

The Use of Asbestos and Its Consequences: An Assessment of Environmental Impacts and Public Health Risks

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Abstract: The use of asbestos, once celebrated for its versatility and fire-resistant properties, has left a lasting legacy of environmental degradation and public health risks. This paper provides a comprehensive assessment of the environmental impacts and health risks associated with asbestos, highlighting its widespread use, environmental persistence, and adverse effects on human health. Through a literature review, this study examines the historical context of asbestos use, its adverse environmental effects and the mechanisms by which exposure to asbestos poses significant health risks, including the development of asbestos-related diseases such as mesothelioma, lung cancer, asbestosis, etc. It also assesses the current regulatory framework and provides a methodological analysis of the strategy for recycling end-of-life materials containing asbestos fibers, proposing the inclusion of asbestos-containing materials (ACMs) in the rock wool industry to reduce Greenhouse Gasses (GHG) emissions. Drawing on interdisciplinary insights from environmental science, public health, and regulatory analysis, this paper concludes with recommendations for improving asbestos management strategies, promoting safer alternatives and mitigating the long-term environmental and human health impacts of asbestos.

Keywords: asbestos management; environmental impact; public health risks; asbestos-related diseases; regulatory framework; asbestos-containing materials; asbestos fiber recycling



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1. Introduction

1.1. Subject Contextualization

The continuous increase in population, along with the resource scarcities and global climate change issues, has made the idea of self-sustainable building design, made of eco-friendly construction materials, into a new challenge currently [1]. For this, the use of safe and efficient building materials will help to reduce the ecological footprint and promote sustainable construction, mainly through the selection of adequate building materials, particularly concerning construction safety, non-toxic, environmentally safe, and made of recycled products [2]. Based on this principle, traditional building materials, like the ones adopted in the construction design in the XX century (lead, mercury, polychlorinated biphenyls (PCBs), chlorofluorocarbons, asbestos, etc.), should be removed from existing buildings and recycled. In the specific case of the use of asbestos containing materials (ACMs), the use of asbestos began to rise between the 1920s and the 1930s of the XX century and peaked between the 1970s and the 1980s of the XX century, due to the excellent physical properties of this natural fiber, such as high tensile strength, good electrical, and acoustic insulation, good chemical and fire resistance, high thermal resistance, and good durability [3,4]. Based on these improved mechanical and chemical properties, this fiber has been widely used in building construction, mainly in asbestos–cement structural products for roofing and walls and also in drywall and joint compound, vinyl floor tiles

and adhesives, panels, countertops, pipes, acoustic ceilings, fireproofing technical solutions, thermal pipe insulation, heating, ventilation and air conditioning (HVAC) ducts, and, above all, in roofing sheets, particularly the “white asbestos” (chrysotile), the “brown asbestos” (amosite), and the “blue asbestos” (crocidolite) [5].

In the particular case of Portugal, the commercial exploitation of asbestos minerals was not so developed and spread. However, some references can be found, showing that, even in small amounts, the exploitation of asbestos was a reality. For example, Gomes et al. (2010) [6] studied several occurrences in northeastern Portugal, particularly in Donai, Pena Maquieira, and Mourisqueiro, where the commercial exploitation of amphibole asbestos minerals was closely linked with serpentinites, amphibole schists, and steatitic rocks. These sites have been significant for their commercial use, where asbestos has been extracted and utilized in various industries. The Donai quarry and the talc mines of Pena Maquieira and Mourisqueiro have been the focus of detailed studies to assess their environmental impact, especially since long-term exposure to amphibole asbestos is known to cause severe pulmonary diseases. At Donai, tremolite asbestos is found in shear zones and faults intersecting serpentinites, while non-fibrous tremolite is present as intercalations within amphibole schists and chloritites. Notably, the serpentinites from the Donai quarry are largely tremolite-free. In contrast, at Pena Maquieira, tremolite asbestos fills faults cutting through serpentinites, and at Mourisqueiro, actinolite asbestos is found within amphibole schists and steatitic rocks in a highly deformed zone. The commercial exploitation of these serpentinites and steatitic rocks necessitates precise geological mapping, petrographic microscope examinations, and electron microprobe analysis, including the determination of SiO_2 , CaO , and MgO in serpentinites and CaO and MgO in steatitic rocks. Using these resources, but importing the majority of the materials, in the 1980s, the use of ACM was extensively adopted, mainly for the application of “white asbestos” in most of the covering solutions in roof and façade coating as a simple and inexpensive solution. Therefore, a strategy towards recycling end-of-life materials containing asbestos fibers is a topic broadly addressed as a societal problem yet to be solved, despite all well-documented asbestos-associated illnesses, such as mesothelioma and asbestosis, pleural plaques, thickening and effusions, and lung cancer [7]. On the other hand, the identification of the best practices to promote a set of awareness-raising actions aimed at employers, the workplace in general, and among citizens for eradicating asbestos-associated illnesses is a societal problem that must be addressed [8].

This paper aims to provide an overview of the assessment of the environmental impact and public health risks of asbestos and a methodological analysis of the strategy for recycling end-of-life materials containing asbestos fibers. To this end, this paper is structured as follows: Section 1 describes the background to the subject, the aim of the study, the purpose of the review, and the structure of the paper. Section 2 describes asbestos, including its composition, types, origin and natural occurrence, chemical and mineralogical structure, properties, classification, and forms. Section 3 presents the history of asbestos use, including ancient and traditional applications, industrial expansion and growth in use, and current prohibition. Section 4 highlights how asbestos is applied and used. Section 5 highlights the negative health and environmental impacts of asbestos. Section 6 looks at the removal and management of asbestos as waste, both in terms of legislation and guidelines for safe handling, as well as removal and decontamination techniques and the destination and treatment of the waste generated. Finally, Section 7 summarizes the conclusions of the study.

1.2. Objectives and Rationale for the Review

The World Health Organization (WHO) reports that over 125 million individuals globally face asbestos exposure risks in their workplaces and homes [9]. In response to this issue, the Fifty-eighth World Health Assembly (2005) urged all Member States to take action to reduce the cancer risks associated with chemical exposure in workplaces, homes, and other environments [10]. Asbestos, in particular, is highlighted as the most

significant carcinogenic substance, responsible for approximately half of occupational cancer fatalities [11].

In 2007, the Sixtieth World Health Assembly endorsed an action plan targeting the elimination of asbestos-related diseases [12]. This WHO plan includes providing technical support to Member States to help eradicate asbestos-related diseases in countries where the use of chrysotile asbestos remains common, along with support for managing exposure from traditional asbestos applications.

In Europe, the disposal of asbestos has been regulated within the European Union since 2005. However, due to its widespread use in the 1980s, particularly in Portugal, asbestos remains prevalent, especially in the roofing sheets of buildings (Decreto-Lei n° 101/2005, Diário da República I Série—A, 119 (05-06-23) 3937–3939 [13]). Estimates from 2008 indicate that approximately 600,000 buildings in Portugal were covered with asbestos–cement roofing sheets, which contain between 10 and 15% of carcinogenic material [14]. In 2003, the Portuguese National Assembly urged the government to create an inventory of public buildings containing asbestos within a year and to implement a refurbishment plan for these buildings (Resolução da Assembleia Da República n.o 24/2003, DR I-A Série. 77 (2003-04-01) [15]. Despite these recommendations, as of 2023, the Portuguese public administration is still struggling to compile a comprehensive list of potentially contaminated public buildings. The cost of removing 500 m² of asbestos roofing averages around €5000, which includes analysis and waste management. In contrast, treating mesothelioma, a family of rare neoplasms arising from mesothelial linings caused solely by asbestos exposure, costs the Portuguese Health Service an average of €262,939, according to WHO data, consistent with the European average. This figure does not account for the full extent of the costs, particularly the human suffering experienced by patients and their families. The economic loss for the Portuguese State is therefore about 50 times greater than the cost of removing an asbestos roof [16]. However, removing asbestos and treating mesothelioma do not exclude each other.

In 2011, the Portuguese Government passed a new law (Lei n° 2/2011. Diário da República I Série, 28 (11-02-09) 706 [17]) to promote the removal of asbestos from public buildings and facilities. However, the law has not been fully implemented, and in many cases, retrofitting works on public buildings proceed without prior surveys to determine the presence or location of asbestos. Moreover, there is no publicly accessible list of companies accredited to safely remove and recycle asbestos roofing, leaving building owners uncertain about the reliability of the services they hire. Later, Ordinance 40/2014 (Portaria n° 40/2014, de 17 de fevereiro. Publicação: Diário da República n° 33/2014, Série I de 2014-02-17, páginas 1435–1442 [18]) was enacted to establish guidelines for the removal, transport, and management of asbestos waste, designating authorized landfills for disposal. Nonetheless, a report presented to the Portuguese Parliament in February 2021 by the Technical Monitoring Committee, created under this Ordinance, identified several instances of non-compliance regarding proper asbestos waste storage in landfills and reported cases of illegal asbestos disposal. These findings highlight an urgent need for recycling or reuse solutions, though, to date, Portugal lacks licensed operations for the recovery of asbestos waste.

Numerous studies have sought solutions for managing asbestos waste or transforming asbestos-contaminated materials into non-hazardous waste. Wajima (2016) [19] discusses tests involving mechanical grinding for physical–chemical transformations and plasma treatments through thermal processes, among other methods. Talbi et al. (2019) [20] explore chemical treatments that destroy fibrous asbestos structures, converting the by-products into valuable materials. Zeng et al. (2020) [21] developed a porous ceramic glass from fly ash and asbestos-containing residues, which could serve as insulating building materials. However, there is no evidence that these laboratory studies have been implemented on a large scale for managing hazardous waste. Consequently, controlled landfill disposal remains the chosen solution in many countries.

2. Asbestos Characterization

2.1. Asbestos Definition and Types

Asbestos is a nomenclature adopted to designate a set of fibrous metamorphic minerals, which due to their characteristics, such as resistance to fire, heat, corrosion and electricity, have historically led to them being used in various industrial sectors [22]. However, it is important to highlight that asbestos exposure can be extremely harmful to health, being associated with several diseases, including cancer [23]. There are two main groups of asbestos minerals: the serpentine group and the amphibole group [24]. In the serpentine group, chrysotile is the only member and is the most common type of asbestos used commercially. This mineral is mainly made up of flexible, curved fibers, and is often used in products such as shingles, curbs, and siding [25]. On the other hand, the amphibole group includes several types of asbestos, such as amosite, crocidolite, tremolite, actinolite, and anthophyllite. These minerals are characterized by straighter and more rigid fibers compared to chrysotile. Crocidolite, in particular, is notable for its strength and durability, but it is also considered the most dangerous to human health due to its fineness and the ease with which its fibers can be inhaled [26].

2.2. Origin and Natural Occurrence

The formation of these minerals occurs naturally, being the result of complex geological processes. Chrysotile, for example, is often found in veins next to serpentinite rocks, formed under conditions of low temperatures and moderate pressures [27]. Amphiboles are typically associated with metamorphic rocks and can be formed in a variety of geological environments [28]. Globally, the exploitation of asbestos was intense, especially during the 20th century, due to its properties such as heat resistance, thermal and acoustic insulation, and durability. However, from the end of the 20th century, several countries began to restrict and even ban the use of asbestos, in response to scientific evidence linking exposure to the mineral to serious health problems, including cancer and lung disease [29]. The use of asbestos is currently the subject of much public health debate and concern, which has led to its total elimination in many regions of the world. [30]. However, there are still countries where the exploration and use of this mineral continues, under specific regulations [31].

2.3. Chemical and Mineralogic Structures

This category of minerals is mainly composed of magnesium and iron silicates, with the main asbestos categories being actinolite, amosite, anthophyllite, chrysotile, crocidolite, and tremolite [32]. Regarding its chemical structure, a variable composition is observed; however, the base is often a hydrated silicate with magnesium ions and, in some cases, iron ions [33]. Chrysotile, the most common type, is usually presented as hydrated magnesium silicate [34]. On the other hand, crocidolite and amosite are characterized by containing iron in their composition [35]. From a mineralogical point of view, asbestos is distinguished by its fibrous and flexible structure. These fibers are notable for their high thermal, chemical, and mechanical resistance, as well as their ability to be woven [36]. This fibrous structure gives asbestos its diverse industrial applications but is also the cause of the health risks associated with its inhalation [37]. In terms of mineralogical classification, asbestos belongs to the silicate group, more specifically to phyllosilicates (in the case of chrysotile) and amphiboles (for the other types mentioned). This classification is due to the way the atoms are arranged in the mineral's crystalline structure, giving it unique characteristics [38].

2.4. Heat Resistance and Thermal Insulation

The heat resistance that asbestos presents is due to its mineralogical composition and unique fibrous structure [39]. In heat resistance, asbestos fibers demonstrate an exceptional ability to withstand high temperatures without suffering degradation or alteration [40]. This property means that asbestos is often used in applications where heat resistance is a crucial requirement. On the other hand, concerning thermal insulation, asbestos fibers exhibit low thermal conductivity [26]. This means that heat transfer through asbestos is significantly

reduced, which contributes to its effectiveness as a thermal insulator. This insulation is especially valued in industries and constructions, where heat transfer management is a fundamental aspect [41].

2.5. Chemical and Electrical Resistance

The crystalline structure of asbestos gives it a high tolerance to chemical reactions, making it resistant to a wide range of acidic and alkaline substances [36]. This property is largely due to the mineralogical composition of asbestos, which includes hydrated magnesium silicates and other elements [42]. The electrical resistance of asbestos is significant [6]. The minerals that make up asbestos have low electrical conductivity, which allows them to be used as insulators in various industrial applications. This characteristic is particularly valued in environments where safety is a concern, such as in electrical installations and machinery components.

2.6. Flexibility and Durability

The flexibility of asbestos minerals is remarkable, allowing for them to be woven or mixed with cement and other materials, making them extremely useful in a variety of industrial and commercial applications [36]. The durability of asbestos is another significant feature [43]. Asbestos minerals are resistant to heat, fire, and chemical reactions, in addition to being excellent thermal and electrical insulators. This resistance makes asbestos a preferred material in products such as roof tiles, vehicle brakes, and insulation materials.

2.7. Asbestos Forms and Classification

Asbestos can be classified according to its morphology into three main categories: long fibers, short fibers, and matrix asbestos [44]. About long fibers, they are characterized by their considerable length concerning their width. This form of asbestos is often associated with a greater risk of inhalation due to its ability to be suspended in the air for prolonged periods [45]. On the other hand, short-form asbestos fibers are relatively shorter in length. Even though their ability to suspend in the air is reduced compared to long fibers, the risk associated with their inhalation should not be underestimated. Finally, matrix asbestos refers to how asbestos fibers are integrated or embedded in other materials. This form of asbestos is common in products in which the mineral is used as reinforcement or insulation. In this configuration, the risk of fibers being released into the air is significantly lower, especially if the material remains intact and undisturbed.

3. Asbestos Use History

3.1. Ancient and Traditional Applications

Historically, the use of asbestos dates back to ancient civilizations [46,47]. In Ancient Greece, it was used to make tablecloths and clothing due to its ability to resist fire [48]. These clothes and towels could be cleaned through exposure to fire, a property that amazed observers at the time. The Romans also used asbestos, especially in fabrics intended to wrap bodies before cremation, preserving the ashes of the remains [49]. Over the centuries, the use of asbestos has diversified. During the Industrial Revolution, its demand increased significantly, driven by industrial needs for fire-resistant and thermal-insulating materials [50]. It has been incorporated into products such as shingles, cement products, vehicle friction materials, and a variety of insulation products. In the 20th century, the use of asbestos reached its peak, being used in countless applications in commercial and residential buildings, and public infrastructures [51]. However, over time, the health risks associated with inhaling asbestos fibers became evident, leading to a decline in its use and a search for safer alternatives. The history of asbestos is thus marked by a trajectory of extensive use, driven by its unique properties, followed by a growing recognition of its health hazards, resulting in a significant decline and restrictions on its use [52].

3.2. Industrial Expansion and Growing Use

As previously mentioned, asbestos minerals have been extensively used in various industries due to their unique properties, such as heat resistance, thermal and acoustic insulation, and durability [53]. This use began at the end of the 19th century, when the potential of these minerals for industrial production was discovered. Initially, asbestos was used on a small scale, predominantly for thermal insulation in steam engines and boilers [53]. Over time, its application diversified, encompassing the construction industry, where it was used in tiles, panels, coverings, and asbestos-cement products. Its presence has also been found in products such as brake pads, fire-resistant fabrics, and various components of machines and equipment. During the 20th century, there was significant growth in the asbestos industry, driven by the two World Wars and the subsequent period of reconstruction, in which the demand for resistant and low-cost materials was high. This growth was also fueled by the expansion of the automobile industry and the construction boom, especially in developing countries. However, from the second half of the 20th century, concerns began to arise about the impacts of asbestos on human health. Studies have revealed that prolonged exposure to asbestos fibers could cause serious illnesses such as asbestosis, mesothelioma and lung cancer. These discoveries led to a gradual decline in the use of asbestos, culminating in strict regulations and bans in many countries.

3.3. Current Prohibition

The historical use of asbestos has left profound and enduring consequences, with a direct correlation observed between a country's past consumption of this mineral and the incidence of asbestos-related diseases within its population [54]. This correlation underscores the long-term health risks associated with asbestos exposure, as evidenced by the latency period between exposure and the onset of diseases such as mesothelioma and asbestosis, typically occurring 30 to 40 years later. Asbestos is often characterized as a "latency weapon" due to this delayed manifestation of health effects [55].

The relationship between asbestos consumption and mesothelioma cases is particularly striking, with statistical analyses revealing a significant correlation [56]. Research indicates that for every 170 tons of asbestos produced and consumed, at least one death from mesothelioma can be expected. This sobering statistic highlights the profound impact of asbestos exposure on public health and underscores the urgent need for continued efforts to mitigate asbestos-related risks and support exposed individuals and communities.

The reduction in asbestos use in developed countries has indeed prompted a global shift within the industry, often characterized by a stark "double standard". While developed nations have phased out and replaced asbestos due to its well-documented health risks, the mineral continues to be portrayed as an indispensable resource in many developing countries [57].

Despite scientific evidence dating back to the 19th century highlighting the dangers of asbestos to human health, meaningful action to restrict its use was slow to materialize. It was not until the 1970s that discussions regarding asbestos restrictions gained traction, and it took until the 1990s for a larger group of countries to implement bans [58]. This delay of almost a century between the initial scientific evidence and regulatory action underscores the challenges in addressing complex public health issues within the global regulatory landscape [59].

In 1993, the European Union proposed a comprehensive project to ban asbestos use entirely [60]. However, this initiative encountered resistance from several member states, including Portugal, Spain, France, and Greece. As a result, the plan was ultimately shelved, highlighting the complex political and economic dynamics that can impede efforts to address asbestos-related health risks at a regional level. Portugal was the last country in the European Union to ban the sale and use of all types of asbestos in 2005. This year, the European Union banned the production and use of this product (Commission Directive 1999/77/EC of 26 July 1999 adapting to technical progress for the sixth time Annex I to Council Directive 76/769/EEC (asbestos) [61]). The ban was the result of strong and long-

standing pressure from trade union organizations, victims, and representatives of victims who had been directly or indirectly harmed. In April 2022, the US Environmental Protection Agency (EPA) made available a rule to eliminate asbestos [62], which is expected to ban chrysotile asbestos, the only remaining use of asbestos in the US, used, for example, in the production of caustic soda. Similarly, according to the WHO, more than fifty countries have banned asbestos completely [63]. These countries oppose the controlled use of asbestos because scientific studies have not established a minimum level at which its handling and consumption would not cause damage to health and the environment. However, mines are currently operating in countries including South Africa, Russia, Brazil, Kazakhstan, Zimbabwe, and China. The persistence of asbestos mining and use in certain regions, despite well-documented health risks, underscores the need for continued advocacy and international cooperation to promote safer alternatives and facilitate the global transition away from asbestos [64]. Efforts to raise awareness, strengthen regulatory frameworks, and support exposed communities are essential to mitigate the ongoing health effects of asbestos exposure and prevent further harm in the future [65].

4. Asbestos Application and Use

Asbestos is the general designation for the fibrous varieties of six natural silicate minerals: chrysotile, from the serpentine group; crocidolite (riebeckite), amosite (cummingtonite-grunerite), anthophyllite, tremolite, and actinolite, from the group of amphiboles [39]. Due to properties related to flexibility, high tensile strength, electrical resistance, and resistance to heat and chemical degradation, as well as good affinity with cement, resins, and plastic binders, asbestos has been widely used in the production of asbestos cement (fiber cement), consisting of 10 to 20 percent of asbestos fibers with almost all the rest being filled with cement [52]. The production of asbestos has been banned in 52 countries around the world, and since 2015, the production of asbestos in mines around the world has fallen from more than 2 million tons per year to figures between 1 million and 1.5 million tons per year. Despite the good properties and its low production price, inhaling the fibers can cause serious health risks, such as asbestosis, lung cancer, and mesothelioma, favored by the fact that asbestos fibers are light and aerodynamic, floating, and drifting [66].

Before its 2005 prohibition in Europe, asbestos was widely applied in industry due to its high insulating capacity and great resistance to fire and corrosion, mainly in the production of thermal insulation of cables and tapes, in fire protection technologies, as coating of buildings and roofs (fiber cement); in water pipes and gutters; in cardboard; rope; textile and blankets production; in elevators; in textured coatings; in air, gas, and liquid filter; and in acoustic insulation solutions [67].

In the construction industry, the main applications of asbestos include fiber cement tiles and sheets. Given its good performance, this composite material, made up of cement and asbestos fibers, was often used in the manufacture of tiles and sheets for roofing and external cladding of buildings and was very popular due to its weather resistance and durability, as well as thermal and acoustic insulation of walls, floors, and ceilings, since, as fibers mixed with other materials, such as mortar, plaster, or resins, it can form good insulating panels. Another popular application is pipes and ducts where asbestos fibers are incorporated into water pipes, ventilation ducts, and boiler linings, taking advantage of their heat- and fire-resistant properties [68].

However, with growing awareness of the health risks associated with asbestos exposure, many countries have moved to adopt stricter regulations and, in some cases, completely ban the use of asbestos in the construction of new buildings [69]. Exposure to asbestos fibers can lead to serious respiratory illnesses when inhaled. Therefore, workers who come into contact with asbestos are especially vulnerable. The onset of the first signs of an asbestos-related illness may take up to 30 years. Asbestos is linked to 78% of documented occurrences of occupational cancer in the EU, according to data on occupational diseases compiled by Eurostat. Up to 30 years may pass before an asbestos-related illness manifests its symptoms [70]. Based on this, replacing ACM with safer alternatives has

become a priority to ensure the protection of public health. Materials such as glass fibers, rock wool, cellulose, polymers, and other insulators have been used as substitutes for asbestos in construction, ensuring the proper performance and safety of buildings.

5. Negative Impacts of Asbestos

5.1. Environmental Impacts

Asbestos is a naturally occurring mineral, but its negative impact on the environment is primarily caused by the mining and improper disposal of materials containing it. Mineral exploitation is the main environmental impact associated with the use of asbestos, as it involves the excavation and removal of asbestos-containing rocks. This can lead to the destruction of natural habitats, soil erosion, and contamination of nearby water resources [71]. During the manufacture, installation, or removal of asbestos-containing materials, asbestos fibers can be released into the air, posing a risk to human health and the environment, and can remain suspended in the air for long periods and be transported to other areas, contaminating soil, vegetation, and water. ACMs, such as fiber cement tiles, must be treated as hazardous waste and require special care during removal and disposal [72]. Improper disposal in landfills not designed for this type of material can lead to soil and groundwater contamination, but disposal of asbestos in hazardous waste landfills is a common and regulated practice in many countries [73]. These landfills are specifically designed to accept hazardous waste and prevent soil and groundwater contamination by using impermeable layers, drainage systems, and environmental monitoring to ensure that hazardous waste is stored safely [74]. However, even with these precautions, asbestos is considered hazardous waste due to the health risks associated with inhaling its fibers. Therefore, the proper management of asbestos, including its transport and final disposal in hazardous waste landfills, must be carried out under local regulations and best practices established by the competent authorities [75].

5.2. Health Impacts

5.2.1. Occupational and Non-Occupational Exposure

Exposure to asbestos has been associated with serious risks to human health, both in occupational and non-occupational contexts [37,76,77]. At the occupational level, workers exposed to asbestos, especially those involved in mining, manufacturing asbestos products, and construction, are at increased risk of developing serious illnesses. Among these, asbestosis, a fibrosing lung disease, and several types of cancer, such as mesothelioma and lung cancer, stand out. Inhaling asbestos fibers, which can remain suspended in the air, is the main way these diseases are contracted. The severity of exposure is directly related to the duration and intensity of contact with the material. Outside of the workplace, non-occupational exposure to asbestos also poses a considerable risk. This exposure can occur in homes or public buildings that contain asbestos-based materials, such as tiles, insulation panels, and other construction products. As these materials deteriorate over time, asbestos fibers can be released into the environment, leading to unintentional exposure. While exposure levels in these settings are generally lower than in occupational environments, the risk of developing asbestos-related diseases remains. Notably, there is convincing evidence that environmental (non-occupational) exposure to asbestos significantly increases the risk of mesothelioma. However, the corresponding evidence for lung cancer and asbestosis is currently less conclusive. It is important to remember that the effects of asbestos exposure are often long-term, with symptoms of related diseases potentially taking decades to appear after initial exposure. Therefore, early detection and regular health monitoring are crucial for individuals who have been exposed to asbestos. In response to these risks, many countries have implemented strict regulations, and in some cases, complete bans on the use of asbestos. These measures aim to reduce both occupational and non-occupational exposure to asbestos in order to protect public health and prevent future cases of asbestos-related diseases, but only the total eradication of asbestos can ensure the elimination of asbestos-related diseases.

5.2.2. Asbestos-Related Diseases

Asbestos is causally associated with several serious illnesses due to its microscopic fibers [78]. Among the most relevant pathologies, asbestosis, mesothelioma, and lung cancer stand out. Asbestosis is characterized by the inhalation of asbestos fibers, which cause pulmonary fibrosis [39]. This disease manifests itself through symptoms such as dyspnea and persistent cough, often progressing to more severe conditions. Mesothelioma, in turn, is a mesenchymal neoplasm arising more often from pleural linings and, albeit less frequently, from peritoneal, pericardial, and testicular tunica vaginalis linings too. Asbestos exposure is considered one of the main causes of this pathology, which is characterized by symptoms such as chest pain and breathing difficulties [79]. Lung cancer is another disease directly linked to asbestos exposure. The likelihood of developing this type of cancer rises substantially with extended exposure to asbestos fibers, particularly in occupational settings. Beyond lung cancer, asbestos exposure can also lead to other health issues, such as pleural abnormalities and pleural effusions. While these conditions are generally less severe, they still necessitate medical attention due to the potential risks they pose over time [44].

5.2.3. Vulnerable Groups and Risk Factors

In countries where asbestos has already been banned, the most at-risk groups include construction workers and people living in old buildings where asbestos was used. On the other hand, in countries where the use of asbestos is still legal, mining, shipyard, construction industry, and railway workers are groups at high risk of suffering from mesothelioma. Often, exposure to asbestos occurs without the knowledge of exposed individuals. Asbestos fibers can be released into the air during the renovation or demolition of old buildings. Inhalation of these fibers is the main route of exposure, especially when we are talking about non-occupationally exposed people. Individuals who work directly with asbestos-containing materials are most at risk, but residents and workers in older buildings may also be exposed [80].

6. Removal and Management of Asbestos Waste

6.1. Legislation on Safe Handling

Directive (EU) 2023/2668 represents the most recent regulation within the European Community on asbestos protection. Adopted on 22 November 2023, this directive amends Directive 2009/148/EC concerning the safeguarding of workers from risks associated with asbestos exposure in the workplace. Notably, the new directive introduces significant changes to exposure limit requirements, mandating that employers ensure workers are not exposed to airborne asbestos concentrations exceeding 0.002 fibers/cm³ by 2029, marking a notable reduction from prior limits. Additionally, the directive introduces compulsory training for individuals exposed to asbestos, encompassing both theoretical knowledge and practical skills pertaining to the use of protective equipment, safe work practices, and emergency procedures. Given that asbestos is predominantly found in older structures, the legislation prioritizes asbestos removal over encapsulation techniques in demolition and renovation projects.

Among its innovations, the directive emphasizes the importance of integrating a gender analysis in the measurement and management of asbestos-related diseases. Furthermore, it advocates for the use of electron microscopy techniques to enhance the accuracy of asbestos fiber measurement in workplaces, thereby enhancing worker protection. Compliance with these provisions will necessitate employers to invest in advanced measuring equipment and enhance health-monitoring protocols.

The directive also establishes a high standard of protection for workers in sectors such as construction, building renovation, and waste management, thereby minimizing the risks of asbestos exposure and associated diseases. Member States are mandated to transpose the directive's provisions into national legislation by December 2025, with specific technical measures to be implemented by 2029. Overall, Directive (EU) 2023/2668 represents a

significant step towards bolstering worker safety and health by imposing stricter limits on asbestos exposure, enhancing training requirements, and prioritizing asbestos removal in construction and renovation activities.

In Portugal, Ministerial Order (MO) n° 40/2014, of 17 February, establishes the rules for the correct removal of asbestos-containing materials and for the packaging, transport, and management of construction and demolition waste generated, to protect the environment and human health, and Order n° 10401/2015, of 7 September, approves the procedures to be adopted for the management, processing, and making available of the information resulting from the application of MO n° 40/2014.

Concerning the removal of asbestos-containing materials, Law n°. 63/2018, of 10 October, establishes procedures and objectives for the removal of products containing asbestos fibers still present in company buildings, installations, and equipment (Lei n° 63/2018, de 10 de outubro—Diário da República n° 195, Série I de 10.10.2018 [81]). Decree-Law n°. 102-D/2020 of 10 December approves the general waste management regime, the legal regime for the landfill of waste, and amends the regime for the management of specific waste streams, transposing Directives (EU) 2018/849, 2018/850, 2018/851, and 2018/852.

6.2. Removal and Decontamination Techniques

The most effective regulation in Portugal for ACMs (asbestos containing materials) is the Portuguese Ministerial Order 40/2014, which sets out the rules for the correct removal of ACM, its packaging, transport, and management, as well as the demolition waste generated. This legal document aims to protect the environment and human health by designing a series of sequential steps for the implementation of the asbestos removal process. Once the materials suspected of containing asbestos have been identified on site, a work plan for their removal must be drawn up, including three basic measures necessary for the health and safety of workers and the protection of people and the environment: The removal of asbestos or ACM should be carried out before demolition techniques are used, unless removal poses a greater risk to workers than leaving the asbestos or ACM in place [82]. This requires the use of personal protective equipment (PPE) by workers and, once demolition or asbestos removal has been completed, verification that there is no risk of asbestos exposure at the site. Other specifications regarding the work plan must be taken into account, namely the prior approval of this document by the Portuguese Authority for Working Conditions (ACT), as well as the recognition of the competence to carry it out. For this reason, the ACT must be notified by the company carrying out the asbestos or ACM removal work, by filling in a specific form to request authorization to carry out asbestos or ACM removal and/or demolition work, which is available on the ACT website.

A significant increase in exposure to asbestos dust or ACM, as determined by in situ monitoring, constitutes a significant change in the conditions contained in the work plan originally approved by the ACT, in particular about the number of workers involved, the duration of the work, the storage capacity for ACM, if these changes may result in an increased risk to workers' health, and if the plan must therefore be redrafted. The reuse of ACMs is prohibited because of the adverse effects on the environment and human health.

The asbestos dust or ACM work areas must be isolated and identified as hazardous areas, and only authorized personnel may enter these hazardous areas, where smoking is prohibited. In order to limit the presence of personnel who are not part of the project team or the contractor, it is essential to provide specific signage to identify the areas where asbestos removal will be or is taking place. The temporary works notice is usually placed at the entrances to the area where the removal will take place. In higher-potential-risk scenarios, the use of physical barriers to prevent unauthorized access by isolating the work area will depend on factors such as the environment in which the removal is taking place, the level of risk, whether friable or non-friable asbestos is being removed, the method, the existence of existing barriers (walls, doors, etc.), and the amount and type of barrier to be used. If it is necessary to isolate the work area given the above factors, it must be tested to ensure complete isolation. The test shall consist of the use of smoke-producing

devices within the isolated work area to check for leakage. The results of the test must be recorded. In all forms of work areas, there must be a suitable place for workers to eat and drink without risk of contamination by asbestos dust.

Workers who are exposed or likely to be exposed to asbestos dust or ACM must have appropriate training, which must enable them to acquire specific skills on the asbestos removal methods that aim to eliminate or minimize the production of asbestos fibers as far as possible. As regards personal protective equipment, it must be appropriate to the risks present in the workplace, in particular, protective clothing impermeable to asbestos dust.

The most commonly used method of ACM removal, particularly for friable asbestos, is the wet method, which consists of wetting the asbestos with a constant low-pressure stream of water to reduce the release of asbestos fibers. It is necessary to ensure that the asbestos material to be removed is saturated and that run-off is minimized, and the asbestos material must be kept moist throughout the removal process. A surfactant, such as detergent, can be added to the water to facilitate faster wetting of the asbestos. The asbestos should be completely wet, and the water should be directed towards the cutting area, with the wet material being removed as the cut progresses. Immediately after the asbestos has been removed from its installed position, the water spray should be directed at the previously unexposed areas. Asbestos removed in sections must be immediately placed in suitable, clearly identifiable waste containers and properly sealed. Where reasonably practicable, a HEPA (high-efficiency particulate arrestance)-filtered vacuum cleaner should be used in conjunction with the wet method, prior to the wet method, and to remove any released dust. This method significantly reduces but does not eliminate asbestos fibers and the use of personal protective equipment (PPE) and respiratory protection is mandatory.

Another commonly used technology for ACM removal is the water saturation and injection method, which should be used when the asbestos is so thick that the wet method cannot fully saturate the asbestos plaques. It consists of injecting water or a water-based solution directly into the friable asbestos and requires the use of specific materials and processes. This method is carried out using a special applicator consisting of an injection head with several lateral holes or outlets through which the water or water-based solution is released into the asbestos. Holes, cuts, or tears must be made in the covering to allow the water or water-based solution to be injected to saturate the asbestos. The amount of water or water-based solution used will depend on the thickness of the material and access to it or the location of the holes or cuts. As with the wet method, the asbestos should be removed in sections and placed in suitable, correctly labeled waste containers and properly sealed. The water used in the process should then be collected and treated.

The third method of ACM removal is the so-called dry method, which should be used when the wet and water saturation methods are not feasible, for example, when electrical conductors or electrical equipment may be permanently damaged or the risk may be increased by contact with water. If the dry method is to be used, a prior check must be carried out: if the ACM is non-friable, the work area must be isolated as far as reasonably practicable; if it is friable, the work area must be completely isolated and maintained under negative pressure, and it is essential to ensure that all workers involved in the removal operation wear full-face positive pressure airline respirators. On the other hand, if the ACM to be removed has friable parts and other non-friable parts, the asbestos should be removed in small pre-cut sections with minimum disturbance to minimize the release of fibers. Where reasonably practicable, a HEPA vacuum cleaner should be used. The removed asbestos must be placed in suitable, correctly labeled waste containers and properly sealed to prevent the generation of dust and the release of fibers. For all ACM removal work, all workers must be provided with and wear all necessary personal protective equipment (PPE). All equipment used must be inspected beforehand to ensure that workers are protected.

Once removed, ACMs are contaminated materials that must be properly packaged in closed containers and labeled to indicate that they contain asbestos. ACM waste must be collected and removed from the workplace as soon as possible. As they are classified as

hazardous waste, asbestos or asbestos-contaminated materials must not be stored on site for more than 3 months. Asbestos waste must be disposed of at an approved hazardous waste facility licensed to dispose of hazardous waste. Properly packaged waste must be transported under national legislation on the transport of dangerous goods, taking into account the following requirements: securing of the load, marking of the vehicle, prior written agreement with the authorized disposal site, emergency procedures in case of spillage, and driver training.

6.3. Disposal and Treatment of Asbestos Waste

According to Article 7 of Portuguese Law 63/2018, waste resulting from asbestos removal activities must be sent to an appropriate final destination that is duly licensed and authorized to receive this type of waste. Authorized destinations for asbestos waste may be landfills, underground mines, or vitrification plants. In landfills and underground mines, asbestos waste is buried at this type of approved site. Records must be kept at the site so that the material can be traced from its origin to its disposal. In some countries, the waste is sealed, for example, with concrete. Vitrification plants treat asbestos waste at high temperatures to chemically transform it into an inert and vitrified product that can be used as an aggregate for flooring or other applications. This method is considered to be completely effective in eliminating the risk of exposure to the end product, but it uses considerably more energy than other processes.

As mentioned above, the main solution for the disposal of ACM has been to dispose of it in controlled landfills. However, both the quantity and volume of asbestos waste generated by the demolition of buildings and the whole activity of managing this waste require new approaches that include recycling/reuse solutions while taking into account the protection of the environment and human health. In order to reduce ACM landfills, new sustainable treatments to destroy the fibrous structure of asbestos are being stimulated by the European Parliament since 2013. Among these treatments to be applied to detoxify the ACMs (thermal, physical, chemical, and biological), the thermal and physical are referred to have very high energy expense, the chemical is referred to have strong reagent consumption, and the biological is referred to have low effectiveness [83–85]. Based on this, although the existing studies carried out so far indicate the efficiency of heat treatments to destroy the fibrous structure of asbestos, the costs associated with these processes limit their application [83–85]. There are several industries which, due to the nature of the materials/products they manufacture, already involve heat treatments with high energy consumption. These include the metallurgical, cement, glass, and rock wool industries. Incorporating residues that require heat treatment into products that are already high-energy consumers does not result in additional energy consumption for their treatment. On this basis, the incorporation of ACMs into the rock wool industry can be an effective solution to eliminate emissions, as this material is later used in construction solutions [7].

7. Conclusions

Asbestos, once widely utilized for its fire-resistant properties, has led to widespread contamination of the environment due to past and ongoing use in construction, industrial applications, and natural erosion of ACMs with extensive environmental impacts. In the same way, exposure to asbestos fibers poses serious health risks to humans, including the development of asbestos-related diseases with long latency periods, complicating diagnosis and treatment, and resulting in significant morbidity and mortality rates among exposed individuals. Despite recognizing the health hazards posed by asbestos, regulatory frameworks for asbestos management vary globally from Europe to the United States and the rest of the World, with inconsistencies in asbestos bans, exposure limits, and remediation strategies. Based on this inconsistency, it is recommended to harmonize regulatory frameworks worldwide to ensure consistency and effectiveness in asbestos management and to establish guidelines and standards for the safe handling, removal, and disposal of ACMs in construction and building renovation by providing specific training

and certification for asbestos abatement professionals to ensure compliance with best practices. At the same time, it is decisive to increase public awareness of asbestos-related risks and promote education initiatives on safe handling practices and the importance of regular health screenings for individuals at risk of asbestos exposure. This paper provides an overview of the assessment of the environmental impacts and public health risks of asbestos and a methodological analysis of the strategy for recycling end-of-life materials containing asbestos fibers, taking into account the need for new technologies and approaches to mitigate environmental impacts based on heat treatments to destroy the fibrous structure of asbestos, thus allowing the waste to be reused and recovered. On this basis, the inclusion of ACM in the rock wool industry can be an effective solution to reduce greenhouse gas (GHG) emissions, as this material is later used in construction solutions [7].

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References

1. Hussain, A.; Kamal, M.A. Energy efficient sustainable building materials: An overview. *Key Eng. Mater.* **2015**, *650*, 38–50. [\[CrossRef\]](#)
2. OBE, R.K.D.; de Brito, J.; Silva, R.V.; Lye, C.Q. *Sustainable Construction Materials: Recycled Aggregates*; Woodhead Publishing: Cambridge, UK, 2019.
3. Wu, P.-Y.; Mjörnell, K.; Mangold, M.; Sandels, C.; Johansson, T. A data-driven approach to assess the risk of encountering hazardous materials in the building stock based on environmental inventories. *Sustainability* **2021**, *13*, 7836. [\[CrossRef\]](#)
4. Elizalde, R.R. Asbestos presence in 20th century buildings. *J. Eng. Appl. Sci. Technol.* **2022**, *4*, 1–14. [\[CrossRef\]](#)
5. Townsend, T.G.; Anshassi, M. Hazardous and dangerous materials in CDD. In *Construction and Demolition Debris; Waste Management Principles and Practice*; Springer: Berlin, Germany, 2023; pp. 137–189.
6. Teixeira, R.J.S.; Neiva, A.M.R.; Gomes, M.E.P. Geochemistry of amphibole asbestos from northeastern Portugal and its use in monitoring the environmental impact of asbestos from quarrying. *Comun. Geol.* **2010**, *97*, 99–112.
7. Spasiano, D.; Pirozzi, F. Treatments of asbestos containing wastes. *J. Environ. Manag.* **2017**, *204*, 82–91. [\[CrossRef\]](#)
8. Vincenten, J.; George, F.; Martuzzi, M.; Schröder-Bäck, P.; Paunovic, E. Barriers and Facilitators to the Elimination of Asbestos Related Diseases—Stakeholders’ Perspectives. *Int. J. Environ. Res. Public Health* **2017**, *14*, 1269. [\[CrossRef\]](#)
9. Berry, T.-A.; Belluso, E.; Vigliaturo, R.; Gieré, R.; Emmett, E.A.; Testa, J.R.; Steinhorn, G.; Wallis, S.L. Asbestos and other hazardous fibrous minerals: Potential exposure pathways and associated health risks. *Int. J. Environ. Res. Public Health* **2022**, *19*, 4031. [\[CrossRef\]](#)
10. World Health Organization. Resolutions and decisions, annex. In *Proceedings of the Fifty-Eighth World Health Assembly*, Geneva, Switzerland, 16–25 May 2005; p. 143.
11. Nicholson, W. Cancer risk in the workplace, including asbestos. *Eur. J. Cancer Prev.* **1996**, *5*, 393–396.
12. World Health Organization. *Emergence and Spread of Artemisinin Resistance Calls for Intensified Efforts to Withdraw Oral Artemisinin-Based Monotherapy from the Market*; World Health Organization: Geneva, Switzerland, 2014.
13. Decreto-Lei n° 101/2005, *Diário da República I Série—A*, 119 (05-06-23) 3937–3939; Ministério da Economia e da Inovação: Lisboa, Portugal, 2005. (In Portuguese)

14. Gualtieri, A.F.; Lassinantti Gualtieri, M.; Scognamiglio, V.; Di Giuseppe, D. Human health hazards associated with asbestos in building materials. In *Ecological and Health Effects of Building Materials*; Springer: New York, NY, USA, 2022; pp. 297–325.
15. *Resolução da Assembleia Da República n.º 24/2003, DR I-A Série. 77 (2003-04-01)*; Government of Portugal: Lisboa, Portugal, 2003. (In Portuguese)
16. Santos, C.; Dixe, M.d.A.; Sacadura-Leite, E.; Astoul, P.; Sousa-Uva, A. Asbestos exposure and malignant pleural mesothelioma: A systematic review of literature. *Port. J. Public Health* **2023**, *40*, 188–202. [[CrossRef](#)]
17. *Lei n.º 2/2011. Diário da República I Série, 28 (11-02-09) 706*; Government of Portugal: Lisboa, Portugal, 2011. (In Portuguese)
18. *Diário da República n.º 33/2014, Série I de 2014-02-17, páginas 1435–1442*; Government of Portugal: Lisboa, Portugal, 2014. (In Portuguese)
19. Wajima, T. Synthesis of tobermorite from the ash after treatment of asbestos-containing disaster waste, and its removal ability of Cs (I) from aqueous solution. *Eng. J.* **2016**, *20*, 79–91. [[CrossRef](#)]
20. Talbi, G.; Cambon, M.; Cambon, O. Virtuous cycle of destruction and total recycling of pure asbestos and asbestos-containing waste. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 1167–1176. [[CrossRef](#)]
21. Zeng, L.; Sun, H.; Peng, T.; Zheng, W. Preparation of porous glass-ceramics from coal fly ash and asbestos tailings by high-temperature pore-forming. *Waste Manag.* **2020**, *106*, 184–192. [[CrossRef](#)] [[PubMed](#)]
22. Van Gosen, B.S. The geology of asbestos in the United States and its practical applications. *Environ. Eng. Geosci.* **2007**, *13*, 55–68. [[CrossRef](#)]
23. Sen, D. Working with asbestos and the possible health risks. *Occup. Med.* **2015**, *65*, 6–14. [[CrossRef](#)]
24. Ross, M.; Langer, A.M.; Nord, G.L.; Nolan, R.P.; Lee, R.J.; Van Orden, D.; Addison, J. The mineral nature of asbestos. *Regul. Toxicol. Pharmacol.* **2008**, *52*, S26–S30. [[CrossRef](#)] [[PubMed](#)]
25. Kanarek, M.S. Mesothelioma from chrysotile asbestos: Update. *Ann. Epidemiol.* **2011**, *21*, 688–697. [[CrossRef](#)]
26. Kusiorowski, R.; Zaremba, T.; Piotrowski, J.; Adamek, J. Thermal decomposition of different types of asbestos. *J. Therm. Anal. Calorim.* **2012**, *109*, 693–704. [[CrossRef](#)]
27. Schwarzenbach, E.M.; Caddick, M.J.; Beard, J.S.; Bodnar, R.J. Serpentinization, element transfer, and the progressive development of zoning in veins: Evidence from a partially serpentinized harzburgite. *Contrib. Mineral. Petrol.* **2016**, *171*, 1–22. [[CrossRef](#)]
28. Martin, R.F. Amphiboles in the igneous environment. *Rev. Mineral. Geochem.* **2007**, *67*, 323–358. [[CrossRef](#)]
29. Murray, R. Asbestos: A chronology of its origins and health effects. *Occup. Environ. Med.* **1990**, *47*, 361–365. [[CrossRef](#)]
30. Lee, R.J.; Strohmeier, B.; Bunker, K.; Van Orden, D. Naturally occurring asbestos—A recurring public policy challenge. *J. Hazard. Mater.* **2008**, *153*, 1–21. [[CrossRef](#)] [[PubMed](#)]
31. Ali, S.H.; Giurco, D.; Arndt, N.; Nickless, E.; Brown, G.; Demetriades, A.; Durrheim, R.; Enriquez, M.A.; Kinnaird, J.; Littleboy, A.; et al. Mineral supply for sustainable development requires resource governance. *Nature* **2017**, *543*, 367–372. [[CrossRef](#)]
32. Dogan, M.; Dogan, A.U. *Asbestos Mineralogy and Health Effects, in Malignant Mesothelioma: Advances in Pathogenesis, Diagnosis, and Translational Therapies*; Springer: New York, NY, USA, 2005; pp. 209–224.
33. Ramberg, H. Chemical bonds and distribution of cations in silicates. *J. Geol.* **1952**, *60*, 331–355. [[CrossRef](#)]
34. Bernstein, D.M.; Hoskins, J.A. The health effects of chrysotile: Current perspective based upon recent data. *Regul. Toxicol. Pharmacol.* **2006**, *45*, 252–264. [[CrossRef](#)]
35. Croce, A.; Arrais, A.; Rinaudo, C. Raman micro-spectroscopy identifies carbonaceous particles lying on the surface of crocidolite, amosite, and chrysotile fibers. *Minerals* **2018**, *8*, 249. [[CrossRef](#)]
36. Paolini, V.; Tomassetti, L.; Segreto, M.; Borin, D.; Liotta, F.; Torre, M.; Petracchini, F. Asbestos treatment technologies. *J. Mater. Cycles Waste Manag.* **2019**, *21*, 205–226. [[CrossRef](#)]
37. Osinubi, O.; Gochfeld, M.; Kipen, H.M. Health effects of asbestos and nonasbestos fibers. *Environ. Health Perspect.* **2000**, *108* (Suppl. S4), 665–674.
38. Dichicco, M.C.; Paternoster, M.; Rizzo, G.; Sinisi, R. Mineralogical asbestos assessment in the southern Apennines (Italy): A review. *Fibers* **2019**, *7*, 24. [[CrossRef](#)]
39. Strohmeier, B.R.; Huntington, J.C.; Bunker, K.L.; Sanchez, M.S.; Allison, K.; Lee, R.J. What is asbestos and why is it important? Challenges of defining and characterizing asbestos. *Int. Geol. Rev.* **2010**, *52*, 801–872. [[CrossRef](#)]
40. Koňáková, D.; Pommer, V.; Šádková, K.; Černý, R.; Vejmelková, E. High-temperature resistance of cement composites with randomly distributed aluminium silicate fibbers. *Cem. Concr. Compos.* **2024**, *145*, 105339. [[CrossRef](#)]
41. Abu-Jdayil, B.; Mourad, A.-H.; Hittini, W.; Hassan, M.; Hameedi, S. Traditional, state-of-the-art and renewable thermal building insulation materials: An overview. *Constr. Build. Mater.* **2019**, *214*, 709–735. [[CrossRef](#)]
42. Gadikota, G.; Natali, C.; Boschi, C.; Park, A.-H.A. Morphological changes during enhanced carbonation of asbestos containing material and its comparison to magnesium silicate minerals. *J. Hazard. Mater.* **2014**, *264*, 42–52. [[CrossRef](#)] [[PubMed](#)]
43. Dodson, R.F.; Atkinson, M.A.; Levin, J.L. Asbestos fiber length as related to potential pathogenicity: A critical review. *Am. J. Ind. Med.* **2003**, *44*, 291–297. [[CrossRef](#)]
44. Boulanger, G.; Andujar, P.; Paireon, J.C.; Billon-Galland, M.A.; Dion, C.; Dumortier, P.; Brochard, P.; Sobaszek, A.; Bartsch, P.; Paris, C.; et al. Quantification of short and long asbestos fibers to assess asbestos exposure: A review of fiber size toxicity. *Environ. Health* **2014**, *13*, 1–18. [[CrossRef](#)] [[PubMed](#)]
45. Musk, A.; de Klerk, N.; Reid, A.; Hui, J.; Franklin, P.; Brims, F. Asbestos-related diseases. *Int. J. Tuberc. Lung Dis.* **2020**, *24*, 562–567. [[CrossRef](#)]

46. Vallyathan, V.; Green, F.H.; Abraham, J.L. The role of analytical techniques in the diagnosis of asbestos-associated disease. *Crit. Rev. Clin. Lab. Sci.* **1985**, *22*, 1–42. [\[CrossRef\]](#)
47. Gochfeld, M. Chronologic history of occupational medicine. *J. Occup. Environ. Med.* **2005**, *47*, 96–114. [\[CrossRef\]](#)
48. Laufer, B. Asbestos and Salamander, an essay in Chinese and Hellenistic Folk-Lore. *T'oung Pao* **1915**, *16*, 299–373. [\[CrossRef\]](#)
49. Browne, C. Salamander's wool: The historical evidence for textiles woven with asbestos fibre. *Text. Hist.* **2003**, *34*, 64–73. [\[CrossRef\]](#)
50. Košny, J.; Yarbrough, W. Short history of thermal insulation and radiation control technologies used in architecture. In *Thermal Insulation and Radiation Control Technologies for Buildings*; Springer: New York, NY, USA, 2022; pp. 1–35.
51. Erker, P. A comparative perspective of asbestos as an industrial and environmental hazard. *Glob. Environ.* **2014**, *7*, 72–105. [\[CrossRef\]](#)
52. Bolan, S.; Kempton, L.; McCarthy, T.; Wijesekara, H.; Piyathilake, U.; Jasemizad, T.; Padhye, L.P.; Zhang, T.; Rinklebe, J.; Wang, H.; et al. Sustainable management of hazardous asbestos-containing materials: Containment, stabilization and inertization. *Sci. Total Environ.* **2023**, *881*, 163456. [\[CrossRef\]](#)
53. Frank, A.L.; Joshi, T. The global spread of asbestos. *Ann. Glob. Health* **2014**, *80*, 257–262. [\[CrossRef\]](#)
54. Ramazzini, C. Asbestos is still with us: Repeat call for a universal ban. *Arch. Environ. Occup. Health* **2010**, *65*, 121–126. [\[CrossRef\]](#)
55. Maynard, R.L. Chemical Weapons—Threat, Effects and Protection. *Occup. Environ. Med.* **2003**, *60*, 460. [\[CrossRef\]](#)
56. Lemen, R.A. Mesothelioma from asbestos exposures: Epidemiologic patterns and impact in the United States. *J. Toxicol. Environ. Health Part B* **2016**, *19*, 250–265. [\[CrossRef\]](#) [\[PubMed\]](#)
57. Luo, S.; Liu, X.; Mu, S.; Tsai, S.P.; Wen, C.P. Asbestos related diseases from environmental exposure to crocidolite in Da-yao, China. I. Review of exposure and epidemiological data. *Occup. Environ. Med.* **2003**, *60*, 35–42. [\[CrossRef\]](#) [\[PubMed\]](#)
58. Bird, T.; Steffen, J.E.; Tran, T.H.; Egilman, D.S. A review of the talc industry's influence on federal regulation and scientific standards for asbestos in talc. *New Solut. J. Environ. Occup. Health Policy* **2021**, *31*, 152–169. [\[CrossRef\]](#) [\[PubMed\]](#)
59. Behrens, M.A.; Anderson, W.L. The Any Exposure Theory: An Unsound Basis for Asbestos Causation and Expert Testimony. *Southwest. Univ. Law Rev. J.* **2008**, *37*, 479.
60. Kazan-Allen, L. The asbestos war. *Int. J. Occup. Environ. Health* **2003**, *9*, 173–193. [\[CrossRef\]](#)
61. Council Directive 76/769/EEC of 27 July 1976 on the Approximation of the Laws, Regulations and Administrative Provisions of the Member States Relating to Restrictions on the Marketing and Use of Certain Dangerous Substances and Preparations; European Union: Brussels, Belgium, 1976.
62. Qian, E. The Staying Power of Asbestos Hazards: A Critical Environmental Justice Case Analysis. *Sociol. Between Gaps Forgot. Neglected Top.* **2023**, *9*, 3.
63. Kameda, T.; Takahashi, K.; Kim, R.; Jiang, Y.; Movahed, M.; Park, E.K.; Rantanen, J. Asbestos: Use, bans and disease burden in Europe. *Bull. World Health Organ.* **2014**, *92*, 790–797. [\[CrossRef\]](#) [\[PubMed\]](#)
64. Ramazzini, C. The global health dimensions of asbestos and asbestos-related diseases. *J. Occup. Health* **2016**, *58*, 220–223. [\[CrossRef\]](#)
65. Marsili, D.; Canepa, A.; Mossone, N.; Comba, P. Environmental Health Education for Asbestos-Contaminated Communities in Italy: The Casale Monferrato Case Study. *Ann. Glob. Health* **2019**, *85*, 84. [\[CrossRef\]](#) [\[PubMed\]](#)
66. LaDou, J.; Castleman, B.; Frank, A.; Gochfeld, M.; Greenberg, M.; Huff, J.; Joshi, T.K.; Landrigan, P.J.; Lemen, R.; Myers, J.; et al. The case for a global ban on asbestos. *Environ. Health Perspect.* **2010**, *118*, 897–901. [\[CrossRef\]](#) [\[PubMed\]](#)
67. Maines, R. *Asbestos and Fire: Technological Tradeoffs and the Body at Risk*; Rutgers University Press: New Brunswick, NJ, USA, 2013.
68. Deegoda, I.; Buddika, S.; Yapa, H.; Navaratnam, S.; Zhang, G. Review on the Application of Organic Fibers as Substitutes for Asbestos in Thin Fiber Cement Sheets from a Sri Lankan Perspective. *Sustainability* **2023**, *15*, 10235. [\[CrossRef\]](#)
69. Jeffers, D.; Liao, Y.-C.; Takahashi, K.; Lin, R.-T. Asbestos awareness among the residents of St. Kitts and Nevis: A cross-sectional study. *Glob. Health* **2022**, *18*, 83. [\[CrossRef\]](#)
70. Moda, H.M.; Sawyerr, H.; Clayson, A. What will go wrong has gone wrong: Asbestos exposure risk among construction workers in Nigeria. *Policy Pract. Health Saf.* **2018**, *16*, 212–223. [\[CrossRef\]](#)
71. Luus, K. Asbestos: Mining exposure, health effects and policy implications. *McGill J. Med.* **2007**, *10*, 121. [\[CrossRef\]](#)
72. Obmiński, A. Asbestos cement products and their impact on soil contamination in relation to various sources of anthropogenic and natural asbestos pollution. *Sci. Total Environ.* **2022**, *848*, 157275. [\[CrossRef\]](#)
73. Osazee, I.T. Landfill in a sustainable waste disposal. *Eur. J. Environ. Earth Sci.* **2021**, *2*, 67–74. [\[CrossRef\]](#)
74. Ogunwumi, O.T.; Salami, L. Perspective Chapter: Industrial Waste Landfills. In *Solid Waste and Landfills Management—Recent Advances*; IntechOpen: London, UK, 2023.
75. Parkitny, W.; Wojcik, W.; Generowicz, A. Logistic problem connected with removing asbestos as dangerous waste from terrains of country communes. *IOP Conf. Ser. Earth Environ. Sci.* **2017**, *95*, 042062. [\[CrossRef\]](#)
76. Goldberg, M.; Luce, D. The health impact of nonoccupational exposure to asbestos: What do we know? *Eur. J. Cancer Prev.* **2009**, *18*, 489–503. [\[CrossRef\]](#)
77. Magnani, C.; Agudo, A.; A González, C.; Andrión, A.; Calleja, A.; Chellini, E.; Dalmasso, P.; Escolar, A.; Hernandez, S.; Ivaldi, C.; et al. Multicentric study on malignant pleural mesothelioma and non-occupational exposure to asbestos. *Br. J. Cancer* **2000**, *83*, 104–111. [\[CrossRef\]](#)

78. Churg, A. Fiber counting and analysis in the diagnosis of asbestos-related disease. *Hum. Pathol.* **1982**, *13*, 381–392. [[CrossRef](#)] [[PubMed](#)]
79. Baur, X.; Woitowitz, H.; Budnik, L.T.; Egilman, D.; Oliver, C.; Frank, A.; Soskolne, C.L.; Landrigan, P.J.; Lemen, R.A. Asbestos, asbestosis, and cancer: The Helsinki criteria for diagnosis and attribution. Critical need for revision of the 2014 update. *Am. J. Ind. Med.* **2017**, *60*, 411–421. [[CrossRef](#)] [[PubMed](#)]
80. Kakooei, H.; Normohammadi, M. Asbestos exposure among construction workers during demolition of old houses in Tehran, Iran. *Ind. Health* **2014**, *52*, 71–77. [[CrossRef](#)] [[PubMed](#)]
81. *Diário da República n.º 195/2018, Série I de 2018-10-10, páginas 4908–4908*; Assembleia da República: Lisboa, Portugal, 2018. (In Portuguese)
82. Verbeek, J.H.; Hoving, J.L.; van der Molen, H.F.; Gagliardi, D.; Curti, S.; Hulshof, C.T.; Scheepers, P.T.; Marinaccio, A.; Belackova, L. Personal protective equipment for preventing asbestos exposure in workers. *Cochrane Database Syst. Rev.* **2022**, *2022*, CD015158. [[CrossRef](#)]
83. Iwaszko, J. Making asbestos-cement products safe using heat treatment. *Case Stud. Constr. Mater.* **2019**, *10*, e00221. [[CrossRef](#)]
84. Carneiro, G.O.; Santos, T.A.; Simonelli, G.; Ribeiro, D.V.; Cilla, M.S.; Dias, C.M. Thermal treatment optimization of asbestos cement waste (ACW) potentializing its use as alternative binder. *J. Clean. Prod.* **2021**, *320*, 128801. [[CrossRef](#)]
85. Kusiorowski, R.; Zaremba, T.; Piotrowski, J.; Podwórny, J. Utilisation of cement-asbestos wastes by thermal treatment and the potential possibility use of obtained product for the clinker bricks manufacture. *J. Mater. Sci.* **2015**, *50*, 6757–6767. [[CrossRef](#)]

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