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Review

Climate change and allergic diseases: A scoping review

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A B S T R A C T

Introduction: Increased greenhouse gas emissions since the industrial age have led to higher global temperatures and frequency and severity of climate events, such as heat waves, wildfires, floods, and storms. These changes are adversely affecting human health and increasing disease risk, including risk of allergic diseases. Further understanding of the environmental factors and the cellular and molecular mechanisms mediating these increases can assist in developing strategies to adapt to and mitigate climate change.
Materials and Methods: We conducted a scoping review of the literature from 2010 through 2024 using PubMed and Scopus.
Results: Thunderstorms, dust storms, wildfires, and other climate change factors increase allergies both directly and indirectly through increases in particulate matter, pollen, migration of disease vectors and decreases in biodiversity. The epithelial barrier, hygiene, "old friends," and biodiversity hypotheses have been put forward to explain the underlying mechanism mediating these increases.

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Global warming
Mitigation
Pollen

Conclusion: There is an urgent need to reduce the use of fossil fuels to mitigate climate change and protect planetary and human health. While international accords such as the 2015 Paris Agreement have been signed with the aim of lowering greenhouse gases and limiting future global temperature increases, it is clear that increased efforts are needed to meet these goals. Evidence-based solutions for adapting to the increased prevalence of allergic diseases and cost-benefit analysis of current mitigation strategies for lowering allergic diseases are also needed.

1. Introduction

Asthma and allergies are caused by dysregulation of the immune system leading to inappropriate immune reactions on exposure to common foods (e.g., milk, eggs, peanut), airborne particles (e.g., house dust mites, pollens, animal dander, molds), drugs (e.g., penicillin, vaccines), insect stings (e.g., bees, wasps), or other substances (e.g., latex, dyes). Examples of allergic diseases include food allergy, oral allergy syndrome, atopic dermatitis, allergic rhinitis, allergic conjunctivitis, allergic asthma, eosinophilic esophagitis, drug allergy, and venom allergy. Food allergy is estimated at 8−11 %, atopic dermatitis at 10−20 %, allergic asthma at 8 %, and allergic rhinitis between 10 and 40 % of the overall population [1]. Symptoms vary and can range from mild to life-threatening [1].

Further increases in the prevalence of allergies and asthma are expected due to the increases in greenhouse gases (GHGs), global temperatures, and natural and anthropogenic pollutants (e.g., particulate matter (PM), carbon dioxide, oxides of nitrogen (NOx), sulfur dioxide, pesticides, microplastics, volatile organic compounds), a consequence of extensive industrialization, modern agricultural practices, and use of fossil fuels for transportation and energy production [2]. Currently global temperatures are around 1.1 °C higher than at prehistorical times and are projected to further increase to between 1.5 °C to 4.4 °C by 2100 [2]. To keep these increases at the lower projection of 1.5 °C we would need to: (i) make significant reductions in fossil fuel use; (ii) implement eco-friendly sustainable practices; and (iii) implement climate justice [3].

Children, pregnant women, the elderly, those with preexisting chronic diseases or those socio-economically disadvantaged are most vulnerable to climate change related health risks [4,5]. Socio-economically disadvantaged groups such as immigrants with limited language proficiency, communities of color, indigenous groups, or outdoor workers on daily wages face the brunt of climate change because of poor housing infrastructure, proximity to highly polluted areas or flood zones, increased exposure to heat or air pollutants, or poor access to medical care [4,5].

Global warming and climate change events impact asthma and allergies by: (i) changing pollen characteristics (geographical distribution, concentration, season length, and allergenicity); (ii) accelerating loss of biodiversity; and (iii) increasing the concentration and toxicity of outdoor air pollutants such as PM, GHGs, and others through increased incidence of wildfires and sand and dust (SDS) storms [6-9]. Based on the literature reviewed in this scoping review, Figs. 1 and 2 depict Climate Change and other factors increasing the risk of asthma and allergies.

While there is ample epidemiological evidence associating climate change and allergies and asthma, the climatic factors mediating these changes and the mechanisms underlying these associations need further study. As global temperatures and outdoor and indoor pollution increase steeply, evidence-based mitigation and adaptation measures are urgently needed to reduce the effects of climate change on allergies and asthma [10]. Here, we briefly review the pathophysiological mechanisms underlying allergies and asthma, the effects of climate change-associated environmental factors and exposures on asthma and allergic disease, and adaptation and mitigation strategies that may assist in curbing the rising incidence of these diseases.

2. Methods

2.1. Aim and research question

This scoping review aims to understand the adverse effects of climate change on allergic disease and actions needed to best mitigate these effects.

- How do these factors mediate allergic disease?
- What are the climate factors that affect allergies and asthma?
- What are common adaptation and mitigation strategies and is there evidence that they effectively decrease allergic disease burden?

2.2. Study protocol and search strategy

Searches were conducted from 2010 through 2024: PubMed String Search: (“Climate change”[title] or pollution[title] or allerg* [title] or asthma[title] or immun*[title] or pollen[title] or wildfire [title] or storm[title] or biodiversity[title] or greenspace[title] or microbiome[title]) or ((“climate change”) and (mitigation[title] or adaptation[title] or action[title] or prevention[title])). Scopus search string (article title, keywords and abstract): ("Climate change" or “fossil fuels” or “greenhouse gases” or pollution) and (pollen or wildfire or storm* or flooding or biodivers* or greenspace or microb* or mitigation or adaptation or action or prevention) and (health or allerg* OR asthma). Gray literature and books were identified by searching Google or Google Scholar.

2.3. Eligibility criteria

Peer-reviewed quantitative, qualitative, and mixed-methods studies, as well as reviews published since 2010 were considered for inclusion. Only articles in English were eligible for inclusion. Included articles addressed the effects of climate change or extreme weather on allergic disease or addressed adaptation and mitigation strategies for lowering risk of these diseases.

2.4. Data extraction and analysis

The authors reviewed all the manuscripts found from their overall search and then grouped them into themes based on the three aims described above. As the number of manuscripts retrieved were large, we divided them up amongst the 27 authors to review the papers on the first round. 506 manuscripts were then recommended for full text review. We then had groups of 3−4 authors to go through the full text of the manuscripts, of which 85 were selected. Manuscripts were excluded due to a combination of any of these factors: editorials or commentary, low impact factor journals (lower than 5), not in English, or not health or climate change related. Authors further suggested 8 books and websites for inclusion. The final number of records selected was 93.

3. Results

We searched for manuscripts using PubMed and Scopus databases. We reviewed 506 full text articles and included 85

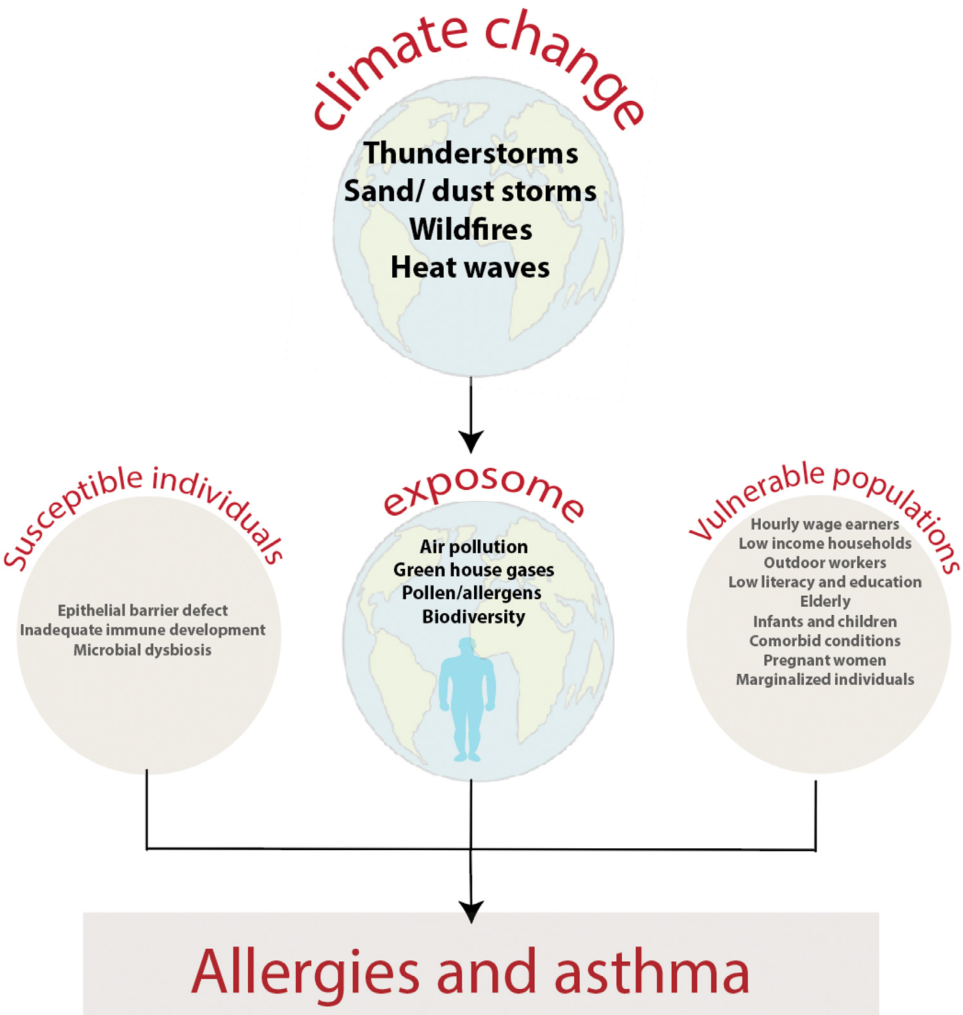

Fig. 1. The effects of climate change events on the human exposome and increased risk of asthma and allergies. Susceptible individuals and vulnerable populations increase this risk.

manuscripts. At each stage, at least three authors reviewed the manuscripts. We also identified seven websites and one book chapter (Fig. 3).

3.1. Mechanism: hygiene, "old friends," biodiversity, and epithelial barrier hypotheses

The immune system is vital for maintaining human health. In this scoping review, the following themes affecting immune dysregulation were identified (1) microbial dysbiosis [11], (2) epithelial barrier dysfunction [12], and (3) inadequate early life exposure to allergens. Increased urbanization, hygiene, time spent indoors, antibiotic use, exposure to toxic chemicals, decreased exposure to biodiverse environments (including diverse diets), and lack of physical activity have been implicated in allergy pathogenesis [13,14].

The hygiene [15], "old friends," [16] biodiversity [17], and epithelial barrier hypotheses [18] have been put forth to explain the rising incidence of allergies and asthma. The hygiene, "old friends" and biodiversity hypotheses suggest that decreased exposure to common environmental agents is responsible for inadequate immune training and increased hyper-reaction. The hygiene hypothesis was first proposed in 1989 and suggested that the rapid rise in childhood allergies was due to a smaller family size and higher standards of home and personal hygiene reducing risk of exposure to infectious agents [15]. The biodiversity and "old friends" hypotheses can be seen as an extension of the hygiene hypothesis. The "Old friends" hypothesis was put forward in 2010. It suggests that decreased exposure to non-harmful microbes as well as parasites that have co-evolved with humans leads to immune dysregulation. The "old friends" hypothesis implicates not just increased hygiene but emphasizes the coevolution of microorganisms and humans and their role as essential drivers of the regulatory and anti-inflammatory arm of the immune system [16]. The biodiversity hypothesis which was postulated in 2011 suggests that biodiversity loss leads to immune dysfunction and disease [19]. It states that contact with natural environments enriches the human microbiome, promotes immune balance and protects from allergy and inflammatory disorders [17]. Microbial dysbiosis has been shown to affect asthma pathogenesis. For example, airway infection can lead to the activation and/or dysregulation of inflammatory pathways that contribute to bronchoconstriction and bronchial hyperresponsiveness; gut microbial dysbiosis can affect immune development and differentiation and the systemic release of pro-inflammatory mediators [20,21].

The epithelial barrier hypothesis proposes that increases in exposure to air pollutants and other toxic substances, such as detergents, household cleaners, packaged food emulsifiers, preservatives, pesticides and microplastics damage the epithelial barrier and increase penetration of allergens and microbes and increase proinflammatory reactions. The constant contact with pollutants, which have permeated every aspect of our lives due to industrialization and contemporary living, results in the breakdown of the innate protective barriers within the skin, respiratory system, and digestive tract [12,22,23].

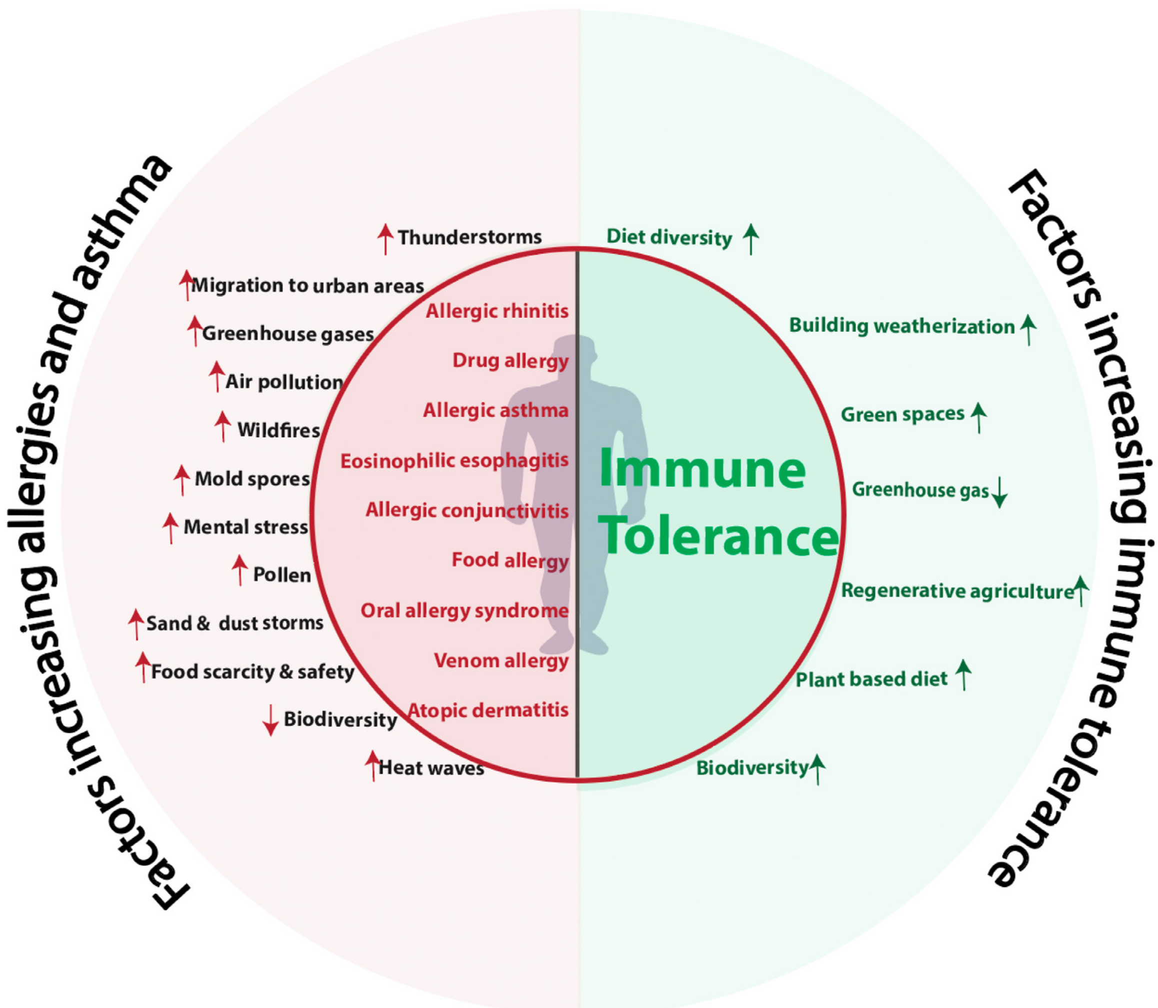

Fig. 2. Factors increasing allergies and asthma and those increasing immune tolerance.

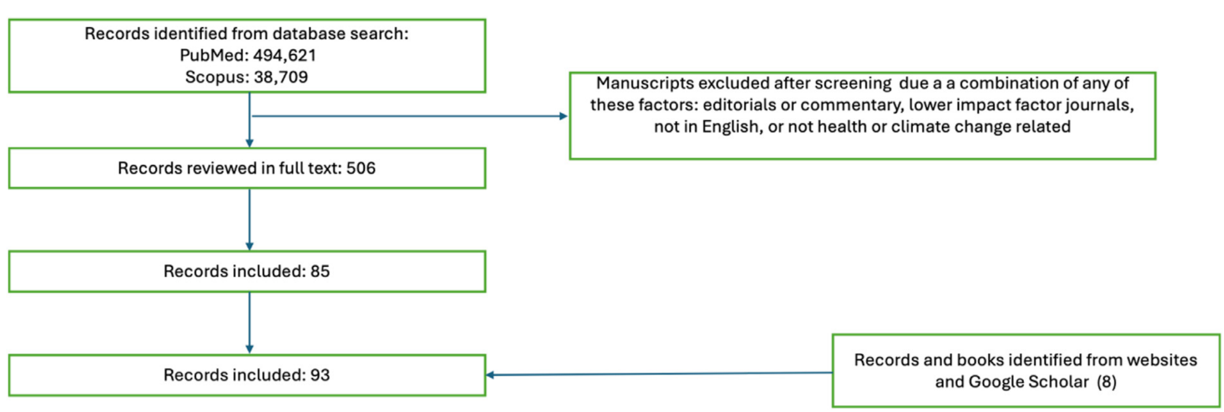

Fig. 3. PRISMA flow diagram of study selection.

Over the past 60 years, industrialization, urbanization, and technological advancements have led to significant changes in the exposome, which is the measure of all the exposures of an individual in a lifetime and how those exposures relate to health [19]. This has given rise to concerns regarding their potential impacts on the health of both humans and animals. A recent meta-analysis, which examined 22 different chemical inventories from 19 countries, found that more than 350,000 new substances have been released into our environments since the 1960 [24]. Unfortunately, the potential health effects of these substances have not been adequately studied or regulated. Of these approximately 50,000 substances remain undisclosed due to confidential submissions, while nearly 70,000 have been inadequately described, further complicating the challenge at hand [24].

A defective epithelial barrier on affected tissues has been demonstrated in asthma [25], chronic rhinosinusitis [26], and allergic diseases [27,28]. In addition, many metabolic and autoimmune diseases, such as diabetes, obesity, inflammatory bowel disease, rheumatoid arthritis and multiple sclerosis show epithelial barrier damage and microbial dysbiosis [29]. The epithelial barrier hypothesis is not an alternative to hygiene and biodiversity hypotheses, rather it includes them. Individuals with compromised epithelial barriers often experience inflammation within their epithelial cells. This condition leads to the release of various signals that raise an alarm, such as IL-33, IL-25, TSLP, and several chemokines, which serve as the primary trigger, attracting proinflammatory cells to the site of the damaged epithelial barrier. The immune mechanisms contributing to epithelial barrier dysfunction predominantly involve a type-2 immune response with the release of type 2 cytokines, such as IL-4 and IL-13, by T helper 2 cells and type-2 innate lymphoid cells leading to the development of allergic sensitization and reactions. In this context, the immune response strives to achieve biodiversity by eliminating invading opportunistic pathogens that have infiltrated the tissues [30,31].

3.2. Climate change-associated environmental factors and exposures associated with asthma and allergic disease

3.2.1. Biodiversity

Biodiversity is a key factor in maintaining a healthy and functioning ecosystem and for human health. Biodiversity was defined by the United Nations (UN) Biodiversity Convention as the variability among living organisms from all sources [32]. This includes diversity within species, between species and of ecosystems. Climate change, continuous deforestation and intensive land use for agriculture and human habitats have led to loss of biodiversity. Long-term global warming has also reduced soil microbial diversity [33]. Loss of habitat is another major factor for species extinction and biodiversity loss. Millions of species worldwide could face extinction as a result of climate change in the next few decades. The loss of biodiversity has a huge impact on human health, both directly and indirectly [34]. Living in an environment with more biodiversity has been shown to be associated with less asthma and allergy [35]. A study from Finland found that biodiversity intervention in yards and playgrounds in daycare centers enhanced immune regulation and health-associated commensal microbiota [36]. The placebo-controlled, double-blinded intervention consisted of a playground/sandbox sand enriched with microbially diverse soil (intervention group) and microbially poor sand (placebo control group). At two weeks, the skin microbiota was richer and more diverse in the interventional group compared with the placebo group. The intervention group also had more immunomodulatory effects than the placebo group. These results support the biodiversity hypothesis of immune-mediated diseases, but longer follow-ups are needed to show clinically relevant prevention of allergic symptoms [37].

3.2.2. Air pollution

Air pollution is linked to multiple non-communicable diseases in children including low birth weight, asthma, cancer, and neurodevelopmental disorder [38]. Global warming contributes to air pollution by increasing frequency and severity of wildfires and SDS, and increasing GHGs, pollen and ozone (O_3) concentrations. A systematic review of the literature evaluated concentration-response functions and found compelling evidence that exposures to NO_2 and inhalable PM contributed to risk of asthma development in childhood. Inhalable PM includes those $\leq 10\mu$m (PM_{10}) in diameter [39]. A systematic review found that long-term exposure to O_3 was associated with a decrease in forced expiratory volume in one second (FEV1) in children [40]. Inhaled $PM_{2.5}$ are especially damaging to developing lungs as they are small enough to enter lung tissues, thus increasing the $PM_{2.5}$ oxidative potential [41]. The case of Ella Adoo Kissi-Debrah, who lived near a heavily congested road in south London is the first case in which exposure to air pollution has been recorded as a medical cause of death. She had severe asthma and died in February 2013, having been taken to a hospital nearly 30 times over the previous three year [42].

3.2.2.1. Indoor air pollution. Climate change affects outdoor air pollutants, which permeate indoor spaces. Additionally, other air pollutants can be found indoors due to emissions from cooking and heating with biomass, volatile organic compounds (VOCs) from consumer products, and allergens (molds, dust mites, and animal dander). Mold spores, often found in homes with poor infrastructure (leaky roofs, poor ventilation, areas with high humidity), can also contribute to indoor air pollution. These pollutants are directly or indirectly a consequence of climate change. While PM is the major indoor pollutant, indoor gases such as NO_2 and VOCs also have adverse respiratory health effects [43,44]. Recent studies have found that indoor air pollution from gas stoves account for about 13 % of childhood asthma in the United States [45]. Analysis of data from over 3500 participants from the Dutch PIAMA (Prevention and Incidence of Asthma and Mite Allergy) birth cohort found that higher exposure to NO_2 and PM_{10} was associated with a higher incidence of asthma until the age of 20 years [46]. A cross-sectional National Surveys of Children's Health (2017–2018) found that the prevalence of asthma in children who were exposed to homes with mold was greater than those in homes without mold (10.8 % versus 7.2 %, respectively) [47].

3.2.2.2. Outdoor air pollution. Outdoor pollutants include industrial and vehicular emissions as well as pollutants from wildfires and SDS storms. Exposures to PM, O_3, and NOx are related to incidence and exacerbations of asthma in both children and adults [48]. A review conducted by the Health Effects Institute found that each 10 $\mu g/m^3$ increase in NO_2 was associated with a relative risk of 1.05 and 1.10 in children and adults, respectively [49]. Recent reviews have observed similar elevations in risk for asthma hospitalizations among children [50]. In Mexico City, the relative risk of asthma-related emergency hospital admission in adults increased by 3 % for a 10 $\mu g/m^3$ increase in PM_{10}, 1 % for a 5 $\mu g/m^3$ increase in $PM_{2.5}$ and by 1 % for a 5 $\mu g/m^3$ increase in NO_2 [51].

3.2.2.2.1. Wildfires. Wildfires are growing in size and increasing in frequency due to climate warming leading to increased number of trees and infrastructure destroyed [52]. The fires release large quantities of PM, carbon dioxide (CO_2), carbon monoxide, methane, NOx, formaldehyde, acrolein, polycyclic aromatic hydrocarbons, trace minerals and various other toxins into the atmosphere increasing respiratory health effects, including asthma [53]. One study found that $PM_{2.5}$ emissions from wildfire smoke is about 10 times more harmful on children's respiratory health than from $PM_{2.5}$ emissions from vehicles [54]. After the onset of a wildfire in California, there were increases of approximately 220 % in $PM_{2.5,}$ 20 % in $O_{3,}$ and 151 % of CO concentration [55]. Wildfires are estimated to contribute to at least 25 % of the PM in the atmosphere [56] and the smoke has been shown to travel many miles, affecting respiratory health in regions far away from the wildfire. In a study by Xu et al., PM levels were 10–15 fold over the 24-hour US standard (35 $\mu g/m^3$) 1000 kms away from the wildfire source [57]. Clinical effects of acute and chronic exposure to wildfire smoke include increases in asthma-related hospitalizations and emergency department visits [58], decreases in respiratory peak flow [59], and increased use of dermatological clinics for atopic dermatitis and itch [60]. Decreases in respiratory peak flow was observed one year after the wildfire event indicating long-term effects of wildfire smoke.

3.2.2.2.2. Sand and dust storms. Like wildfires, sand (particles $\geq 60\mu$m) and dust (particles $< 60\mu$m) storms are increasing due to climate change [61,62]. A warmer climate with droughts, desertification, and land degradation by human activity increase the incidence and severity of dust storms. In particular, the regions stretching from the Sahara Desert to the Gobi Desert of China and Mongolia face the brunt of SDS earning it the name of the global dust belt [63]. SDS vary widely in composition and contain fine $PM_{2.5}$, minerals, organic matter, pathogens, allergens (dust mites, pollen, and fungal spores) and industrial pollutants [64]. Regions in the global dust belt see an increase in asthma and hospital admission for asthma [65-67]. For example, asthma rates in children in Kuwait are greater than that

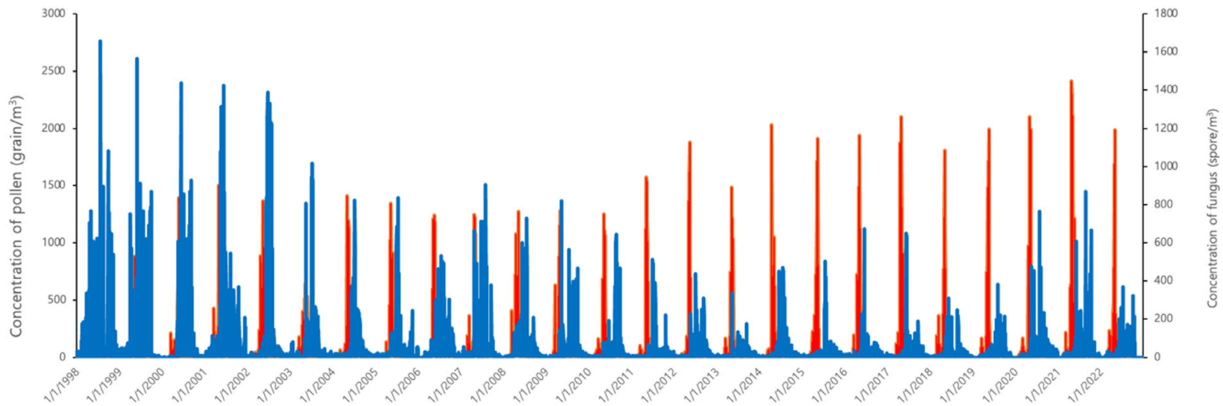

Fig. 4. Comparison of the annual concentrations of pollen grains (red) and fungal spores (blue) in Seoul for the past 25 years. In contrast to atmospheric fungal concentration, pollen concentration increased annually during the same period (Reproduced from Choi et al. [88]. No changes were made to the original figure).

seen in the children in the US (22.4 % versus 7.8 %, respectively [68]. SDS also carry pathogens such as *Coccidioides immitis* or *Coccidioides posadasii*. In recent years, increases in coccidioidomycosis has been found in the Southwest US, leading to increases in Valley Fever in the region [69].

3.2.2.2.3. Pollen and other allergen exposure. Increased GHGs, rising temperatures levels, and other factors have led to alterations in pollen production in plants including increased pollen quantity, allergenicity, and longer season during which pollen is released [6,7,70-72]. Pollen concentrations are estimated to increase further in the future as temperatures and GHGs increase [73,74]. Earlier flowering of *Betula pendula Roth* in Augsburg, Germany was associated with higher temperatures and NO_2. However, the pollen season of *Betula* spp. frequently did not coincide locally with the flowering period of *Betula pendula,* raising questions about the relationship between flowering times and airborne pollen seasons and on the rather underestimated role of the long-distance transport of pollen [75]. Increased allergenicity has been shown to be brought about via increased nitrification and oxidation due to increased CO_2, NO_2 and O_3 in the atmosphere [76,77] while increased temperatures and CO_2 have been associated with increased pollen production [78]. Studies show that elevated ambient CO_2 levels elicit a strong ragwood-induced allergic response in vivo and in vitro and that ragwood extract increased allergenicity, which was dependent on the interplay of multiple metabolites [79,80]. Further, urban birch trees, located next to high-traffic roads with higher NO_2 levels, are more likely to be infected by birch idaeovirus. Increased environmental stress is thought to lead to more plant viral infections [81].

Increased pollen concentration has public health consequences, especially for atopic diseases such as allergy and asthma. A systemic review and meta-analysis found a significant increase in the mean number of asthma emergency department presentations, which correlated with increases of 10 grass pollen grains per cubic meter [82]. Early onset of spring and pollen release is associated with increased risk of asthma hospitalization and increased pollen allergenicity is associated with more severe symptoms in allergic individuals [6,73,83,84]. Weather conditions also aggravate allergy and asthma during the pollen season. In particular, asthma incidence and severity are increased during thunderstorms. A systematic review and meta-analysis found that thunderstorms increased the risk ratio of asthma events by 1.24 (95 % CI 1.13−1.36) [85]. This phenomenon is termed thunderstorm asthma. During a thunderstorm, rain and moisture rupture pollen grains increasing their allergenicity [86].

Airborne fungal spores are associated with respiratory allergies in humans, and some fungal spores can cause allergic diseases. Environmental and biological factors influence the concentrations of atmospheric spores. Greater fungal growth and allergenic mold spores have been observed in the floods ensuing thunderstorms. A study in South Korea found that levels of indoor mold were related to the presence of water damage in dwellings. The adjusted odds ratio of allergic rhinitis was elevated by over tenfold in the water-damaged dwellings [87]. However, allergenic fungal sporulation has also been observed to decrease with desertification and drought (Fig. 4) [88].

3.2.3. Heat stress

Climate change is increasing the frequency of heat waves causing increased morbidity and mortality [89]. One study found increased childhood asthma emergency department admissions during heat waves [90]. Another study explored the effects of temperature and air pollution exposure during pre- and post-natal periods among preschoolers and found that they are synergistically (and independently) associated with increased asthma risk in early childhood [91].

3.2.4. Indirect effects of climate change on allergies and asthma

Climate change, affecting water and food insecurity, leads to social instability and conflicts leading to migration and human displacement. Human migration is generally from rural to urban areas and the UN predicts that by 2050, 70 % of human populations will live in urban areas [92], which are associated with greater ambient air pollution with lower biodiversity leading to higher asthma burden [93]. These factors indirectly affect allergies and asthma. Climate change has expanded the geographical habitats of certain disease vectors and migration has led to humans encountering novel allergens and disease vectors. For example, the geographical expansion of the lone star tick has led to increased incidence of alpha-gal allergy (also called red meat allergy) [94]. When the lone star bites a human, it transmits and sensitizes a person to a sugar called alpha-gal, which is found in mammalian meat. On consuming mammalian meat, these sensitized individuals undergo an allergic reaction [95].

3.3. Solutions: Adaptation and mitigation

The WHO estimates that by 2050 half the world's population will be affected by allergies and asthma, primarily due to lifestyle changes and climate change [96]. The Paris Agreement was signed it 2015. It marked the first truly global treaty and charted a new course in the effort to combat climate change, requiring countries to make commitments and progressively strengthen them. Its goal was to promote low-emission and climate-resilient development to halt the increase in global temperature to well below 2 °C above pre-industrial levels and to ensure that efforts are pursued to limit the temperature increase to 1.5 °C by the end of the century. However, the 2023 report by the Intergovernmental Panel on Climate Change (IPCC) found that there is more than a 50 % chance that global temperature rise will exceed 1.5 °C between 2021 and 2040 across certain scenarios. Under a high-emissions pathway, the world may hit this

Box 1 **Modifying the exposome through mitigation and adaptation to prevent allergies and asthma**

- Decrease fossil fuel consumption and lower greenhouse gas emissions.
- Decrease indoor and outdoor air pollution.
- Provide early warning systems for sand and dust storms and wildfires prediction.
- Increase biodiversity.
- Practice regenerative agriculture.
- Weatherize buildings.
- Increase green spaces to sequester carbon.
- Focus on predominantly plant-based diet.
- Live sustainably (reduce, recycle, reuse, and use local products).
- Mitigate conflicts by practicing principles of justice, equity, diversity, and inclusion.

threshold even sooner (between 2018 and 2037) [97]. There is urgent and increased need to accelerate adaptation and mitigation strategies to reduce GHG emissions.

Box 1 lists some of the adaptation and mitigation strategies. Adaptation aims to help society increase resilience to the health effects of climate change. Mitigation involves reducing GHGs and limiting global temperatures, the root cause of climate change [98]. Climate change affects all individuals on earth and international agencies, countries, national and local organizations as well as individuals need to work towards solutions to make meaningful progress. Individuals can assist in reducing their carbon impact in many ways such as reducing fossil fuel use, reusing, repairing and recycling products, and eating a predominantly plant-based diet. Transitioning to a predominantly plant-based diet has the potential to significantly reduce GHG emissions from food production by 61 % to 73 % [99,100]. It is also associated with decreased land and water use [101]. Below, we discuss some of the strategies and provide examples of climate change adaptations and mitigations that were identified in this review that have been shown to lower risk of asthma and allergies.

3.3.1. Adaptation

To protect against adverse health effects of climate change, the identified literature notes that different adaptation strategies are needed. These include early warning systems, individual behavior changes, and infrastructure changes. Although climate change is a global issue, effects are felt locally and therefore local organizations need to prepare for extreme climate change events, such as flooding, heat waves, and air pollution.

Air pollution increases asthma and allergy. Behavioral adaptations during periods of high air pollution include limiting time spent outdoors and wearing appropriate masks in order to reduce exposure. Infrastructure changes include use of air filters in homes to reduce $PM_{2.5}$. While reduction in indoor air pollutants with air filters have been demonstrated, studies have been unable to show significant decreases in asthma control, quality of life, or measures of lung function [102,103]. A study by Park et al., however, found that air filters significantly decreased indoor $PM_{2.5}$ levels by up to 43 % and that after 12 weeks, total and daytime nasal symptoms scores were significantly reduced with a trend towards improvement of childhood asthma control test scores and mean evening peak flow rates [104].

Global warming is increasing the number of heat waves, which are associated with increased asthma burden. As temperatures rise, adaptation to heat stress include alerts systems warning the public of high temperatures. Behavioral changes to protect against high heat could include limiting outdoor exposure, drinking adequate amounts of water, and wearing light colored and loose clothing. Individuals at high risk are outdoor workers and those living in urban heat islands [105,106]. It is estimated that temperatures in urban areas are sometimes up to 10–15 °C higher than in their rural surroundings [107]. Heat islands are created by a combination of heat-absorptive surfaces (such as dark pavement and roofing), heat-generating activities (such as engines and generators) and the absence of vegetation (which provides evaporative cooling) [106].

Another climate change effect is increased flooding and sea level increase. Infrastructure adaptations include building of gray infrastructure (e.g., dikes, levees, and seawalls) as well as use of nature-based solution such as reforestation and use of porous pavements to decrease water runoff and reduce flash floods. A study found that a combination of low impact interventions (rain gardens, bio-retention cells, green roofs, infiltration trenches, permeable pavement, and vegetative swale) reduced total flood runoff volume by 73.7 % [108].

3.3.2. Mitigation

Mitigation strategies aim to improve planetary health by reducing GHG emissions or removing them from the atmosphere. Many studies have evaluated the effectiveness of mitigation strategies or policies to lower GHGs but only a few studies have further evaluated health benefits associated with reduced emissions.

The U.S. Regional Greenhouse Gas Initiative (RGGI) is the United States' first regional market-based regulatory program designed to reduce GHG emissions from the electric power sector within the Northeast. Under the RGGI program, participating states are expected to reduce their annual CO_2 emissions from the power sector by 45 % below 2005 levels by 2020, and by an additional 30 % by 2030. Although RGGI is focused on reducing GHG emissions, it also reduces emissions of other pollutants, such as $PM_{2.5}$, NOx, and sulfur dioxide (SO2). NOx and SO_2 react in the atmosphere to form $PM_{2.5}$. Analysis of data between 2009 and 2014 estimated that this initiative increased the number of estimated avoided cases of asthma, preterm births, autism spectrum disorder, and term low birth weight (TLBW) in RGGI states and neighboring states by 537, 112, 98, and 56, respectively; this reduction is associated with an avoided cost estimate ranging from $191 to $350 million [109].

A study estimated benefits across a suite of child health outcomes in 42 New York City (NYC) neighborhoods under the proposed regional Transportation and Climate Initiative. The benefits varied widely over the different cap-and-investment scenarios. For a 25 % reduction in carbon emissions from 2022 to 2032 and a strategy prioritizing public transit investments, NYC would have an estimated 48 fewer medical visits for childhood asthma, 13,000 avoided asthma exacerbations not requiring medical visits, 640 fewer respiratory illnesses unrelated to asthma, and 9 avoided adverse birth outcomes per 100,000 children and infants (infant mortality, preterm birth, and TLBW) annually, starting in 2032 [110].

Another study in Seattle, Washington quantified intervention scenarios such as reductions in emission of CO_2, NO_x and $PM_{2.5}$ and health benefits of urban transportation policies promoting electric vehicles (EV) and walking and bicycling (35 % of gasoline vehicles were switched to EV, and 50 % of car trips less than 8 kms were replaced by walking or bicycling) and projected them to the year 2035. The study found that implementing these changes would result in 30 % less CO_2 and lower annual average concentrations of primary traffic-generated NO_x and $PM_{2.5}$ by 0.32 ppb (13 %) and 0.08 $\mu g/m^3$ (19 %), respectively. In Seattle, the lower air pollutant concentrations due to electric vehicle and active transport intervention would prevent 20 cases of incident asthma per year [111].

Another study looked at energy savings, emission reductions, and health co-benefits associated with green buildings. Based on modeled energy use, LEED (Leadership in Energy and Environmental Design)-certified buildings, which come from only 3.5 % of the total commercial building floor space in the United States as of 2016, saved $7.5B in energy costs and averted 33MT of CO_2, 51 kt of SO_2, 38 kt of NOx, and 10 kt of $PM_{2.5}$ from entering the atmosphere, which amounts to $5.8B (lower limit = $2.3B, upper limit = $9.1B) in climate and health co-benefits from 2000 to 2016 in the six countries the study investigated. In the U.S., it was estimated that this avoided an estimated 172 −405 premature deaths, 171 hospital admissions, 11,000 asthma exacerbations, 54,000 respiratory symptoms, 21,000 lost days of work, and 16,000 lost days of school [112].

A large study in Shanghai, China, investigated the association between greenspace surrounding residential addresses and asthma in children and found that higher residential greenspace exposure was associated with a reduced risk of asthma in children [113]. A systematic review found 108 papers that examined greenspace and respiratory health and found that many studies showed a positive association between urban greenspace and respiratory health, especially lower respiratory mortality [114].

4. Discussion and conclusion

Our review highlights key environmental factors caused by climate change that adversely affect allergic diseases. There is also greater understanding of the underlying mechanisms by which these environmental factors mediate inflammation and allergy; however, further work is needed. There is now agreement of the anthropogenic causes of climate change and the need to decrease GHG emissions and there is increased global discussion on ways to meet the 2015 Paris Agreement aims. In 2023, it was clear that meeting the goals will be a challenge and further efforts to reduce GHG emission by all countries who signed the accord are needed.

While there is a large body of research that provides evidence of the beneficial effects of lowering GHG emissions for decreasing air, water, and soil pollution, their effects on lowering allergic disease is scarce. There is a large gap in our understanding of needed cost-effective, feasible, practical, just, equitable, and inclusive action (both adaptation and mitigation) to lower allergic diseases. Health care practitioners can expect to see increased incidence of allergies and asthma and should be prepared to cope with the increase in healthcare burden. They should educate their patients how they can adapt to these increases in allergies and asthma and also play a role in adapting and mitigating to climate change.

The strength of our review is the broad literature search, both peer reviewed and gray literature, comprising any aspect of allergic disease, climate change, adaptation, and mitigation that could be affected by climate change. A large international group of authors rigorously and comprehensively reviewed the literature. The weaknesses of our search were that it only included manuscripts in English, there is the possibility of bias, there were a limited number of databases used (PubMed and Scopus), and there was limited assessment of study quality.

This scoping review has identified some key areas for future research: (1) Additional research on the most effective adaptations for community organizations, healthcare providers, and individuals to implement; (2) While studies have demonstrated that certain adaptation and mitigation strategies are effective in reducing air pollution, research on the benefits of these strategies on allergies and asthma is scarce. Even fewer address these solutions with a climate lens.

Climate change has increased the risk of allergies and asthma, and further increases are expected. Individuals, organizations, and nations need to work towards adapting and mitigating the effects of climate change. There is an urgent need to develop sustainable practices and reduce the use of fossil fuels so that future generations can enjoy a clean environment. Justice, equity, inclusion and diversity principles should be followed while addressing environmental issues. This will require a multidisciplinary, cross-sector, and transborder approach to change practices and policies at every scale, from global to local.

Author contributions

All authors contributed to the conceptualization; data curation, formal analysis, writing, review, and editing of the manuscript.

Author agreement

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