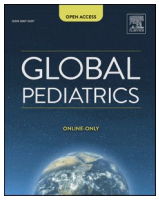
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Environmental determinants of child health: present challenges and future outlook

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ABSTRACT

Children exhibit unique biological and developmental susceptibility to environmental exposures, characterized by rapid growth, immature organ systems, and a proportionally higher pollutant intake per unit of body weight. Compared to adults, their capacity for detoxification is limited, and the developing brain and immune systems are particularly prone to neurotoxic and inflammatory harms during critical windows of growth. This comprehensive review aims to synthesize current evidence on current and emerging environmental threats for the design of effective strategies for pediatric health policy and clinical practice. The diverse health impacts from key hazards, including outdoor and household air pollution, chemical contaminants, and water quality issues are discussed. Attention is also given to novel stressors such as endocrine-disrupting chemicals (EDCs), microplastics (MPs), and nanoplastics (NPs), as well as the multifaceted threats posed by climate change. Exposure to these factors is robustly linked to a wide spectrum of pediatric morbidities, notably acute respiratory infections, asthma, impaired neurodevelopment, and cardiometabolic disorders. Critically, this health burden is highly inequitable, disproportionately affecting vulnerable populations, particularly those in low- and middle-income settings. The safeguard of children's health requires urgent, evidence-based, child-centered prevention strategies and robust intersectoral collaboration to mitigate these pervasive global challenges.

1. Introduction

Children are uniquely sensitive to environmental exposures due to their rapid growth, developmental plasticity, and distinct patterns of physiology and behaviour. Compared to adults, their organ systems are still maturing, their metabolic pathways differ, and their capacity for detoxification is limited. For instance, the developing brain is highly susceptible to neurotoxic insults during critical windows of growth, while the immature immune and respiratory systems make children more prone to infections and inflammatory responses. Moreover, children breathe more air, drink more water, and consume more food per unit of body weight than adults, thereby increasing their proportional exposure to pollutants. Their exploratory behaviour—such as frequent hand-to-mouth activity and close contact with soil or surfaces—further elevates their risk of ingesting environmental toxins. These biological and behavioural factors underscore the reasons environmental hazards disproportionately affect children and why early exposures can have life-long consequences, ranging from impaired neurodevelopment to increased risk of chronic diseases in adulthood.[1]

Abbreviations: CO, Carbon Monoxide; CO_2, Carbon Dioxide; EDCs, Endocrine-Disrupting Chemical HEPA, High-Efficiency Particulate Air MPs, Microplastics; NPs, Nanoplastics; NO_2, Nitrogen Dioxide; O_3, Ozone; PBDE, Polybrominated Diphenyl Ether; PFAS, Per- and Polyfluoroalkyl Substances; PM, Particulate Matter; $PM_{2.5}$, Fine Particulate Matter (≤2.5 μm) PM_{10}, Particulate Matter (≤10 μm); SO_2, Sulfur Dioxide; VOC, Volatile Organic Compound; WHO, World Health Organization.

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1.1. Global overview of emerging environmental threats

In recent decades, the environmental determinants of child health have gained increasing attention as new and evolving hazards emerge alongside persistent challenges. Among the most pressing is air pollution, now recognized as a leading contributor to childhood morbidity and mortality. Exposure to fine particulate matter ($PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3) has been linked to impaired lung development, asthma exacerbations, cardiovascular risk factors, and even adverse neurocognitive outcomes.[2] In many low- and middle-income countries, the burden is compounded by household air pollution from biomass fuels, disproportionately affecting children in vulnerable communities.

Water quality represents another critical determinant. Inadequate access to safe drinking water and poor sanitation contribute to diarrhoeal disease, malnutrition, and stunting, while chemical contaminants such as arsenic, nitrates, and heavy metals impose additional risks for growth, neurodevelopment, and long-term metabolic health. These threats remain highly unequal across regions, with marginalized populations bearing the heaviest burden.

The increasing presence of endocrine-disrupting chemicals (EDCs)—such as bisphenol A, phthalates, pesticides, and flame retardants—has raised growing concern due to their capacity to interfere with hormonal signalling during sensitive developmental periods. Evidence suggests links between early-life exposure and outcomes such as obesity, insulin resistance, pubertal abnormalities, and reproductive disorders. Likewise, the emergence of microplastics (MPs) as an environmental contaminant represents a novel and largely unexplored risk. While research on human health effects is still at an early stage, preliminary findings indicate that micro- and nanoplastics (NPs) may accumulate in tissues, exert oxidative stress, and transport toxic additives, raising questions about their long-term impact on child health.[3]

Finally, climate change poses one of the most far-reaching and multifaceted threats to paediatric well-being. Increasing frequency of extreme weather events—including heat waves, floods, hurricanes, and wildfires—directly threatens child survival through injuries, dehydration, and infectious outbreaks.[4] Indirectly, climate change affects food security, displaces populations, and alters the distribution of vector-borne diseases such as malaria and dengue, placing children at heightened risk. These compounded stressors not only compromise physical health but also affect mental health and psychosocial development, particularly in regions facing recurrent climate disasters.

Together, these environmental challenges form a complex web of exposures that interact with genetic susceptibility, socioeconomic inequalities, and health system capacity, thereby shaping child health outcomes across the globe. All the environmental determinants of child health analyzed in this review are summarized in Fig. 1.

1.2. Aims and structure of the review

The aim of this review is to synthesize current evidence on the major environmental determinants impacting child health, emphasizing both persistent and emerging threats. By focusing on air pollution, water and chemical contaminants, novel hazards such as EDCs, NPs, MPs, and the wide-ranging implications of climate change, we will firstly highlight the impact of these exposures on paediatric morbidity and long-term health trajectories, particularly focusing on disparities in exposure and vulnerability in different resource settings.

Secondly, we will explore how environmental health can be integrated into paediatric practice, education, and policy by developing child-centred prevention strategies safeguarding present and future generations.

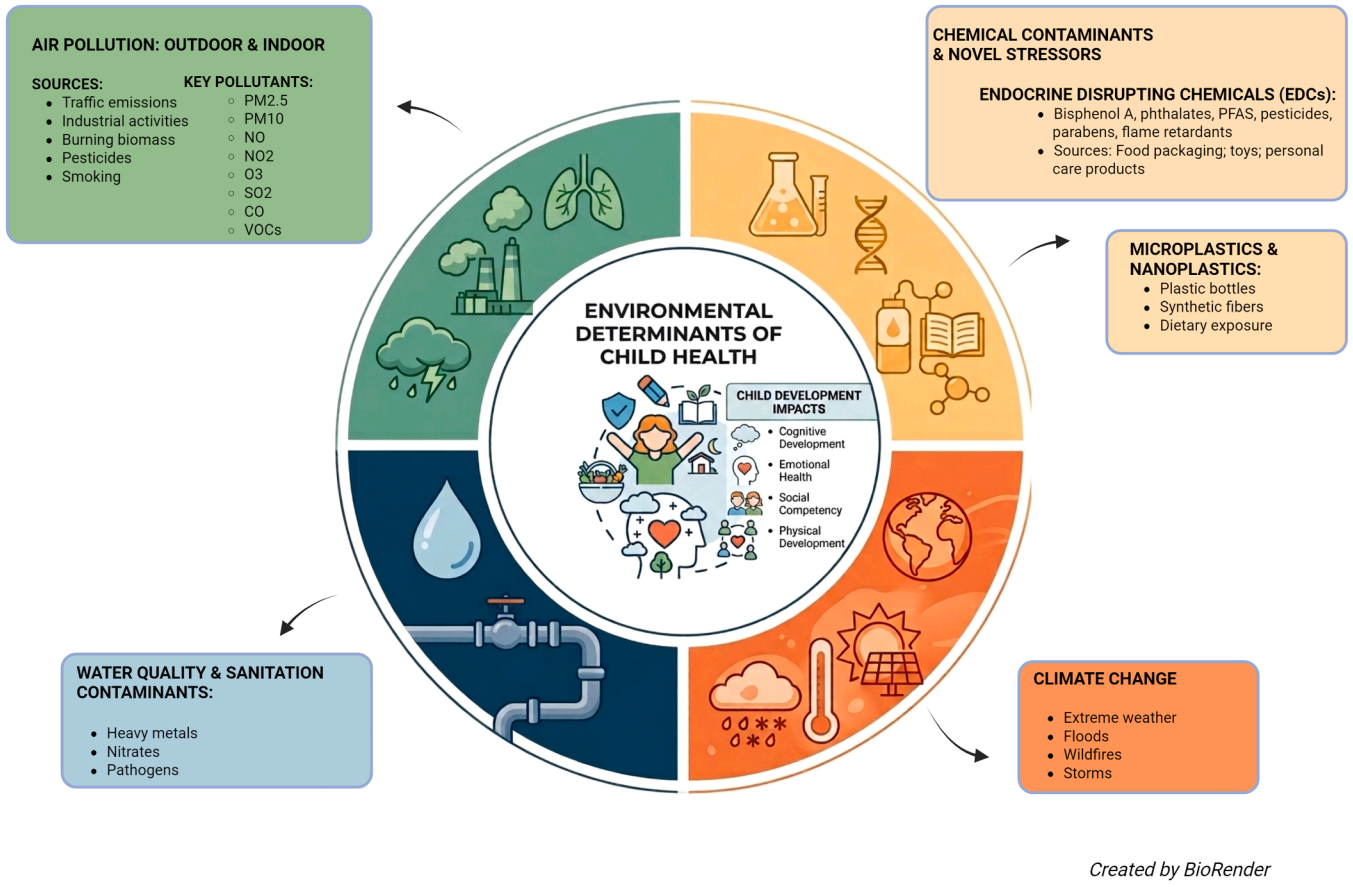


Fig. 1. Environmental determinants of child health.

1.3. Methods

This overview followed the methodological principles of narrative review aiming to provide an integrated synthesis of the most relevant environmental determinants of child health. A targeted literature search was conducted between January and October 2025 using PubMed/MEDLINE, Scopus, and Web of Science. The search strategy combined Medical Subject Headings (MeSH) and free-text terms related to environmental exposures and pediatric outcomes. Keywords included air pollution, indoor air quality, water contamination, endocrine-disrupting chemicals, microplastics, climate change, child health, pediatric morbidity, and environmental determinants. Boolean operators ("AND," "OR") were applied to refine the search. Additional publications were identified through backward citation tracking of key reviews.

Articles deemed eligible were peer-reviewed articles published in English; studies addressing environmental exposures relevant to fetal, infant, or child health; systematic reviews, meta-analyses, cohort studies, narrative reviews, and international guidelines;epidemiological, mechanistic, clinical, or public health research studies.

Given the heterogeneity of study designs and the narrative nature of the review, no quantitative synthesis was performed. By contrast, evidence was synthesized narratively, prioritizing high-quality systematic reviews and large cohort studies to support a comprehensive understanding of established and emerging environmental issues for child health.

2. The air we breathe: indoor and outdoor environmental pollution

2.1. Outdoor air pollution

Outdoor air pollution arises from various sources, both human-made and natural. These include traffic emissions, industrial activity, burning biomass, pesticides and episodic events like wildfires. Particulate matter such as PM_{10}, $PM_{2.5}$, and ultrafine particles, nitrogen oxides (NO and NO_2) O_3, sulphur dioxide (SO_2), and carbon monoxide (CO) represent the most relevant pollutants for children's health. Fine and ultrafine particles can deeply penetrate the lungs and may even enter the bloodstream, while gases such as NO_2 and O_3 act as potent oxidants that impair epithelial integrity and trigger inflammatory cascades. Simultaneous exposure to multiple pollutants can amplify oxidative stress and immune dysregulation, causing significantly more harm than a single pollutant alone.[5]

The negative effects of air pollution on child health are broad, biologically plausible and increasingly well quantified. Exposure to high levels of ambient $PM_{2.5}$ and NO_2 during pregnancy and early life has been associated with changes in placental biology and negative birth outcomes such as reduced birthweight and preterm birth.[6] Early-life exposure to fine particles and NO_2 is also associated with epigenetic changes and impaired neurodevelopment. This can lead to lower cognitive scores and a higher risk of behavioural disorders.[7]

Mechanistic studies suggest that ultrafine particles may reach the brain via olfactory pathways, triggering microglial activation and neuroinflammation.[8] Children are more vulnerable to air pollution because of their higher minute ventilation, immature antioxidant and immunologic defences.[9] Both short-term peaks and long-term background concentrations of $PM_{2.5}$, NO_2, and O_3 have been linked to an increased risk of lower respiratory tract infections and severe bronchiolitis in children.[10] Additionally, all regulated air pollutants except $PM_{2.5}$ are associated with hospital admissions for pneumonia.[6]

Air pollution has a dual effect on asthma in children: it acts both acutely, triggering sudden attacks, and over the long term, worsening the overall clinical condition and lung function. A recent meta-analysis found that $PM_{2.5}$ exposure consistently caused a measurable reduction in peak expiratory flow (PEF), especially in children with severe asthma.[11] Cardiometabolic effects are also being recognized, with higher risks of developing high blood pressure and obesity in exposed children.[12]

Outdoor air pollution is unequally distributed, with inequities extending from global to subnational scales.[13] More than 90% of children worldwide live in areas exceeding World Health Organization (WHO)-recommended air pollution thresholds, with the vast majority of those exposed to unsafe annual $PM_{2.5}$ concentrations residing in low- and middle-income countries.[13] Children in these countries often face more severe health impacts and higher mortality rates from outdoor air pollutant exposure, compounded by coexisting factors like limited healthcare access.[14]

2.2. Indoor air pollution

In most societies, children spend a significant amount of time indoors, where air quality is affected by both indoor emissions and the entry of outdoor pollutants. Major indoor pollution sources include combustion for cooking and heating (solid biomass and coal that generate high concentrations of $PM_{2.5}$, CO and polycyclic aromatic hydrocarbons, kerosene, and gas), tobacco smoke including e-cigarette emissions, unvented gas or kerosene appliances, volatile chemical products such as paints, cleaning agents, and personal care products, candles and incense, cooking-generated particles, ultrafine emissions, damp, mould, microbial products, building-related contaminants and other volatile organic compounds. Poor ventilation, temperature and humidity can also affect indoor air quality.[15]

Indoor pollutants harm children through similar mechanisms as outdoor pollutants: oxidative stress, airway epithelial barrier damage, immune modulation and changes in the respiratory and gut microbiome. Exposure to indoor pollutants in early life may predispose children to allergic sensitization and persistent wheezing, whereas long term exposure to NO_2 from gas stoves is linked to a higher incidence and worsening of pediatric asthma.[16]

Emerging evidence suggests that exposure to indoor pollutants may also contribute to adverse neurocognitive outcomes by causing inflammation, oxidative stress, increasing vulnerability to neurodevelopmental, anxiety, and depressive disorders.[17] Among chemical volatile indoor substances, endocrine disruptors have been linked to reproductive and developmental disorders. They can affect thyroid function, glucose metabolism, body composition, and increase the risk of obesity, altered puberty, and later fertility.[18]

In resource-limited settings where solid fuels are used for cooking and heating, household air pollution is strongly associated with a higher risk of childhood acute lower respiratory infections which remain the leading cause of mortality in children under five years of age.[19] Cleaner fuels and improved stove designs can reduce indoor pollutant concentrations by up to 70%, with lower risk of acute respiratory infections and improvement of infant birth weight. Nevertheless, sustained adoption and affordability remain barriers in many countries and CO emissions often remain above the WHO-recommended limits.[20]

In higher-resource settings, second-hand tobacco smoke remains a significant source of indoor air pollution; it is considered the most modifiable risk factor associated with Sudden Infant Death Syndrome (SIDS).[21] Also, emissions from unvented gas combustion during cooking are an important determinant of paediatric respiratory illnesses. This burden disproportionately affects children living in smaller homes or in socioeconomically disadvantaged and minority households where ventilation is limited and exposure duration is higher.[16]

Elevated carbon dioxide (CO_2) concentrations in classrooms, which indicate inadequate ventilation, represent a major determinant of poor indoor air quality in schools. Schools and childcare facilities represent critical environments where targeted interventions (e.g. improved ventilation systems, use of High-Efficiency Particulate Air (HEPA) filters, avoidance of phthalates and cleaning products with high Volatile Organic Compound (VOC) emissions) can improve indoor air quality and children's well-being, with varying effectiveness in reducing asthma morbidity, respiratory symptoms, and improving lung

function.[22]Interestingly, the use of HEPA filter air cleaners during pregnancy has been associated with higher birth weight in at-term infants.[23]

Across diverse settings, integrated strategies that combine air-quality monitoring with housing policies and maternal-child health programs are crucial to effectively reduce the global respiratory and developmental burden in children worldwide.

3. Hidden threats: endocrine disrupting chemicals and microplastics

3.1. Endocrine disrupting chemicals

EDCs have been defined by the International Program on Chemical Safety and the WHO as "an exogenous substance or mixture that alters the function(s) of the endocrine system and consequently causes adverse effects in an intact organism, or its progeny, or subpopulations".[24] These natural or synthetic compounds interfere with endocrine homeostasis by several key mechanisms of action.[18,25] These include acting as an agonist, as an antagonist, altering hormone metabolism or synthesis or impacting receptor degradation and gene expression, including epigenetic alterations (e.g., DNA methylation) that can be inherited across generations.[26,27] Moreover, a "cocktail effect" may ensue after exposure to a mixture of EDCs, causing additive or synergistic adverse effects that can be difficult to predict, unlike those deriving from individual compounds.[28]

EDCs encompass a heterogeneous group of substances belonging to different key classes, including bisphenols (Bisphenol A and its substitutes, detectable in polycarbonate plastics and epoxy resins for food or beverage packaging), phthalates (as in plastics, personal care products), per- and polyfluoroalkyl substances (PFAS) (used in stain- and water-resistant materials), pesticides (e.g., organochlorines, organophosphates), parabens (widely found in cosmetics), and flame retardants (e.g., Polybrominated Diphenyl Ethers or PBDEs).[29]

Children's unique physiology, and high rate of development make them especially vulnerable to the detrimental effects of these substances during critical windows of susceptibility, including *in utero*, early postnatal life (the so-called "first 1000 days"), and puberty.[30]

Daily exposure to environmental contaminants threatens children's health. Dietary consumption is a primary route, as EDCs are present in agricultural products and can leach from food and beverage containers.[31,32] Other sources include consumer products like toys (via hand-to-mouth behaviour), personal care products, cosmetics, and house dust.[33] Exposure can begin when EDCs cross the placenta, and continue postnatally via breastfeeding[34,35] with effects on paediatric health often manifesting several years after exposure.

One major concern is represented by metabolic disorders. EDCs are considered "metabolism-disrupting chemicals" that may promote insulin resistance, childhood obesity, and metabolic syndrome by interfering with energy homeostasis mechanisms and regulation of adipose tissue, often via interaction with the PPARγ receptor.[36] A correlation between EDC exposure and neurodevelopmental disorders has also been hypothesized since EDCs can interfere with thyroid hormone signalling, which is in turn essential for proper brain development.[37] Indeed, epidemiological evidence suggests associations between prenatal exposure to PBDEs or phthalates and adverse outcomes like cognitive deficits, lower IQ, and neurobehavioral disorders such as autism spectrum related traits.[38]

As for reproductive health, exposure to EDCs, particularly during development, has been linked to changes in the timing of pubertal onset and to conditions like infertility.[39] Hence, addressing this issue by limiting this pervasive exposure during critical developmental windows is a public health imperative to secure the health of present and future generations.[40]

3.2. Microplastics and nanoplastics: dietary exposure and health impacts

Dietary exposure to MPs and NPs is a significant route of human intake, though multiple pathways contribute to the overall burden in children.[41]

Dietary sources of MPs include both seafood, which is a well-documented vector and non-marine products, such as tap and bottled water, table salts, meat, vegetables and milk.[42] In particular, the process of preparing and storing milk and infant formula in plastic bottles has been identified as a major source of exposure.[43] However, children's exposure is not limited to ingestion but is facilitated by inhalation of airborne particles from synthetic textiles or mouthing of plastic toys.

The potential health risks of MP and NP exposure have been shown primarily in *in vitro* and *in vivo* animal models.[44] MPs and NPs can induce both physical and chemical toxic effects. The small size of NPs enables them to cross biological barriers like the intestinal, air-blood, and even the blood-brain and placental barriers thus causing accumulation in several organs.[45] The main toxic mechanisms described include oxidative stress, cytotoxicity, and inflammation, manifesting as structural and functional damage.[46] As for the digestive system, potential harmful effects encompass gastrointestinal injury, liver dysfunction, and dysbiosis. Exposure has also been associated with neurotoxicity and developmental toxicity, raising concerns for the developing nervous and reproductive systems.[47,48]

Despite the urgent nature of this environmental threat, significant research gaps persist, particularly in the context of paediatric health. One challenge is the lack of standardized and validated quantification methods for reliably measuring MP and NP exposure levels in human biological samples across different age groups. Therefore, exposure estimates often rely on approximate assumptions rather than empirical and child-specific data. Thus, there is a critical need for epidemiological studies on large cohorts to shed light on causal dose-response relationships between MP and NP exposure and specific childhood health outcomes, moving beyond reliance on *in vitro* and animal models. Another emerging concern is cumulative exposure in children, who are expected to face higher lifetime burdens than previous generations.[49] Researchers must also explore the synergistic toxicity of MPs and NPs with other plastic-associated chemicals. Filling these gaps would help shape public health interventions aimed at mitigating the risks posed by MPs and NPs.

4. A changing planet: climate change and child health

Climate change stands as a monumental threat to global health, with children and adolescents representing the most vulnerable demographic due to their unique physiological, developmental, and behavioural characteristics.[50–52] This vulnerability is further amplified in low- and middle-income nations and within communities already facing socioeconomic disadvantages and limited access to quality healthcare. The WHO projects that between 2030 and 2050, climate change alone could lead to an estimated 250,000 additional deaths annually, primarily due to malnutrition, malaria, diarrhoea, and heat stress (https://www.who.int/news-room/fact-sheets/detail/climate-change-and-health). The health burden manifests through an intricate network of pathways, acting both directly and indirectly on the well-being of the young, making a holistic understanding essential for informing public health strategies and clinical practice.[51]

4.1. Direct impacts of climate change

The direct impacts on child health stem from immediate environmental changes driven by a warming climate. In particular, extreme weather events like heatwaves, floods, and droughts present significant and immediate risks. Research has established a strong association between temperature extremes and adverse child health outcomes.[51,53]While evidence for an increased risk of child mortality specifically from heatwaves remains somewhat inconclusive, several

studies have observed a heightened risk among infants compared to older age groups.[51] Furthermore, subsequent studies have emphasized an increased overall mortality risk from heatwaves in children, particularly infants.[54,55] In line with this, a recent systematic review highlighted an increased risk of preterm birth in conjunction with heatwaves.[56]

Heatwaves have been directly associated with a higher risk of heatstroke, electrolyte imbalance, kidney-related disease, respiratory and infectious diseases, while increases in mean temperature correlate with paediatric kidney stones and Kawasaki disease.[51] Children are especially susceptible to heat stress due to their higher body surface-to-mass ratio, making them more prone to fluid loss and overheating, with studies reporting an increase in paediatric emergency hospital admissions for renal diseases during heatwaves.[57]

Floods, driven by shifting precipitation patterns, also contribute significantly to the disease burden. Floods can lead to physical trauma, drownings, and the contamination of water sources with pathogens, increasing the risk of waterborne diseases. Conversely, droughts can lead to food and water shortages, contributing to malnutrition and dehydration. Flood exposure has been linked to adverse pregnancy outcomes, which in turn impact the health of newborns.[50] Furthermore, prolonged periods without rain, exacerbated by higher temperatures that increase water evaporation, can trigger droughts.[51] These dry spells, which are characteristically slow to begin and long-lasting, critically endanger the water supply for households and significantly deteriorate children's respiratory and mental health, in addition to contributing to undernutrition and the spread of infectious diseases. Even with various coping mechanisms, droughts can devastate local environments, drive families into financial hardship, and force.[58–60]

Another critical direct impact is the degradation of air quality. Rising global temperatures contribute to increased ground-level O_3 formation, a potent respiratory irritant. This, along with particulate matter from intensified wildfires and other sources, can exacerbate pre-existing respiratory conditions like asthma and increase the incidence of respiratory infections in.[56,61]

For example, one study projected a 14% increase in emergency department visits for asthma caused by aeroallergens in the USA over the course of this century.[62]

Moreover, some studies have linked particulate matter exposure during pregnancy to adverse birth outcomes such as small for gestational age, low birth weight, and to the later development of respiratory disorders.[63]

4.2. Indirect impacts of climate change

The indirect pathways through which climate change affects child health are equally, if not more, profound and widespread. Food security and nutrition are deeply impacted by climate-related disruptions to agricultural systems. Extreme temperatures, droughts, and floods can lead to food shortages, increased food prices, and consequently, malnutrition, stunted growth, and micronutrient deficiencies in children, especially in regions already facing food scarcity.[61,56] A child's nutritional status is a critical determinant of their overall health, immune function, and cognitive development, and climate-induced food insecurity can have irreversible consequences on their long-term well-being.

Furthermore, a changing climate is anticipated to modify the geographic distribution of disease-carrying vectors and influence the survival of infectious pathogens.[51] Vector-borne diseases like malaria, dengue fever, and Zika virus are spreading to new territories, placing millions more children at risk.[56] Malaria, in particular, has a well-understood relationship with local weather trends, and climate change is under investigation for its long-term impact on the distribution of its vectors, the parasite itself, and child mortality and morbidity. In regions like Uganda, Mali, and Zambia, short-term weather changes have created more favorable conditions for malaria transmission, while geospatial models project that high-prevalence areas in sub-Saharan Africa may shift eastward and southward during this century.[51] Furthermore, climate variability, especially average temperature variation, is associated with a change in the geographical distribution of dengue fever, with some studies estimating that nearly half of the world's population could be at risk by the end of the century.[51] In North America and Europe, rising temperatures have expanded the geographical areas of transmission for Lyme disease, with one study projecting a 20% increase in its incidence in the USA by mid-century.[64]

Water scarcity and quality are also major concerns, as climate change alters hydrological cycles, causing water shortages in some regions and contamination in others due to flooding that can overwhelm water treatment systems. The compromised quality and availability of water increase the risk of waterborne diseases such as cholera, typhoid, and diarrhoeal diseases caused by *Escherichia coli, Cryptosporidium*, Rotaviruses, and parasites (e.g., *Giardia* and *Toxoplasmma gondii*), which are leading causes of mortality in young children globally.[51]

Beyond physical health, climate change has significant mental health impacts. The direct experience of climate-related disasters, displacement from homes or communities, and chronic environmental anxiety can lead to a range of psychological stressors, including post-traumatic stress disorder, depression, and anxiety in children and adolescents.[61] A phenomenon known as "eco-anxiety" is emerging, in which young people experience chronic distress and fear about the future of the planet.[61,65] These mental health burdens are a growing concern and can undermine a child's ability to learn, play, and thrive, contributing to long-term psychological and developmental issues.

5. Future perspectives, practical strategies, and collaboration

5.1. Prevention, mitigation and adaptation strategies

To address the health threats posed by climate change, a multipronged approach that integrates prevention, mitigation, and adaptation strategies is necessary. Mitigation, focused on reducing greenhouse gas emissions, offers substantial co-benefits for child health.[66] For example, policies that promote clean energy and active transport can significantly improve air quality, directly reducing the incidence of childhood respiratory illnesses. Healthcare systems and paediatricians are pivotal in this effort, as they can advocate for policies that prioritize child health in climate action plans. Adaptation strategies are crucial for building resilience and preparing for the health impacts that are already occurring. Healthcare systems must enhance their readiness to respond to climate-related emergencies, such as by establishing effective heat-health warning systems and improving infectious disease surveillance and response capabilities.[61,66]

The growing and irrefutable body of evidence on the detrimental effects of climate change on child health makes it clear that the pathways of harm are complex and interconnected, requiring a holistic and proactive approach. Although low- and middle-income nations bear the heaviest burden, no child is immune to the risks. Effective countermeasures require a dual focus on global mitigation efforts to address the root causes of climate change and local adaptation strategies to build community and individual resilience.

5.2. Integrating environmental health into paediatric practice

To translate scientific insights into real-world child health benefits, the involvement of healthcare professionals in climate action is not only an environmental imperative but a fundamental component of patient care and public health advocacy. In particular, paediatricians must integrate environmental health into everyday practice. Thus, clinical screening for environmental exposures should become a routine part of patient history-taking, including questions about indoor air quality, household chemicals, parental occupations, and lifestyle factors. Such screening enables early risk identification and targeted counselling. For

example, providers can guide families on reducing indoor pollutants (e.g., improving ventilation, avoiding tobacco smoke, and using low-VOC products) as well as safer alternatives for plastics and chemical usage.

In parallel, paediatricians are in a unique position to serve as advocates for policy change. By contributing to public consultations, collaborating with environmental health agencies, and engaging with local and national policy makers, clinicians can lend the voice of child health to regulatory debates (e.g., standards for air quality, chemical safety, and plastic bans). Their credibility with patients and communities amplifies impact beyond the clinic.

To support this role, education and training for paediatricians must be strengthened. Core competencies in children's environmental health have been proposed—covering vulnerability principles, exposure assessment, risk communication, and advocacy skills. Medical and residency curricula should incorporate modules on environmental health, and continuing professional development programs should offer updated content on emerging exposures (e.g., MPs and climate-related risks).[67] Training can include use of toolkits, decision-support resources, and case-based learning.

5.3. Research priorities

Advancing environmental paediatric health requires ambitious research agendas. Longitudinal cohort studies and biomonitoring are foundational: following birth cohorts over time, with repeated measurements of chemical, physical, and biological markers, allows disentangling exposure–outcome relationships and detecting critical windows of vulnerability. The U.S. ECHO (Environmental influences on Child Health Outcomes) program is a good example of collaborative cohort infrastructure enabling such integrative research across multiple sites and exposures.[68]

Since children are exposed simultaneously to multiple agents, assessment of cumulative exposures and mixtures is essential. Novel statistical methods (e.g., Bayesian mixture models, and exposome frameworks) are needed to address high-dimensional data and synergistic interactions. Recent methodological work proposes Bayesian varying-coefficient models for longitudinal chemical mixtures in neurodevelopmental studies.[69]

Complementing observational work, intervention studies should test pragmatic strategies (e.g., household air filters, safer consumer products, and dietary modifications) to reduce exposures and measure health outcomes. These trials can inform evidence-based guidance for families, healthcare providers, and policy makers.

5.4. Policy recommendations and intersectoral collaboration

Achieving scale and sustainability requires alignment across the health, environment, education, urban planning, and industry sectors. At the international and national level, world bodies (e.g., WHO, UNICEF, UNEP) and regulatory agencies should adopt child-centred standards and harmonize chemical safety regulations, plastic governance, and air quality targets. For example, paediatric input should inform global treaties or frameworks on chemical use and plastic pollution.

At the national level, multi-sectoral approaches to child protection are key. Urban planning policies can prioritize green zones near schools, reduce traffic emissions, and ensure healthy indoor environments in buildings. Education sectors can integrate environmental literacy into school curricula. Public health agencies and paediatric societies can collaborate to develop guidelines, surveillance programs, and advocacy campaigns.

Successful models often emerge from collaborative platforms: multidisciplinary working groups, regional observatories, and alliances that bring clinicians, scientists, policy makers, civil society, and affected communities together. Embedding children's environmental health in national public health strategies ensures that measures are not isolated but woven into broader health and development agendas.

In this collaborative spirit and in line with its core mission to promote and facilitate paediatric research, the Italian Society for Pediatric Research (SIRP) has officially joined AMBO, the Alliance for an Environment Tailored to Children, spearheaded by the Italian Society of Pediatrics. This partnership is dedicated to fostering scientific research into the environmental influences affecting children's health, with a commitment to disseminate fundamental knowledge for the protection of the youngest population.

6. Conclusion

Environmental exposures, including air pollution, chemical contaminants, micro/nanoplastics, and climate change, represent major and interconnected threats to child health. Because children are uniquely vulnerable during critical windows of development, early-life exposures may have lifelong consequences across respiratory, neurodevelopmental, metabolic and infectious disease outcomes. Addressing these challenges requires coordinated action combining research, clinical awareness, public health intervention, and policy measures aimed at reducing exposures and protecting the most vulnerable populations.

CRediT authorship contribution statement

Roberta Romano: Writing – review & editing, Writing – original draft, Resources. **Mayla Sgrulletti:** Writing – review & editing, Writing – original draft, Resources. **Manuela Cortesi:** Writing – original draft, Resources. **Gloria Mantuano:** Writing – original draft, Resources, Conceptualization. **Viviana Moschese:** Writing – review & editing, Validation, Investigation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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