erionite-rich gravel, such as Dunn County in North Dakota, ambient levels can reach 0.001 f/cc, which is 100 times higher than rural asbestos levels (Carbone et al. 2011).

As there are no established occupational exposure limits (OELs) for erionite, exposures are often compared to those for asbestos due to similarities in health effects associated with both and the similarities in fibre composition. When the detectable erionite exposures observed in the US study are compared with international asbestos standards, it is evident that more than 4 of the 50 samples collected exceeded the asbestos exposure limit of 0.1 f/cc as used in the United States and several other countries (HSE 2006; EU 2009; Australia 2013; OSHA 2014; Worksafe 2016; NIOSH 2018; Health-Canada 2023), and more than 28 of the 50 samples exceeded the new European Commission's limit of 0.01 f/cc (EC 2022, 2023). Given that erionite fibres present a higher risk of causing mesothelioma compared to asbestos (Wagner et al. 1985; Coffin et al. 1992), a significantly lower exposure limit for erionite may be required as recommended by Ilgren and colleagues (Ilgren and Browne 1991; Ilgren et al. 2008) and Jurinski and Jurinski (1997). The latter proposed an OEL of 0.0007 f/cc, based on observed excess mortality from environmental exposures in Turkey. Applying this limit to the samples collected in the United States study conducted by Beaucham et al. (2018) shows that, with the exception of one non-detectable sample, all measured erionite levels exceeded this more stringent limit.

Although occupational erionite-associated mesothelioma has not been identified yet, current findings suggest that some workers may be at risk. This underscores the need for effective exposure reduction measures in areas where erionite has been detected and/or where occupational exposure is likely, even in the absence of direct evidence. In the absence of erionite-specific guidelines, existing asbestos regulatory frameworks and management strategies serve as a useful model (see e.g. WHO 2018; EPA 2021).

Conclusions

There is clear evidence that environmental exposure to erionite in the Cappadocia region of Turkey, and Guanajuato in central Mexico are causally associated with the high mesothelioma rates observed in these areas. Evidence for other parts of the world where there is naturally occurring erionite is limited. In particular, although exposure to erionite is emerging as an occupational and public health concern in the United States

(Beaucham et al. 2018), Italy (Giordani et al. 2017b), and New Zealand (Brook et al. 2020; Patel and Brook 2021), very little research has been conducted in those areas to assess occupational and environmental exposures and associated health risks. Thus, it remains unclear whether erionite exposure in those parts of the world represents a significant public/occupational health issue. Recent evidence from one US study suggests that occupational exposure may occur at levels that are of significant concern, thus warranting further research to more extensively assess environmental and occupational exposures, particularly around activities where erionite-containing rock and soil are disturbed. In the meantime, drawing on extensive experience with asbestos over the past seven decades, it is prudent to start implementing the precautionary principle and the hierarchy of controls to minimise potentially hazardous exposures in those situations, thus mitigating the potential health risks associated with erionite exposure.

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Author contributions

Grace Chen: Conceptualisation, study identification, writing - original draft. Andrea ‘t Mannetje: Conceptualisation, study identification, review and editing. Jennifer A. Salmond and Jeroen Douwes: Conceptualisation, review and editing.

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Conflict of interest

The authors declare no conflict of interest relating to the material presented in this Article. Its contents, including any opinions and/or conclusions expressed, are solely those of the authors. The authors declare they have no actual or potential competing financial interests.

Data availability

This review is based on articles previously published in scientific journals. The references for the identified articles are provided in Table 1 and Table 2. The references for the exposure levels are presented in Table 3 and Table 4. Full information from these papers is provided in Supplementary Tables 1 to 3.

Supplementary material

Supplementary material is available at *Annals of Work Exposures and Health* online.

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