Advances and novel developments in environmental influences on allergic diseases

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Advances and novel developments in environmental influences on the development of atopic diseases

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Abstract

Although genetic factors play a role in the etiology of atopic disease, the rapid increases in the prevalence of these diseases over the last few decades suggest that environmental, rather than genetic factors are the driving force behind the increasing prevalence. In modern societies, there is increased time spent indoors, use of antibiotics, and consumption of processed foods and decreased contact with farm animals and pets, which limit exposure to environmental allergens, infectious parasitic worms, and microbes. The lack of exposure to these factors is thought to prevent proper education and training of the immune system. Increased industrialization and urbanization have brought about increases in organic and inorganic pollutants. In addition, Caesarian birth, birth order, increased use of soaps and detergents, tobacco smoke exposure and psychosomatic factors are other factors that have been associated with increased rate of allergic diseases. Here, we review current knowledge on the environmental factors that have been shown to affect the development of allergic diseases and the recent developments in the field.

KEYWORDS
allergy, atopic disease, environment, exposome, pollution

1 | INTRODUCTION

Both genes and the environment shape human health and disease. Although IgE-mediated allergic diseases (atopic diseases) have a genetic component and are more prevalent in individuals with a family history of allergic disease, the observed rapid increases in allergic diseases suggest that environmental factors are the predominant driving forces behind these increases rather than genetic alterations.[1,2] Common atopic diseases include atopic dermatitis, food allergy, allergic rhinitis, and allergic asthma. Human diets and lifestyle have undergone major alterations. The exposome, which is the sum total of all the exposures of an individual in a lifetime, has undergone major shifts in the last few decades, affecting human health and disease.

A number of environmental factors have been implicated in the increased prevalence of allergic diseases. Predominant among them are increased exposure to pollutants and decreased exposure to microbes and parasitic infections. Air pollution has increased significantly in the last few decades. The hygiene hypothesis suggests that increased hygiene and lack of exposure to microbes and parasitic infections at an early age prevents the necessary stimulus to train the immune system to develop tolerogenic responses. Lifestyle factors,

such as increased time spent indoors, use of antibiotics, and consumption of processed foods and decreased exposure to farm animals and pets, limit exposure to environmental allergens, infectious parasitic worms, and microbes. The lack of exposure to these factors is thought to prevent proper education and training of the immune system. Continuous training through adulthood also appears to play a role in maintaining immune function. A study of healthy men in long-term isolation (1 year) in Antarctica found an imbalance of immune function toward a sensitizing of inflammatory pathways.[3] Urbanization has led to reduced biodiversity of plants and animals, which has been associated with increased allergic disease. The biodiversity hypothesis states that contact with natural environments enriches the human microbiome, promotes immune balance and protects from allergy and inflammatory disorders.[4] Other factors that are also associated with increased risk of allergic diseases are Caesarian birth, birth order, tobacco smoke exposure and psychosomatic factors (Figure 1).

Many of the factors that have been implicated in allergic diseases are affected by climate change.[5] It is a risk multiplier that aggravates stressors. It is associated with greater variability in temperature, forest fires, heat waves, thunderstorms, droughts, and floods.[6] Climate change has also been linked to increased concentrations and distribution of air pollutants such as CO_2, ozone, nitric oxide and other volatile organic chemicals. CO_2 has been shown to accelerate plant growth and the onset of pollen season, and increase pollen production, dispersion, allergen potency, and length and duration of the pollen season.[7,8] Climate change has also brought about new pollen species not endemic to the area.[9] Thunderstorms are increasing in frequency and intensity and have been linked during the pollen season with increased asthma exacerbations and emergency room visits.[10,11] Similarly, dust storms and wildfires have been shown to increase inflammatory responses and asthma exacerbations.[12-14] Increases in the level and frequency of house dust mite exposure, sensitization, and asthma symptoms have been observed and is thought to be caused, in part, by global increases in temperature and humidity.[15]

Air pollutants appear to weaken the immune system and make one more susceptible to infections. COVID-19 appears to worsen in those people suffering from air pollution exposure, smoking, and vaping. In addition, global climate change makes access to health care worse (like in an extreme hurricane) and that will affect the marginalized and the elderly who have COVID-19. A nationwide, cross-sectional study in the United States found that a small increase in long-term exposure to $PM_{2.5}$ leads to a large increase in the COVID-19 death rate.[16]

A number of recent high-throughput "omic" technologies are accelerating our understanding of allergic diseases and have revolutionized research and offer the promise of personalized medicine (Figure 2). The use of the term "omics" suggests a comprehensive high-throughput and systematic investigation of biological parameters. Examples of omic technologies include genomics, epigenomics, transcriptomics, proteomics, metabolomics, microbiomics, and exposomics.[17] These technologies generate exponentially growing data sets requiring sophisticated bioinformatics and computational techniques that can integrate, analyze and interpret the data to generate hypothesis, which can

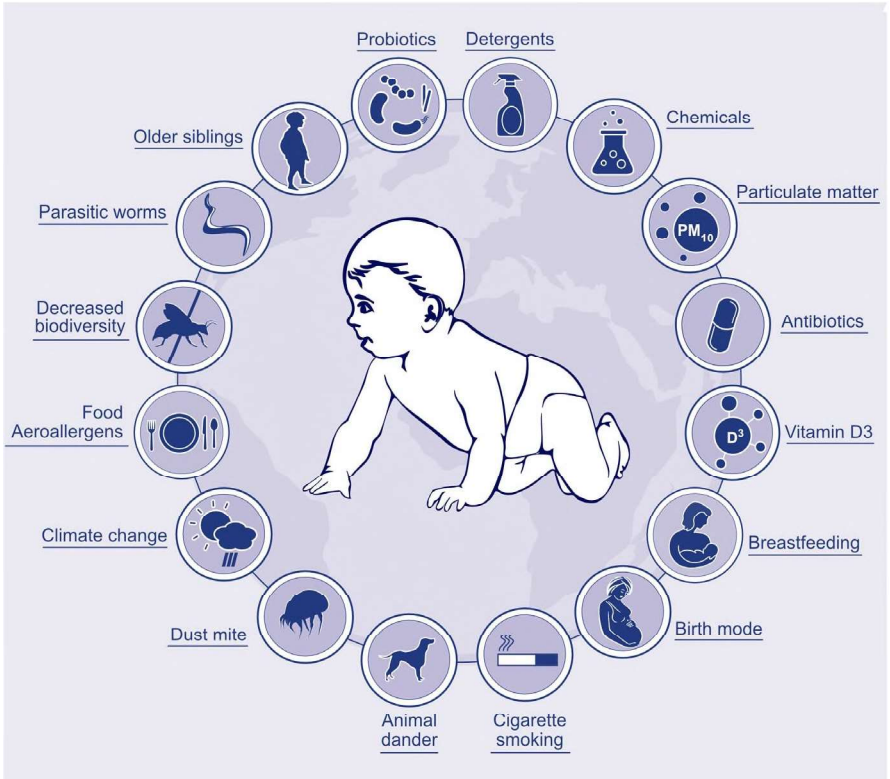

FIGURE 1 A number of environmental factors affect the development of allergy and tolerance in infants. The hygiene hypothesis suggests that increased hygiene and lack of exposure to microbes and parasitic infections at an early age prevents the necessary stimulus to train the developing immune system to develop tolerogenic responses. In modern societies, there is increased time spent indoors, use of antibiotics, and decreased contact with farm animals and pets, which limit exposure to environmental allergens, infectious parasitic worms, and microbes

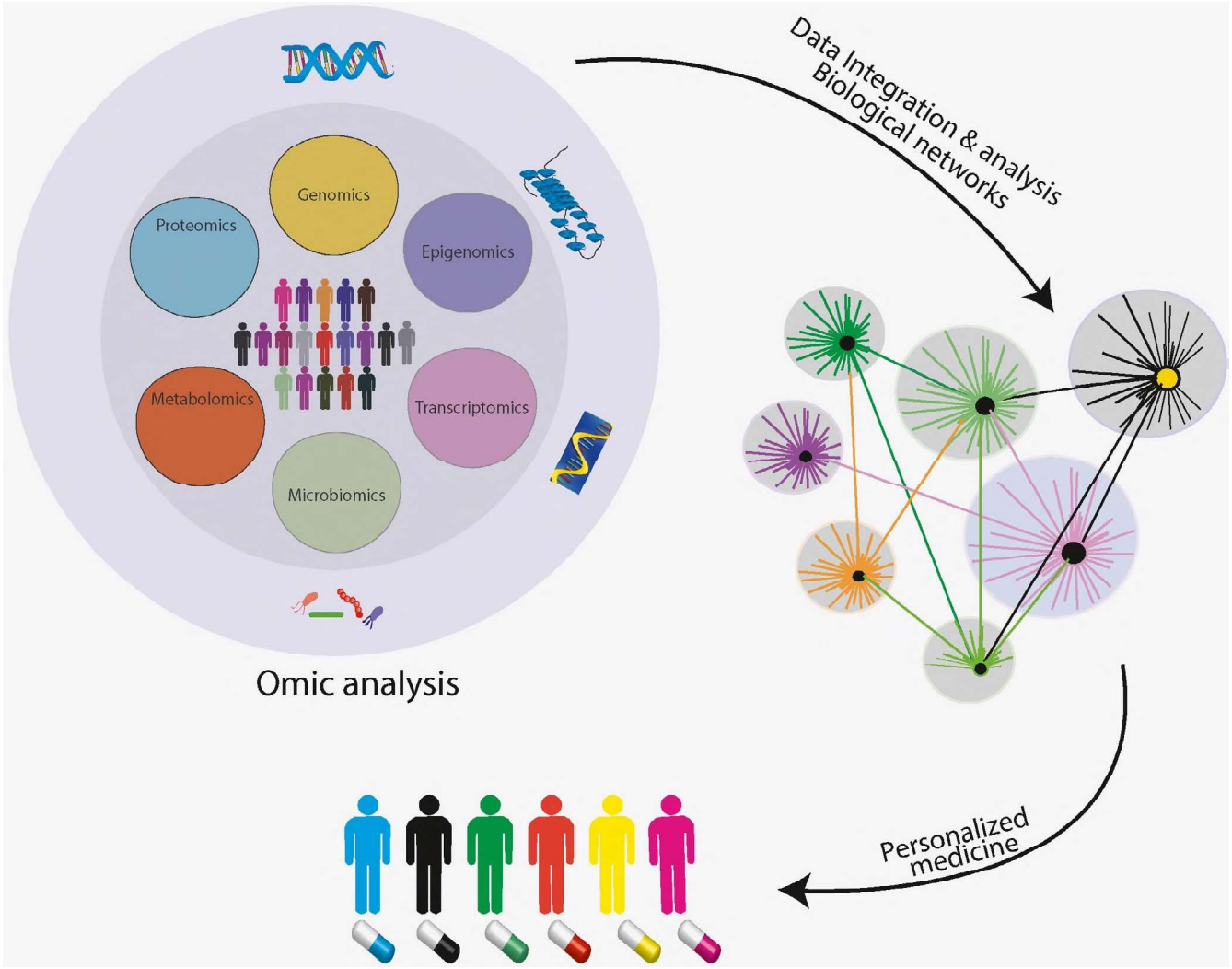

FIGURE 2 High-throughput omics technologies enable generation of large amounts of data that are analyzed and interpreted by sophisticated bioinformatics and computational tools to give us mechanistic information on immune pathways at the DNA, RNA, and protein level. This can allow for personalized medicine

then be further tested. Of these, epigenomics has been key in giving us insight to gene-environment interactions. It has provided us a greater understanding of the mechanisms by which environmental factors modulate epigenetic modifications and expression of genes involved in inflammatory responses and allergy. Technologies such as bisulfite sequencing, ATAC seq and cytometry by Time-Of-Flight (EpiTOF) have made it possible to study DNA methylation and histone modifications, and chromatin accessibility across the whole genome and at a single cell level.[18-21] Here, we review current knowledge on the environmental factors that have been shown to affect the development of allergic diseases and the recent developments in the field. Research on the exposome can improve our understanding of the connections between environmental exposures and health to help mitigate adverse health outcomes and can provide a risk profile instead of single predictors and thus is particularly applicable to allergic diseases and asthma.[22]

2 | FACTORS MODULATING ALLERGIC DISEASE

2.1 | Air pollution

2.1.1 | Direct effects

Air pollutants considered major risk factors for the development of allergic diseases are ground-level ozone, particulate matter (PM), carbon monoxide (CO), sulfur dioxide (SO_2), and nitrogen dioxide (NO_2).[23,24] CO, SO_2, and NO_2 are released from combustion of fossil fuels. Ground-level ozone is a secondary pollutant that is produced when nitrogen oxides and volatile organic compounds released from industrial sources react in the presence of sunlight.

Particulate matter with diameters ≤10 μm or smaller (eg, PM_{10} and $PM_{2.5}$) can carry organic and inorganic components such as heavy

metals and penetrate deeply into the respiratory tract and skin barrier. In a prospective birth cohort study of over 5000 children during the first 6 years of life, strong positive associations were found between the distance to the nearest main road and asthmatic bronchitis, hay fever, eczema, and sensitization.[25] An association between eczema and traffic-related pollutants was also found in children from small towns, where exposure to these traffic-related pollutants was much lower than in urban areas.[26] Some studies speculate that ultrafine particles (UFPs) with diameter ≤100 nm may have greater effects due to their increased capacity to penetrate the lung alveoli and cardiovascular system.[27] A recent meta-analysis estimated that increases in UPFs per 10 000 particles/cm^3 were associated with 7%, 11%, and 5% increase in exacerbations, emergency department visits, and hospital admissions for asthma, respectively.[28]

A recent study estimated that exposure to ambient NO_2 may cause 4 million new cases of pediatric asthma per year, with over 60% occurring in urban areas.[29] Norbäck et al observed robust relationships between lifetime exposure to NO_2 and allergic diseases including asthma, eczema, wheeze and rhinitis for children ages 3-6 years in China.[30] Similar associations have been observed with SO_2 and CO. A study by Penard–Morand et al found that SO_2 exposure significantly increases the prevalence of asthma in children.[31] Similarly, Samoli et al[32] found an association between SO_2 and PM_{10} exposure and the number of pediatric asthma hospital admissions among children aged 0 to 14 years in Athens, Greece. Several time-series studies in China reported positive associations between exposure to CO within a few days and the risk of hospital admission/mortality from asthma.[33] Another Korean study found that for children aged 6-7 years, the odds ratio (OR) for lifetime allergic rhinitis was 1.10 per 100 ppb increase in CO concentration during the first year of life. In addition, the OR for current atopic dermatitis was 8.11 for every 1 ppb increase in the average CO concentration during the preceding 12 months.[34] In the US, the risk for emergency department visits was estimated to increase by 0.8% for asthma or wheeze and 3.7% for bronchitis per interquartile range (IQR) increase in the preceding 3-day average concentration of CO.[35]

Ozone in the stratosphere is protective as it shields living things from ultraviolet radiation from the sun. However, ground-level ozone, which forms just above the earth's surface has been associated with adverse health effects. A birth cohort study in Canada reported that ozone exposure at birth was associated with the onset of asthma and allergic rhinitis during a follow-up at age 17.[36] In France, a higher annual outdoor concentration of ozone was associated with increased total IgE levels.[37] A study estimated that 7-day exposure to ozone was associated with significant increase in physician visits for atopic dermatitis, contact dermatitis and urticaria.[38]

Volatile organic compounds (VOCs) have been associated with increased risk of allergic disease. A study found that indoor total VOC exposure at 6 months in children was correlated with atopic dermatitis at 3 years.[39] Diisononyl phthalate (DINP) is used as a plasticizer and is contained in many consumer products. Children are more likely to have exposure to phthalates than adults through ingestion of dietary sources or inhalation of dust from phthalate containing products. A study in first-grade elementary school children found correlations between urinary phthalate metabolite concentrations and nasal patency and lower small airway dysfunction.[40]

The pathophysiological mechanisms by which air pollution mediates allergic disease are poorly understood; however, oxidative stress, enhanced sensitization to allergens, inflammatory and immunological responses, and epigenetic modifications have been suggested as possible mechanisms.[41-43] Exposure of human nasal epithelium cells to $PM_{2.5}$ was found to decrease loss of barrier function, as determined by measures of transepithelial resistance, permeability, decreased expression of tight junction proteins, and production of proinflammatory cytokines, such as thymic stromal lymphopoietin (TSLP).[44] A genome-wide DNA methylation study found that long-term ambient air pollution exposure impacts DNA methylation of a number of genes, some of which play a role in inflammatory responses.[45] Short-term and long-term exposures to high levels of CO, NO_2, and $PM_{2.5}$ were associated with alterations in differentially methylated regions of Foxp3.[46]

2.1.2 | Indirect effect on plants and ecosystems

The effects of air pollution reported above on the increase in allergies directly affect the immune system or barrier function in humans. However, there is also an indirect effect: air pollution as well as other effects of climate change affect pollen, plants and biodiversity per se. Air pollution (and climate change) affect not only plant growth, pollen and flower production, and duration of the whole pollen season but can also display more indirect health effects by increasing the amount of allergenic encoding transcripts and proteins of the pollen.[47,48] When ragweed plants were grown in climate chambers under controlled conditions and fumigated with enhanced levels of NO_2, transcript levels of Amb a 1, a major ragweed allergen, were up-regulated, indicating potentially higher allergenicity due to NO_2.[47] On exposure of ragweed to varying NO_2 levels during the growing season, a significantly higher allergenicity for Amb a 1 was observed.[48] Elevated CO_2 levels and drought stress were also found to increase Amb a 1.[49]

Therefore, under global change scenarios, the allergenic potential of pollen is also expected to change. A study found that grass pollen exposure in the first months of life was associated with lower lung function later in childhood and adolescence.[50] Epidemiologic studies have demonstrated that urbanization, high levels of vehicle emissions, and westernized lifestyle are correlated to an increase in the frequency of pollen-induced respiratory allergy prevalent in people who live in urban areas compared to those who live in rural areas – this can in part be due to the effects of pollution on the pollen and plants themselves and therefore indirectly impacting human health.[51]

2.2 | Tobacco smoke and e-cigarettes

Epidemiological studies and meta-analyses indicate that pre- or postnatal maternal smoking increases the risk of wheezing and asthma

in children ≤2 years[52] and that secondhand smoke during infancy without prior exposure in utero leads to an enhanced risk of food sensitization and eczema.[53]Tobacco smoke and e-cigarettes may mediate their effects via a number of inflammatory mechanisms. For instance, tobacco smoke provokes oxidative stress[54] which leads to upregulation of TSLP[55] and IL-33[56] suggestive of a pro type-2 inflammation in the lungs. In addition, phagocytic activity of alveolar macrophages from smokers is reduced compared to non-smokers.[57] Repetitive exposure to cigarette smoke in normal human airway epithelial cells was found to impact the adhesive intercellular junctions and disrupt monolayer integrity. Cortical tension of epithelial cells was observed due to increased actin polymer levels, which further destabilized cell adhesion.[58] Tobacco smoke may also mediate its effect through microbiome dysbiosis. A study found that sensitization to *Staphylococcus aureus* enterotoxins is increased in smokers with asthma, and it may be a marker of eosinophilic inflammation and severe asthma.[57] E-cigarettes were also found to be associated with inflammation. A study found that e-cigarette vapors and cigarette smoke altered virulence of key lung pathogens (*Haemophilus influenzae*, *Streptococcus pneumoniae*, *S aureus and Pseudomonas aeruginosa*), which may increase bacterial persistence and inflammatory potential.[59]

2.3 | Microbiome

The microbiome has been shown to play a key role in the development of the immune system with microbiome dysbiosis mediating immune deviation.[60] Characterizing the constituents of the human gastrointestinal, skin, and airway microbiota as well as microbial peptides and metabolites that influence host immunity and immune response to allergens in food allergy, atopic dermatitis, and asthma is the focus of ongoing research.[60,61] Composition of the microbiome has been found to vary even within an organ system, such as the skin, with variations in the microbiome observed between the scalp, arm, and axilla.[62] Advances in our understanding of host-microbe interactions have been made possible by 16S rRNA sequencing, which permits precise identification and quantification of bacteria. 16S ribosomal RNA gene is a highly conserved locus in the bacteria genome, yet different in sequences among different bacterial species. Another approach is to sequence the total DNA present in one ecosystem using whole genome shotgun techniques, and subsequently map the genes related to microbes, including viruses and fungi.[63] These techniques have enabled us to make inroads in identifying the species found in a healthy microbiota and those that cause dysbiosis. In atopic dermatitis, *S aureus* has been shown to be clearly correlated with severity and to decrease during treatment and to rebound after the end of treatment indicating its use as a potential diagnostic and prognostic biomarker.[64] It is now recognized that early infancy offers a "critical window" of colonization during which microbial communities shape immune maturation.[65] In humans, this critical period appears to be within the first 100 days of life.[66] A number of ecological factors influence development of an infant microbiota and understanding these factors is critical for developing preventative strategies.[67,68] A study found that supplementing infants with a probiotic mixture together with at least partial breastfeeding corrected undesired changes in microbiota composition and function caused by antibiotic treatments or caesarean birth.[69]

Studies in mice and humans have shown associations between intestinal bacteria and allergic response to food. In a murine model, germ-free mice were colonized with feces from healthy or cow's milk allergic (CMA) infants. The healthy and CMA mice showed different transcriptome signatures in ileal epithelium, and the healthy mice were protected against anaphylactic responses to cow's milk allergen. The study identified a clostridial species that protected against the allergic response.[70] In another study, microbiota from infants with a low bifidobacteria/Lachnospiraceae ratio orients the murine immune system toward a Th2 atopic profile with clinical symptoms of allergy.[71] *Bifidobacterium breve* is a species commonly isolated from the intestines of healthy breastfed infants and from human milk and is thought to have a significant impact on the development of immune tolerance.[72] In a longitudinal study of a Canadian child cohort, it was found that infants at risk of asthma showed gut microbial changes during the first 100 days of life. Four bacteria taxa were reduced in high-risk children and this was accompanied by reduced deregulation of enterohepatic metabolites. To understand causality, the same study also found that inoculating the four taxa of bacteria (Lachnospira, Veillonella, Faecalibacterium, and Rothia) in germ-free mice decreased airway inflammation.[73] A prospective study from infants through school age found that the gut microbiota of the allergic children were enriched in Bifidobacterium and depleted of Lactobacillus, Enterococcus, and Lachnospira.[74] Individuals with atopic dermatitis have reduced skin lipids and increases in *S aureus*.[75] A study found a correlation between Staphylococcus species–dominated dysbiosis in the skin microbiome and dysregulation of the skin barrier transcriptome in patients with AD, but whether the microbiome dysbiosis is the cause for or result of the skin barrier defect is unclear.[76] *Staphylococcus aureus* has also been directly correlated with increased expression of inflammatory cytokines, IL-4, IL-13, IL-22, and TSLP and with decreased expression of cathelicidin.[77] *C difficile* colonization during infancy was associated with a higher risk of developing allergic diseases during early childhood.[78]

A number of factors affect the composition of either the skin or gut microbiome. Vaginal delivery, breast feeding, presence of older siblings and exposure to a variety of microorganisms promote healthy microbiota in infants. In contrast, Caesarean section, formula milk, and exposure to antibiotics have a negative impact.[79] Dietary factors also play a role in microbiome health. Some of these factors are discussed below.

2.3.1 | Diet

In addition to prebiotics and probiotics, other dietary factors that have been shown to play a role are vitamin D and omega-3 and omega-6 polyunsaturated fatty acids (PUFAs). A study found that

higher second trimester n-6 PUFAs were associated with atopic dermatitis in children of women with atopy.[80] A meta-analysis found that intake of ω-3 PUFA started during pregnancy may reduce the risk of sensitization to egg and peanut.[81] Levels of ω-3 and ω-6 were measured in the second trimester and found that higher ω-6 PUFAs were associated with a higher risk of all respiratory outcomes among children if the mother has asthma, but that male children born to women with asthma and a higher PUFA ratio had the highest risk for asthma.[82] A meta-analysis of ω-3 consumption suggests that introduction of fish at 6-9 months and routine consumption once a week reduces asthma and wheeze in children up to 4.5 years old.[83] The association between vitamin D insufficiency and increased risk of food allergies have been shown by multiple studies. While controlling for regional and population characteristics, places in northern latitudes were found to have more epinephrine autoinjector prescriptions than those in southern latitudes in both USA and Australia.[84,85] In another study, food allergies were found to be more likely in infants with low vitamin D.[86] In children with asthma, vitamin D deficiency was associated with asthma severity and increased serum IgE levels.[87]

2.3.2 | Farming environment and pet ownership

Childhood environments have been shown to play an important role in the protection against allergies. Individuals living at short distances from farms had a lower risk of atopy, as measured by IgE, compared with those living further away. This decrease in atopy risk was even greater for those who grew up on a farm.[88] Children in rural South African communities with higher exposure to pets and farm animals than children from urban communities were found to be at lower risk of allergic disease.[89] Marrs et al[90] reported an association between dog ownership at three months of age and protection against food allergies. However, urban children with pet exposure in the South African cohort had an increased rate of any allergy compared to urban children without pets so conflicting data exist regarding pet ownership in relation to allergies.[89]

2.3.3 | Antibiotics

Antibiotic usage has been documented to perturb the gut flora of individuals, which places them at an increased risk for the development of allergies and asthma. In mice models of atopic dermatitis, antibiotic use was associated with significantly aggravated phenotypes, including clinical score, transepidermal water loss, and histopathology, compared to those treated with healthy feces or probiotics.[91] Timing, dose, and frequency of antibiotics in prenatal and infant populations have also been associated with the development of childhood allergies and asthma.[92,93] Short chain fatty acids (SCFAs) which are fermentation end products of insoluble fibers by intestinal microorganisms have been implicated in the maintenance of epithelial integrity and IgA production.[94] Antibiotics-induced dysbiosis of intestinal microbiota has been shown to increase severity of atopic dermatitis in mice through alterations in SCFA's and decreases in the number of Foxp3$^+$ T regulatory cells.[91]

2.3.4 | Vaginal vs caesarean section births

The composition of gut flora in children born by caesarean section (C-section) vs vaginal delivery is different and this difference in gut microbiota colonization may impact the development of the immune system.[95] A vaginal mode of birth exposes the baby to maternal vaginal and fecal flora.[96] Studies indicate that babies born via C-section have a higher incidence of allergy, atopy, and asthma, increased susceptibility to infectious wheezing[97] and decreased gut microbiome diversity.[98] In addition, long-term studies show greater incidence of childhood asthma up to the age of 12 years.[99]

2.4 | Detergents

Soaps and detergents are now frequently used in households to maintain hygiene. As mentioned earlier, increased hygiene can prevent proper development of immune tolerance. Another drawback is that on contact with skin, they can lead to scaling, dryness, and swelling and commonly trigger AD flares.[100] Traditional alkaline soap increased transepidermal water loss and skin erythema, which are signs of prolonged damage to the skin barrier.[101] Regular washing with soaps has been shown to decrease the thickness of the stratum corneum in atopic individuals making it detrimental to the skin barrier.[102]

2.5 | Other factors

In addition to environmental and lifestyle factors, household composition has also been shown to affect the risk of allergic diseases. A study that followed 17 414 British children for 23 years found a strong association between the birth order of a child and the risk of hay fever.[103] Specifically, contact with older siblings was hypothesized to increase immunological protection due to an increase in infections in early childhood through unhygienic contacts with siblings. A study on 10 834 children enrolled in the Chicago Family Cohort Food Allergy study found that younger siblings of kids with food allergies had significantly less prevalence of food sensitization and clinical food allergy.[104]

Current research shows that psychosocial stress and poor mental health in mothers increase the risk of allergic diseases in their children. [105-111] Stressful life events in childhood, for example parental divorce, have also been shown to increase the risk for development of atopic eczema later in life.[112] Psychosocial stress might trigger or worsen allergic symptoms, while the interaction with protective or health-promoting factors is still poorly understood. [113,114] Also, in

adults with allergies, psychoneuroimmunologic mechanisms might play an important role. [115] An association of anxiety and depression with allergies was reported in many studies.[116,117]

3 | SUMMARY AND FUTURE DIRECTIONS

There have been exciting new developments in understanding the role of the environment in mediating allergic diseases. Epigenetics, in particular, has provided us with better insight into how pollution and other environmental factors alter gene expression. Novel high-throughput technologies have enabled characterization of a healthy microbiota and the imbalance that is created with microbial dysbiosis.

Epidemiological studies have shown a natural history for the progression of atopic diseases, termed the atopic march, which starts with atopic dermatitis in early infancy subsequently progressing to food allergy, allergic rhinitis, and allergic asthma. It is now clear that these atopic diseases have a common underlying mechanism.

With allergic diseases increasing globally, there has been much interest in research to prevent, treat, or cure these diseases (Box 1). These are also increased interest in sensitive and specific biomarkers for diagnosis and for evaluation of disease severity and prognosis with therapy. With the understanding of the natural progression of the atopic diseases, studies are now in progress to determine whether by preventing skin sensitization and atopic dermatitis, we can prevent the subsequent manifestation of other atopic diseases, such as food allergy.[118] Some of the basic cellular and humoral factors involved in Th2-mediated allergic diseases are well understood and have led to the development of biologics and other novel therapeutics, which are in various stages of development. Further research and a clearer understanding the role that genes, epigenetics, and the environment play in shaping our immune health at the DNA, RNA, and protein level can further assist with the development of targeted therapies for treating allergic diseases.

Box 1 Future directions

- Characterization of microbes in healthy and allergic individuals.
- Identifying type and optimal timing of introduction of probiotics and prebiotics for tolerance induction
- Identifying epigenetic alterations and changes in gene expression on exposure to pollutants
- Evaluating emollients as treatment for prevention of atopic dermatitis and other atopic disorders.
- Targeted therapy for precision medicine
- Identification of sensitive and specific biomarkers for diagnosis, evaluation of disease severity, and prognosis with therapy.
- Identification of molecular mechanisms of tolerance induction.

CONFLICT OF INTEREST

Shifaa Alkotob, Vanitha Sampath, Cade Cannedy, Katharina Harter, Hesam Movassagh, Qi Zhao, Bibek Paudel, Mary Prunicki, Eric Smith, and Tamara Schikowski declare no conflict of interest. Claudia Traidl-Hoffmann reports grants for research and development of CK-CARE, Sebapharma, Töpfer, Traidl-Hoffmann is involved in Clinical trials with Assana; Data and Safety Monitoring Board member at Novartis Personal fees from Novartis, Töpfer, Sebapharma; Consultant and Advisory Board Member at Novartis, Sanofi, Lilly Pharma; Dr Nadeau reports grants from National Institute of Allergy and Infectious Diseases (NIAID), National Heart, Lung, and Blood Institute (NHLBI), and National Institute of Environmental Health Sciences (NIEHS); Food Allergy Research & Education (FARE), Director of World Allergy Organization (WAO) Center of Excellence at Stanford; Advisor at Cour Pharma; Co-founder of Before Brands, Alladapt, Latitude, and IgGenix; National Scientific Committee member at Immune Tolerance Network (ITN) and National Institutes of Health (NIH) clinical research centers; DSMB member for NHLBI, US patents for basophil testing, multifood immunotherapy and prevention, monoclonal antibody from plasmoblasts, and device for diagnostics.

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