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Mitigating and Adapting to Climate Change: Evidence for Public Health

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Interwoven urban crises: how health, housing, and climate change intersect

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climate adaptation, climate and health, gentrification, housing, neighborhood environments

Editorial on the Special Issue
Mitigating and adapting to climate change: evidence for public health

Climate extremes are intensifying, and housing is becoming increasingly unaffordable. Today, 1.6 billion people still live without adequate shelter, and climate change is expected to cause 250,000 deaths each year by 2050. Cities are at the forefront of an interwoven crisis, facing severe housing shortages, widening health disparities, and escalating climate threats. Addressing these interconnected challenges requires a cohesive urban policy agenda that places climate-resilient, healthy, and affordable housing at its core.

Climate change has become one of the most pressing public health challenges of the 21st century [1]. Between 2000 and 2020, 3.39 million people died due to climate-related disasters, with heatwaves, tropical cyclones and floods being the top three deadliest [2]. The joint call for papers of IJPH and PHR "*Mitigating and adapting to climate change: evidence for public health*" pointed to a wide range of global public health issues amplified by and interlinked with climate change. While Schulte et al. addressed the direct impact of heat waves in a wealthy country, Gobena and Mengistu reviewed the indirect links between climate variability and food-borne diseases. Expanding the scope further, Amekpor et al. explored integrated initiatives to mitigate climate change with a focus on maternal and child health. In parallel, Akthar and Reid, along with Traoré and Tetka, investigated the broader challenges that climate change poses to health systems.

However, none of these studies addressed the interconnected crises of climate and housing. In fact, the figures above mask socioeconomic disparities deeply linked to the population's housing conditions. For instance, during the 2003 heatwave in France, lack of thermal insulation and sleeping on top floors were associated with heightened mortality Traoré and Tetka. Similarly, in Barcelona, heat-related mortality was shown to be higher in census tracts with older buildings [3], underscoring how housing quality can amplify climate vulnerability.

Housing conditions shape the link between climate hazards and health, as people experience climate impacts primarily indoors [4]. People spend about 90% of their time inside buildings, mostly at home, and those most vulnerable to climate-related health risks, such as children, older adults, and individuals with disabilities, may remain indoors 100% of the time [5]. Poor insulation worsens heat stress during heat waves, while structural weaknesses increase risk during floods and hurricanes. Climate change also accelerates housing deterioration [4]. In this way, climate change acts as a "risk multiplier", compounding health inequalities through substandard housing conditions [5].

As climate risks intensify, another crisis unfolds: the housing affordability crisis, pushing more people into unsafe living conditions. The financialization of real estate, the rise of mass tourism, and the expansion of the sharing economy have all contributed to rising housing costs, accelerating gentrification and undermining health and wellbeing [6]. In Europe, according to Eurostat, house prices have surged by 37% since 2010, with the steepest increase occurring between 2015 and 2021. Similar trends are emerging across the globe, even in the Global South, positioning gentrification as a growing planetary concern [7]. The housing crisis and climate risks are now deeply intertwined: soaring prices are pushing low- and middle-income residents into less ideal neighbourhoods and homes [8], many lacking adequate cooling, increasing their exposure to extreme heat and respiratory illnesses. As housing affordability decreases, many are left with no choice but to endure substandard living conditions that exacerbate health inequalities and climate vulnerability.

Given these realities, housing must be a cornerstone in climate change mitigation and adaptation. Sustainable and resilient housing, coupled with climate-conscious urban planning, is essential for withstanding extreme weather events, ensuring safe and healthy living conditions, and reducing environmental impact. This is especially urgent given that housing contributes significantly to global greenhouse gas emissions [9]. Adaptations, such as elevated foundations in flood-prone areas, enhanced insulation for temperature regulation, passive cooling, urban greening or climate shelters, as mentioned by Sanz-Mas et al., can reduce vulnerability while promoting sustainability [10]. Beyond reducing emissions and climate vulnerability, these measures can also generate important co-benefits by improving health and wellbeing, lowering household energy costs, and reducing social inequalities.

Yet, adding another layer of complexity, sustainable urban development can also exacerbate existing inequalities. In many urban contexts, green infrastructure and energy-efficient housing projects have fueled climate gentrification, displacing low-income residents under the guise of adaptation. This phenomenon occurs when environmental improvements increase property values, displacing long-term residents who can no longer afford to live in newly "climate-proofed" neighbourhoods [11]. In Miami, higher-elevation areas, historically home to low-income communities, are now targeted by wealthier populations moving away from flood-prone zones [12]. Similar trends appear in European cities, where greening projects, put into place to minimise exposure to climate extremes and other environmental harms, increase costs and displace residents [11]. This cycle leaves vulnerable populations in high-risk, low-resilience housing. As climate change drives demand for resilient homes, property values will increasingly reflect exposure and resilience, widening disparities as lower-income groups are pushed into riskier conditions. Yet, this challenge also presents an opportunity for innovation in urban governance, requiring climate adaptation plans that combine resilience measures with affordability protections, such as rent controls, inclusive housing policies and increasing urban residents' involvement in decision-making.

Finally, it is also important to underscore the unequal impacts of climate change, which disproportionately affect populations in the Global South, thereby highlighting the need for more globally inclusive perspectives in public health research. Worldwide, 1.6 billion people -mainly in the Global South–live in inadequate housing without basic services like water and sanitation. Around 60% of them, including 350–500 million children, live in slums [13]. Climate change affects cities differently: poorer nations face rising health risks, while economic inequality may worsen in wealthier countries. Addressing the climate crisis requires both emission reduction and adaptive strategies tailored to each urban context. Recognising the interconnectedness of all life in a shared environment fosters holistic approaches, including education (formal and non-formal), empowering communities, while transdisciplinary research [14] helps develop innovative, context-specific solutions aligned with sustainable development goals. Combining these efforts can promote more resilient, equitable, and sustainable cities worldwide.

In conclusion, climate change, housing, and the health and wellbeing of people and the planet are profoundly interconnected, with poor housing conditions exacerbating climate risks. Urban policymakers in both high-income and low- and middle-income countries must move beyond siloed approaches and recognise that housing, health, and climate are deeply interrelated crises. The future of cities – and indeed of all life-supporting habitats – depends on breaking these silos, shifting our worldview from human-centrism to ecocentrism [15], thereby optimising global sustainability through integrated policies and strategies that can make a difference to the planet before it's too late.

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Determining the Public Health Impact of Climate Change: A National Study Using a Health Impact Assessment Approach in Wales

Liz Green[1]*, *Kathryn Ashton*[1], *Nerys Edmonds*[1], *Michael Fletcher*[1], *Sumina Azam*[1], *Karen Hughes*[1], *Phil Wheater*[2] and *Mark A. Bellis*[1]

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Objective: Climate change is recognised as the biggest threat to global health of the 21st century and impacts on health and wellbeing through a range of factors. Due to this, the need to take action in order to protect population health and wellbeing is becoming ever more urgent.

Methods: In 2019, Public Health Wales carried out a comprehensive mixed-method Health Impact Assessment (HIA) of climate change. Unlike other risk assessments, it appraised the potential impact of climate change on health and inequalities in Wales through participatory workshops, stakeholder consultations, systematic literature reviews and case studies.

Results: The HIA findings indicate potential impacts across the wider determinants of health and wellbeing. For example, air quality, excess heat/cold, flooding, economic productivity, infrastructure, and community resilience. A range of impacts were identified across population groups, settings, and geographical areas.

Conclusion: These findings can inform decision-makers to prepare for climate change plans and policies using an evidence-informed approach. The work has demonstrated the value of a HIA approach by mobilising a range of evidence through a transparent process, resulting in transferrable learning for others.

Keywords: climate change, health impact assessment, population groups, environment, health and wellbeing

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INTRODUCTION

Climate change has been recognised as the biggest threat to global health of the 21st century, contributing to widening health inequalities [1]. The policies currently in place for reducing emissions with no additional action are projected to result in a global warming of 2.8°C over the 21st century [2]. However, to prevent further global warming, it is clear emissions need to be reduced, which requires a rapid transformation of societies and economies [3]. This fundamental shift is required in political, economic and personal action to protect and promote the health and wellbeing of the global population [4, 5].

In response to rapid increases in extreme weather and public concern, governments internationally have declared a climate emergency [6]. A climate emergency was declared in Wales, United Kingdom in 2019 by the Welsh Government [7] who appointed the first Minister

for Climate Change in 2021 [8]. Wales is a country in the United Kingdom which borders with England and the Irish and Celtic seas, with a population of around 3.1 million people. Increasingly frequent extreme weather events have occurred in Wales in recent years [9], impacting infrastructure, services, and the physical and mental health of the population [10]. Wales has a strong record for assessing the public health implications of policies and events [10–12]. This is further supported by the enabling environment to facilitate sustainable development, address climate change and create a more resilient, healthier Wales. The Wellbeing of Future Generations (Wales) Act (2015) [13] is an example. This legislation focuses on sustainable development, making overt connections to health, equity and determinants of health such as resilient communities and global responsibility to meet the needs of Wales today without compromising the future needs of the country. National recognition of climate change as a cross-cutting policy crisis, highlights the importance of "Health in All Policies" approaches (HiAP) [14].

To further understand the health and wellbeing impacts of climate change on the Welsh population, the national public health agency in Wales, Public Health Wales, carried out a Health Impact Assessment (HIA). HIA is a process that considers the impact of a policy, plan or scenario on the health and wellbeing of any specific populations who may be particularly affected [12, 15]. It is commonly defined as "a combination of procedures, methods and tools by which a policy, plan or project may be judged as to its potential effects on the health of a population, and the distribution of those effects within a population" [16]. HIAs can help to identify evidence-based actions and mitigation to diminish or remove negative impacts and maximize positive ones [12]. As an internationally established process and public health tool, HIA is both systematic and flexible helping to raise awareness and consideration of health, wellbeing and inequalities [17]. HIA is also strongly linked to the HiAP approach and is recognised by the WHO as an important tool to enable collaboration and for health and wellbeing to be considered in all policy sectors [14].

Whilst the environmental and economic impacts of climate change are well documented [1, 2, 18], there is less evidence demonstrating the wider public health and wellbeing impacts on specific population groups beyond the displacement of people [18]. A recent synthesis of systematic reviews of the health effects of climate change [19] concluded that most studies focused on the "meteorological impacts of climate change on adverse physical health outcomes" and that "future studies could fill knowledge gaps by exploring other climate-related impacts and broader psychosocial health outcomes." In addition, the authors highlight a need to "unpack the 'what, how, and where' of these effects." This novel study aims to contribute to this gap by outlining the process and findings from a national level HIA in Wales, which focused on the "what, how and where" of health and wellbeing impacts of climate change as well as the cumulative impacts on specific population groups. It also provides policy focused recommendations for the future.

This assessment is unique in its approach to use the HIA process to identify the populations who may be potentially majorly affected by climate change either positively or negatively, alongside the potential impacts on the determinants of health and wellbeing. It aims to provide relevant and transferrable learning for international, national and cross-sector policymakers and practitioners who have an interest in environmental and sustainability issues, climate change or those who may wish to carry out HIAs on major events and challenges. The data and evidence collected as part of the HIA process can also aid organisations with adaptation planning through enabling prioritisation of impacts and the framing of key messages on climate change. It will inform public health and climate policymakers, public bodies, third and private sector agencies about the potential positive and negative impact on people's health and wellbeing and identify any structural inequality, which may emerge from climate change and extreme weather events.

METHODS

HIA as practiced by the Wales Health Impact Assessment Support Unit (WHIASU) at Public Health Wales is based on the WHO definition of health and follows a systematic yet flexible evidence-based process [17]. It assesses the impact of policies, plans or projects through the lens of the wider determinants of health [20]. The HIA process follows a mixed methods approach, using both quantitative and qualitative methods to consider the potential positive and negative (including unintended) impacts on population groups and health equity. This is achieved by using secondary evidence, but also carrying out primary stakeholder engagement with organisations, public bodies, and communities who could be impacted by a policy, plan or project. The HIA process uses two checklists [21] that focus on the wider determinants of health and population groups to ensure comprehensive potential impacts are considered.

In 2019, a comprehensive mixed method HIA of climate change in Wales was started and conducted over a 6-month period. However, the COVID-19 pandemic led to its suspension at the appraisal stage and the HIA was restarted and updated from mid-2022 [22]. The internationally recognised five-step process of a HIA was followed [17].

Screening and Scoping

A multi-disciplinary, cross-sector Strategic Advisory Group (SAG) was established to oversee the HIA alongside Public Health Wales' governance processes. This consisted of representatives from a wide range of public bodies and groups including national and local government, the national environment agency, local health services providers, academia and a third sector sustainability focused group (Renew Wales, n.d.). The SAG also provided guidance on the HIA process, and feedback on the final report. In addition, an internal Working Group was established. Using the WHIASU Wider Determinants checklist and the Population Groups checklists as a guide [21], the screening process identified a range of potential determinants of health and wellbeing and population groups, which could be affected by climate change. The scope of the HIA was also

determined, with the geographical boundary of the HIA defined as Wales. The scoping allowed for the parameters and timeframe of the project to be set and outlined the resources required to undertake the assessment.

The HIA also utilised the established conceptual framework for assessing socio-spatial vulnerability and climate disadvantage [23]. This enabled identification of vulnerability in different population groups in relation to climate change, and relationships between personal factors linked to vulnerability, the social determinants of health, other structural factors and inequalities. A research protocol was developed for a rapid review of grey and academic peer-reviewed evidence. Academic literature was identified via ProQuest and grey literature via Google Advanced Search. Evidence was included if published in the English language in the last 10 years and focussed on the key topic of climate change, including the wider determinants of health and key population groups. All results were screened and reviewed by two independent researchers. If deemed eligible for inclusion, evidence was reviewed, and relevant information extracted into an extraction table for use in the evidence appraisal process. A community health profile was developed using quantitative health intelligence data obtained from robust evidence sources in Wales. This included the National Survey for Wales [24] and the Welsh Index of Multiple Deprivation [25].

Thirty-three stakeholders were invited to participate in semi-structured qualitative interviews, with 25 interviewed across 19 interviews. Ninety stakeholders were invited to participate in two cross-sector, multidisciplinary participatory workshops. The purpose of the workshops were to gather qualitative evidence and knowledge from key stakeholders. Participating stakeholders, identified through purposeful sampling based on the findings from the screening stage, included representatives from a wide range of public bodies, frontline services, academia and the third sector (for example, health and social care, housing, emergency services, planning and community representatives). In total, 33 stakeholders (approximately 30% of those invited) participated in the workshops, which were independently facilitated by members of the WHIASU team. The HIA team felt that participants were representative of all key stakeholder groups, despite only 33 out of the 90 attending. No formal ethical approval was required to undertake this assessment, and all participants agreed to findings being reported anonymously and consent was taken before participation. Workshop participants also completed a feedback and evaluation form. The workshops and interviews were transcribed, and transcripts thematically analysed by members of the HIA team.

Evidence Appraisal

All evidence gathered at the screening and scoping stage was collated and synthesised to assess and characterise the positive and negative impacts, and form a picture of the scale, scope and duration of these. The impact was considered for both the identified population groups and the wider determinants of health. This process has been used in previous high-profile HIAs and has been published elsewhere [22, 26]. The identified impacts were also classified into the categories defined in **Table 1**.

TABLE 1 | Characterization of impact (Wales. 2020).

Intensity	
Minimal	Of a minimum amount, quantity or degree
Moderate	Average in intensity, quality or degree
Major	Significant in intensity, quality or extent
Duration	
Short term	Impact seen in 0–1 year
Medium term	Impact seen in 1–5 years
Long term	Impact seen in over 5 years
Likelihood	
Possible	Plausible, but with limited evidence to support
Probable	Direct evidence but from limited sources
Confirmed	Strong direct evidence from a wide range of sources that an impact has already happened or will happen

Reporting

A full HIA report was developed including recommendations for action, which was reviewed by the SAG and approved by the Executive Team of Public Health Wales. It was also subject to a stringent quality assurance process using the WHIASU Quality Assurance Review Framework [27]. The final report was disseminated via a network of key stakeholders compiled throughout the HIA process and via relevant specialist public health and climate change networks including the Faculty of Public Health Special Interest Group on Sustainable Development, the Welsh Government climate emergency programme and Green Health Wales.

Monitoring and Evaluation, Including Review and Reflection

Findings of the HIA were shared to inform the development of a monitoring system of health impacts arising from climate change in Wales via public health surveillance. Formative evaluation and learning [28] is an important part of HIA in Wales [12, 26]. A review and reflection session was held by the HIA team after publication to capture the learning from the HIA, what did and did not work, and the impact the process had on other workstreams, policies and decisions to date. Notes were also captured by the lead authors throughout the process of carrying out the HIA.

RESULTS

The HIA findings indicate significant positive and/or negative impacts across the wider determinants of health and mental wellbeing, population groups, settings, and geographical areas. The impacts are both confirmed (current) and potential, and identified as short, medium or long-term in duration (**Table 2**). The evidence highlighted that climate change is complex and an important determinant of wellbeing, having potential major, multifaceted, co-occurring and inequitable impacts. For example, climate change was found to have an impact on: nutrition and food security; community resilience and

TABLE 2 | Determinants of health and wellbeing (Wales. 2023).

Health determinant	Negative/Unintended negative impacts[a]			Positive/Opportunities		
	Intensity[b]	Likelihood[c]	Duration[d]	Intensity[b]	Likelihood[c]	Duration[d]
Food utilisation: healthy eating	Unknown	Unknown	Unknown	No evidence	Possible	Short/long-term
Food availability: production and security	Major	Probable	Short/long-term	No evidence	Possible	Short/long-term
Food accessibility: cost of food	Major	Probable	Short/long-term	Unknown	Unknown	Unknown
Nutritional content of food	Major	Probable	Short/long-term	No evidence	Possible	No evidence
Food Borne Disease	Moderate	Possible	Unknown	Unknown	Unknown	Unknown
Physical activity and outdoor leisure activity	Moderate	Possible/probable	Short/medium term	No evidence	Possible	Short/long-term
Alcohol and substance misuse	No evidence	Possible	Unknown	Unknown	Unknown	Unknown
Community resilience and cohesion	Moderate/major	Possible/probable	Short/long-term	Moderate/major	Probable	Short/long-term
Population displacement, mobility and migration	Major	Probable/confirmed	Short/long-term	No evidence	Possible	No evidence
Violence	No evidence	Possible	No evidence	Unknown	Unknown	Unknown
Family and intergenerational relationships	No evidence	Possible	Short/long-term	Unknown	Unknown	Unknown
Mental wellbeing	Major	Probable	Short/long-term	No evidence	Possible	Short/long-term
Social isolation	Unknown	Possible	Short/long-term	Unknown	Unknown	Unknown
Mental disorder	Major	Probable/confirmed	Short/long-term	Unknown	Unknown	Unknown
Suicide	No evidence	Possible	No evidence	Unknown	Unknown	Unknown
Housing	Moderate/major	Probable/confirmed	Short/long-term	Moderate	Possible	Short/long-term
Air Quality (Outdoors)	Moderate	Possible	Short/long-term	Moderate	Possible	Short/long-term
Flooding	Major	Confirmed	Short/long-term	Unknown	Unknown	Unknown
Higher temperature and extreme heat	Major	Probable	Short/long-term	Moderate	Probable	Medium/long-term
Water Supply	Moderate/major	Probable/confirmed	Short/long-term	Unknown	Unknown	Unknown
Water Quality	Moderate/major	Confirmed	Short/long-term	Unknown	Unknown	Unknown
Natural environment and biodiversity	Major	Confirmed	Short/long-term	Moderate	Possible	Short/long-term
Landslides and coal tip	Major	Possible/probable	Short/long-term	Unknown	Unknown	Unknown
Wildfires	Major	Probable	Short/long-term	Unknown	Unknown	Unknown
Vector borne disease	Moderate/major	Possible -	Short/long-term	Unknown	Unknown	Unknown
Working Conditions	Moderate/major	Probable	Short/long-term	No evidence	Possible	No evidence
Economic Development and skills	Major	Confirmed	Short/long-term	Moderate/major	Possible	Short/long-term
Access to health and care services	Moderate/major	Probable/confirmed	Short/long-term	Moderate	Possible	Short/long-term
Education	Moderate/major	Probable	Short/long-term	Moderate	Possible	Short/long-term
Transport	Moderate/major	Confirmed	Short/long-term	Moderate	Probable	Short/long-term
Infrastructure	Major	Confirmed	Short/long-term	Unknown	Unknown	Unknown

Unknown—no or lack of evidence. This does not mean that there is no impact and therefore is a research gap.
[a]*Unintended negative impacts are impacts that are considered to diminish health status.*
[b]*Intensity: i.e., minimal; moderate; major.*
[c]*Likelihood: i.e., probable; possible; confirmed.*
[d]*Duration: i.e., short/medium/long-term.*

cohesion; mental health and wellbeing (i.e., a person's condition with regard to their psychological and emotional wellbeing). The determinants affected and additional areas were identified as needing more evidence to highlight impacts are depicted in **Table 2**.

Population Groups

This HIA demonstrates that the whole population in Wales is impacted by climate change, with particular population groups being more affected positively, negatively or both (**Table 3**). For example, *older adults* aged 65 and over accounted for 21% of Wales' total population in 2021, and this proportion is projected to increase by around 16% by 2030 [29]. The population aged over 75 is also projected to increase from 9% of the population in 2021 to around 13% in 2030. Older adults are more vulnerable to health impacts from extreme heat, poorer air quality and extreme weather, but would be positively impacted by the potential for warmer winters. *Limiting longstanding illness* affected a third (33%) of adults in Wales in 2021/22 [30] and people in Wales live on average for around 18 years not in good health. People living with a range of health conditions were found to be more vulnerable to climate change related health impacts including higher temperatures, flooding and reduced air quality, with no positive impacts identified.

Occupational groups such as those working in education, social care and emergency services, those who worked outdoors and those who worked in education and transport were identified to be potentially impacted by climate change. Over 40% of the workforce in Wales work in jobs identified as being more exposed to the health and wellbeing impacts of climate change. Coastal Communities were identified to be majorly affected with a significant proportion of the population potentially exposed to the health and wellbeing impacts of sea level rise, coastal erosion and flooding [31].

In addition, the HIA identified that the way that climate adaptation policy and interventions are designed, communicated and implemented also incur impacts for health and wellbeing beyond the meteorological effects. A range of policy responses, action and mitigations to tackle climate change and its effect on health and wellbeing were identified (**Box 1**).

TABLE 3 | Population groups identified as particularly affected by climate change in Wales (Wales. 2023).

Population group	Negative/Unintended negative impacts[a]			Positive/Opportunities		
	Intensity[b]	Likelihood[c]	Duration[d]	Intensity[b]	Likelihood[c]	Duration[d]
Babies, children and young people	Major	Probable/ confirmed	Short/long-term	No evidence	Possible	Short/medium term
Older adults	Major	Probable/ confirmed	Short/long-term	Unknown	Unknown	Unknown
Women	No evidence	Probable	No evidence	No evidence	Possible	No evidence
Pregnant women	Moderate	Probable	Short/long-term	Unknown	Unknown	Unknown
Men	Moderate	Probable/possible	Short/long-term	No evidence	Possible	Short/long-term
People who are displaced including refugee and asylum seekers	Major	Probable	Short/long-term	Unknown	Unknown	Unknown
People with long-term health conditions and/or disabilities	Moderate/ major	Probable	Short/long-term	Moderate/ major	Probable	Short/long-term
People who are homeless	Major	Probable/ confirmed	Short/long-term	No evidence	Possible	No evidence
Ethnic minority groups	Moderate	Probable	Short/long-term	Unknown	Unknown	Unknown
People who are new to an area	Moderate	Probable	Short/long-term	Unknown	Unknown	Unknown
Low-income groups	Major	Probable/ confirmed	Short/long-term	No evidence	Possible	Short/long-term
Occupational groups including outdoor workers; manufacturing; transport workers; and health and social care staff and emergency services	Moderate	Probable	Short/long-term	Unknown	Unknown	Unknown
Coastal areas	Major	Confirmed in some areas	Short/long-term	Unknown	Unknown	Unknown
Flood risk areas	Major	Confirmed	Short/long-term	Unknown	Unknown	Unknown
Former and current industrial areas	Moderate/ major	Possible	Short/long-term	Moderate	Possible	Short/long-term
Urban areas	Major	Probable/ confirmed	Short/long-term	Moderate	Possible	Short/long-term
Rural communities	Major	Probable	Short/long-term	Unknown	Unknown	Unknown
Areas of multiple disadvantage	Moderate/ major	Probable	Short/long-term	Moderate	Probable	Medium/long-term

[a]*Unintended negative impacts are impacts that are considered to diminish health status.*
[b]*Intensity: i.e., minimal; moderate; major.*
[c]*Likelihood: i.e., probable; possible; confirmed.*
[d]*Duration: i.e., short/medium/long-term.*

DISCUSSION

The HIA outlined in this paper examined the health, wellbeing and equity impacts of climate change on the population of a small, high income, temperate country, and identified the potential and actual health impacts for a range of different population groups and key determinants of health. Using a well-established HIA process, a wide range of evidence was appraised, and key cross-sectoral, multi-disciplinary stakeholders participated to ensure a rich level of both positive and negative impacts were captured along with a wide range of perspectives. It has provided key recommendations to inform current planning and future policy decisions and actions to mitigate for the outcomes of climate change. Stakeholder knowledge and engagement is an important building block of the impact assessment process [32–34]. Whilst peer reviewed papers and data are weighted more heavily than the qualitative evidence, the insight and the knowledge captured through the extensive stakeholder involvement has proved valuable to provide local contextual knowledge and a better understanding of the climate change, health, demographic, topographic and policy landscape in Wales and has strengthened the reach of the HIA. The findings of the HIA have been mobilised within Wales, both within Public Health Wales and across public bodies, including Welsh Government. Public Health Wales have a new strategic priority of "Tackling the public health effects of climate change" [35], and the HIA findings fed directly into the Welsh Government New National Adaptation/Resilience Plan which is due to be launched in 2024.This HIA has demonstrated it is imperative that impacts are fully identified and understood so that the "what, how and where" of climate change can inform adaptation planning. The value of HIA in identifying vulnerability and inequalities arising from climate change has been highlighted previously [36–38].

BOX 1 | Identified policy responses, actions and mitigation to tackle climate change (Wales. 2023).

- Enhancing mitigation and adaptive capacity
- Enhancing risk communication and education
- Enhancing public involvement and engagement in adaptation policy
- Enhancing the integration of health and wellbeing into adaptation planning across sectors
- Investing in co-benefits for health.

The granular approach of the HIA using the two checklists as guides makes it particularly useful as it can enable a 'deep dive' into key topics and identify the vulnerable subgroups or determinants that are particularly relevant to specific regions or countries.

A further value of the HIA was that it enabled the application and contextualisation of the international evidence on health impacts of climate change to a specific country level population, demonstrating the proximal rather than distal nature of these impacts to policymakers. High levels of the population believe climate change is something with consequences elsewhere (or at least that the major ones are abroad, for example, wildfires in Australia). Media coverage often shows these big events elsewhere and it is easy to get the impression that Wales, for example, is relatively untouched except for flooding or storms. Another benefit of a nation carrying out their own HIA is that the process can lead to professional stakeholders and others locally/nationally (for example, third sector or community leads) to challenge this concept, recognise that climate change is already significantly impacting issues in the nation itself, and lead to the realisation that they need to take action on those issues.

The findings of this HIA aligns with previous research, which states that the impacts of climate change on health and wellbeing are not distributed equally [19, 23, 39] and that, and, specifically for the United Kingdom, "opportunities for adaptation are unlikely to be unevenly distributed across the UK population" [40]. The HIA also identified significant cumulative impacts for different population groups, highlighting the need for population and place-based vulnerability to be integrated into adaptation and resilience planning as much as sectoral and service-based risks. The HIA highlighted that climate change does not exist in a vacuum, impacting on various determinants of health in a complex systems way. As identified in this HIA and in previous research [41, 42], there are range of action and mitigations that can be implemented by a wide range of policies and actors. It also highlights that there can be co-benefits for both health and the environment from mitigation and adaptation, for example, more active travel leading to less car emissions and cleaner air for those with respiratory conditions [22]. However, caution is also needed as an intervention that may have benefits to health, the environment, or a specific population group could also have unintended negative impacts for others, such as the economy [42, 43].

These results contribute to the growing body of evidence that climate change adaptation is not keeping pace with climate change [44–47]. An enhanced approach and investment is needed in policy and practice across different sectors. For example, through investing in action guided by enhanced, robust public health surveillance of the impact of climate change on health and wellbeing, and involving the public via democratic decision-making processes and policymaking. Investing in co-benefits for health [48], such as investing in strategies and climate resilient infrastructure to increase physical activity and active travel, will contribute to tackling climate change.

It is recognised that there are limitations to this study. It is noted that some impacts are predictive or potential, due to the ever-changing nature of climate change, for which the future is unknown [49]. However, this HIA has been useful in identifying potential impacts and providing recommendations for action by the appraisal of relevant robust evidence and presenting it in a coherent format (**Tables 1**, **2**). Although this HIA is based solely on the Welsh context, many impacts may be generalizable across different contexts and nations. Finally, although the impacts identified within this HIA were based on an extensive review of the available literature at the time, the evidence base on climate change and climate science is rapidly developing [50]. As a result, it is necessary for the findings from this assessment to be reviewed and updated.

The results from this HIA can be used as the basis for future research. It has demonstrated how climate change is not an isolated phenomenon. Therefore, it is essential that further investigation is conducted in several areas to strengthen the evidence base to address interconnected challenges. These include, for example, identifying areas of potential increased health service demand arising from climate change, and on effective approaches to manage and mitigate the impacts of flooding. This study also found that further research is required to identify the impacts of extreme weather on mental health and wellbeing in particular population groups. Significant gaps in the literature were also recognised in relation to the Welsh context, for example, the health impacts of extreme heat, drought and vector borne disease, and also implications for mental health and wellbeing, violence, alcohol and substance misuse, and family and intergenerational relationships. Moreover, this work has demonstrated the applicability and suitability of implementing HIA to capture the holistic impacts of climate change [36]. Further research could build on this to make results more applicable to local populations and different contexts. This can be achieved by mirroring the HIA process undertaken in Wales, and engaging with stakeholders relevant to the context in question.

Conclusion

This study depicts the major potential impacts and opportunities for health and wellbeing which can emerge from climate change at a country level, using Wales as an example. The findings have been beneficial to inform decision-makers developing plans and policies on climate change using an evidence-informed approach. The work has demonstrated the value of an HIA approach for

addressing the impacts of climate change on health and wellbeing, by engaging stakeholders and mobilising a range of evidence through a transparent process, resulting in transferrable learning for others.

AUTHOR CONTRIBUTIONS

LG designed and led the study. LG, NE, KH, and MF carried out the Health Impact Assessment. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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Climate Disaster and Cognitive Ability: Evidence From Wildfire

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Objectives: We investigate the impact of wildfire disasters on cognitive health (i.e., thinking and language skills) in individuals aged 10 years and older using 2014 and 2018 wildfire and cognitive ability survey data from China.

Methods: We distinguished wildfires in each county at different wind directions each day by exogenous wind direction changes, and analyzed the effects of wildfires on cognitive abilities through upwind and non-upwind wildfires.

Results: Our analysis shows that for every 10-unit increase in upwind wildfires compared to non-upwind wildfires, respondents' scores on word and math tests decrease by 0.235 and 0.236 standard deviations, respectively. Furthermore, we find that the impact of wildfire on cognitive ability is more pronounced in younger individuals, and those with lower defensive expenditures experience more severe impacts. Additionally, wildfires negatively affect individuals' cognitive abilities by generating air pollution.

Conclusion: Wildfires significantly reduce individuals' cognitive abilities. Two recommendations are as follows: 1) governments should follow the principle of green development, introduce relevant regulations, and increase investment in adaptive technologies. 2) Individuals should raise awareness of climate hazards preparedness and strengthen defensive protection.

Keywords: human capital, climate disaster, wildfire, cognitive ability, wind direction realization

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INTRODUCTION

The rate and strength of wildfires are increasing due to climate change, leading to higher levels of carbon emissions, degraded air quality, and significant impacts on socioeconomics [1]. The Lancet Countdown to 2021 China Report shows a 24.5% increase in average annual wildfire risk in China from 2016 to 2020 compared to 2001–2005, with 20 provinces experiencing higher wildfire risk. Accurately portraying the economic and social costs of climate disasters is a major concern in academia. At the same time, cognitive ability has long been considered an important component of human capital and is crucial to decision-making, human behavior formation, and economic development [2, 3]. Clarifying the impact of climate disasters on human capital is of great significance for optimizing climate disaster governance policies and promoting stable economic growth in various countries.

In recent years, the issue of global warming has become more prominent, leading to an increase in the severity and consequences of climate disaster such as wildfires. Research in the field of economics has revealed significant harmful effects of wildfires on human health [4]. Wildfires can directly cause fatalities such as burns, heat exposure, and smoke inhalation, as well as a significant economic burden

through the release of fine particulate matter and other pollutants leading to increased rates of respiratory and cardiovascular disease, and psychological disorders such as anxiety and depression, which can increase long-term medical costs [5, 6]. Additionally, some scholars have further estimated the economic losses associated with wildfire disasters on human health. According to the research by Johnston et al. (2021), the health costs caused by the 2019–2020 Australian wildfires amounted to AUD 1.95 billion [7]. In addition to analyzing the impact on human health, economists have increasingly focused on various economic consequences of wildfire disasters. These include individual defensive behavior and willingness to pay [8], the outdoor recreation economy [9], fluctuations in housing prices [10, 11], the value of local facilities and services [12], and mortgage loan risk [13]. Recently, some researchers have started to examine the impact of wildfires on human capital. However, existing research mainly focuses on exploring the impact of wildfires on labor supply and productivity. For instance, Borgschulte et al. discovered that every extra day of wildfire exposure results in approximately a 0.1% reduction in quarterly labor income [14].

In addition to impacting economic activity and physical health, wildfires can also have a direct impact on human cognitive abilities, resulting in increased health costs and loss of human capital [14, 15]. While there is limited focus on the relationship between wildfire disasters and cognitive health, research is increasing on the impact of straw burning, a form of fire pollution from wildfires, on cognitive health. Zivin et al. discovered that as the difference in fires between upwind and downwind increased by one standard deviation, the total test result decreased by 1.42% [16]. Lai et al. found that PM2.5 emissions from upwind straw burning contributed to decreased cognitive health [17]. Based on the aforementioned empirical research, it is theoretically possible that wildfire can also have a significant impact on human cognitive abilities. In particular, recent studies have found that wildfires increase air pollution levels [14, 18]. Furthermore, previous studies have shown that air pollution can lead to damage to the nervous system and impair brain function as a result of the potential neurotoxicity of air pollutants [17, 19–21]. Air pollutants such as particulate matter and nitrogen dioxide have been shown to trigger neuroinflammation and oxidative stress in the brain, leading to chronic inflammation, cell damage, and ultimately cognitive decline [22]. The direct neurotoxic effects of certain pollutants, along with vascular damage and disruption of neurotransmitter systems, further exacerbate these effects. Consequently, this can lead to diminishing individual cognitive abilities and productivity [23–25]. Therefore, we argue that wildfire disasters may impact individual cognitive health through air pollution.

However, the following challenges exist in current research on the effects of wildfire on cognitive health. First, previous studies have focused on some of the areas where large wildfires have occurred, and less on the impacts of less intense wildfires that are farther away from cities [4]. To address data limitations and data accuracy issues, we used VIIRS satellite wildfire monitoring data [26, 27]. Compared to previous wildfire survey data, this data provides a more comprehensive representation of nighttime and small-scale wildfires, and therefore allows for a more accurate monitoring of scattered or short-burning wildfire events [28]. Second, it is difficult to study the pollution effects of wildfires on health purely by excluding other economic factors that affect cognitive ability through causal identification methods. Individual health can be affected by a variety of socio-economic factors, individual behavioral choices, or other environmental pollution factors that can also influence the pollution effects of wildfires [29]. Failure to exclude other influences can lead to biased estimates. To address this issue, this study adopts the approach of Rangel and Vogl [29], which utilizes exogenous changes in different wind directions for empirical analysis. We are specifically comparing the difference in cognitive ability impacts between areas with prevailing winds and those without. Taking the county administrative center point as the center of the circle, with a radius of 50 km, the daily maximum downwind wind direction is connected to the center of the circle, and the area with a 45° between its right and left side is the upwind direction, see the shaded area in **Figure 1**, while the other areas are the non-upwind direction areas, see the blank area in **Figure 1**. This discrepancy is interpreted as the causal effect of wildfires on cognitive ability, taking into consideration confounding factors. The approach assumes that people in areas with prevailing wind directions experience varying wildfire pollution levels but are equally affected by other confounding factors, such as being in counties with the same economic conditions or other pollutants. At the same time, the daily wind direction and the location of fire point sources are frequently changing across districts and counties, which helps to further distinguish pollution effects from confounding effects and reduce the problem of selection bias that has arisen from the selection of stationary sources (e.g., factories) in the previous literature.

Therefore, we gathered daily wildfire data for each county in China in 2014 and 2018. To analyze the impact of wildfires on cognitive ability, we employed different wind direction models.

This paper has the following potential research contributions. Firstly, we expand on the literature about the impact of climate change on cognitive health and human capital. By focusing specifically on the impact of wildfire disasters, this study sheds light on the external costs associated with such events and offers valuable insights into their wide-ranging consequences. While many natural disasters typically result in localized damage, the empirical findings presented in this paper highlight the potential for significant harm even in areas far removed from the fire's location. This generates substantial negative externalities and provides a novel perspective for comprehending the economic and social costs of climate-related disasters. Secondly, we add to the research literature on the determinants of cognitive ability. Existing literature has primarily focused on micro-level factors such as household and individual characteristics [30–32] while giving less attention to the influence of macro-environmental factors on cognitive ability. In particular, the existing studies on how external environmental factors impact cognitive ability has mainly focused on policy reform and environmental pollution [21, 33, 34]. We explore an important gap in existing literature by offering valuable insights into this underexplored area. Thirdly, this paper employs a more detailed approach to measuring

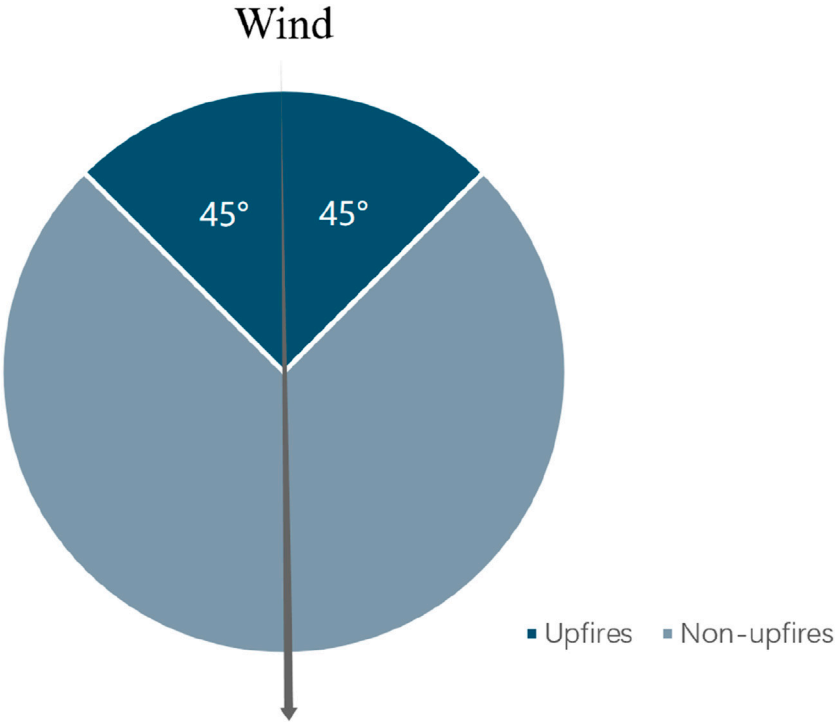

FIGURE 1 | Wildfires under different wind direction types (China. 2023).

individuals' cognitive aptitude. By assessing cognitive ability through verbal and mathematical tests, this study enables a more comprehensive empirical analysis.

METHODS

Variable Selection

This paper selects wildfire data and the China Family Panel Studies Database from counties in China in 2014 and 2018. The reasons for selecting these years are as follows: 1) The VIIRS monitor began releasing complete annual fire point data in 2013, making 2014 an appropriate starting year for this study. 2) In November 2018, the Chinese government formed a new national comprehensive firefighting and rescue team, effectively alleviating fire hazards. We chose 2018 as the cut-off year for the study in order to minimize the potential impact of the policy intervention on the results. Samples with missing or negative values for all variables are excluded from the analysis.

Cognitive Ability

This survey data employs two types of tests to assess the cognitive ability of respondents: a word group test and a math test. The cognitive ability calculator is based on the 2010 cognitive test design method. Such a selection ensures that the results are comparable. See **Supplementary Appendix 1** for specific test methods. This paper standardizes all cognitive ability test indicators. **Supplementary Table S1** describes the characteristics of the respondents.

Wildfire

Wildfire refers to the burning of biomass in wild ecosystems, such as forest wildfires and grassland wildfires. It can have a significant impact on natural ecosystems and global climate change [18, 35, 36]. We draw on the studies of Hantson [26], Marcos [27], and Csiszar [37], and we obtained high-resolution satellite wildfire monitoring data from the Visible Infrared Imaging Radiometer (VIIRS) fire point product dataset [38]. Firstly, We obtained latitude and longitude data from VIIRS for daily wildfire locations in the China region and used ArcGIS software to obtain the specific address of each fire point using an inverse coding method. Secondly, we follow the research of Rangel and Vogl [29], we summed the number of wildfires per day within 50 km of each county's administrative center by year to form county-year data. Finally, the number of wildfires was divided by 10 for ease of interpretation of the results.

We also need to use detailed wind direction data to measure wildfires in different wind directions. We measure the daily wind direction in each county using the wind direction at the weather station's maximum wind speed. We excluded counties with two or more weather stations based on data availability and applicability. The wind direction data is sourced from the daily surface climate dataset of the China Meteorological Data Center.

Control Variables

Meteorological control variable data were also obtained from the daily surface climate dataset of the China Meteorological Data Center. It mainly includes average precipitation (unit: mm), average temperature (unit: ˚C), average wind speed (unit: m/s),

and average humidity (unit: %) in each county. The raw raster data is interpolated to grid data using inverse distance weighting (IDW) interpolation [39]. Regarding the selection of other individual control variables in the baseline regression, this paper follows the practice of Lai et al. [17]. Indicators such as gender, total family income, social status, and medical insurance are selected as individual-level control variables.

Mechanism Variables

This paper selects air pollution as a mechanism variable. This study uses AQI, PM2.5, PM10, and NO_2 to measure air pollution. The original data comes from the National Urban Air Quality Dissemination Site.

The definition of the main variables is shown in **Supplementary Table S2**. The descriptive statistics of the main variables are shown in **Supplementary Table S3**.

Model

We separate the wildfires in each county by wind direction on a daily basis. The model is set as follows:

$$Y_{it} = \beta_0 + \beta_1 Upfire_{it} + \beta_2 Nonupfire_{it} + \beta_3 Control_{it} + \pi_t + \tau_{ph} + \varepsilon_{it} \quad (1)$$

Where i represents the individual, t represents time, h represents the household, and p represents the province. Y represents the cognitive ability, $Upfire$ and $Nonupfire$ represent the number of upwind and non-upwind wildfire, $Control$ represents other control variables that include precipitation temperature, wind speed, humidity, gender, total family income, social status, and medical insurance. β_0 denotes the constant term, β_1 indicates the magnitude of the effect of upwind wildfires on cognitive ability, β_2 indicates the magnitude of the effect of non-upwind wildfires on cognitive ability, β_3 denotes the set of coefficients for the effect of each control variable on cognitive ability. π_t is the time-fixed effect, τ_{ph} is the Upfires-Nonupfires fixed effect of province and household, and ε_{it} is the random error term.

RESULTS

Effects of Wildfire Disaster on Cognitive Abilities

Table 1 presents the empirical results based on Eq. **1**. Columns (1) and (2) display the estimated results for the word test scores. The results in column (1) indicate a significant reduction in individual word test scores with an increase in wildfire incidents when only meteorological control variables are considered. Specifically, relative to non-upwind wildfires, an increase of 10 upwind wildfires reduces individual word test scores by 0.216 standard deviations. In column (2), after further controlling for individual characteristics, relative to non-upwind wildfires, an increase of 10 upwind wildfires reduces word test scores by 0.235 standard deviations. Columns (3) and (4) in **Table 3** show the impact of wildfire on individual math test scores. Column (3) shows that, without controlling for individual characteristics, a 10th increase in the difference between upwind and non-upwind wildfires is associated with a decrease of 0.217 standard deviations in math test scores. Column (4) shows that after controlling for individual characteristics, the cumulative effect estimate coefficient is −0.236. Our empirical findings suggest that wildfires can impair individuals' cognitive abilities, highlighting the importance of implementing measures to prevent and mitigate the impacts of climate-related disasters on cognitive function.

Robustness Checks

To enhance the validity and credibility of the empirical results, we conduct robustness tests from the perspectives of different measurements of dependent and independent variables, sample selection, and different model specifications, respectively. We show here only the test results of the instrumental variables approach; other robustness tests are in the **Supplementary Material**.

Instrumental Variables Method

This study addresses potential endogeneity concerns by utilizing ventilation as an instrumental variable for analyzing the impact of wildfires. In the standard air pollution box model, the ventilation coefficient is calculated as the product of the wind speed and the mixing height of the boundary layer, determining the rate of pollution dispersion [40]. We utilize wind speed and boundary layer height data from the ERA-Interim database of the European Centre for Medium-Range Weather Forecasts. The speed of the wind affects how pollutants spread horizontally, while the height of the boundary layer determines how they spread vertically. Higher ventilation coefficients not only have a direct impact on wildfire fire intensity but also transport contaminant particles from wildfire smoke to farther and higher regions with more severe impacts [41, 42]. Therefore, there is a correlation between ventilation coefficients and wildfires. Large-scale weather systems impact ventilation coefficients, which can be regarded as exogenous to individuals' health and qualify as instrumental variables.

Wildfires are measured by dividing the total number of wildfires within a 50-kilometer radius of the administrative center by 10. Columns (1) to (3) of **Table 2** report the full-sample empirical results using instrumental variables method. The results show that the cross-multiplication terms of the wildfire and instrumental variables were significantly positive and the Kleibergen-Paap Wald F statistic values were 70.785 in the first stage, proving there was no weak instrumental variable problem. The results of the second phase show that word and math test scores decreased by 0.149 and 0.248 standard deviations when wildfires increased by every 10th occurrence. This suggests that after reducing endogenous problems, an individual's cognitive abilities can still be affected by wildfire.

Heterogeneity Analysis

First, there are significant differences between different age groups in their own physical fitness, escape skills, and level of knowledge about wildfires, which directly affects an individual's ability to cope when faced with a fire [43, 44]. In addition, there

TABLE 1 | Effects of wildfire disaster on cognitive abilities (China. 2023).

	(1) Wordtest	(2) Wordtest	(3) Mathtest	(4) Mathtest
Upfires	−0.099***	−0.111***	−0.087*	−0.099**
	(−3.109)	(−3.519)	(−1.895)	(−2.139)
Nonupfires	0.118***	0.124***	0.130**	0.137**
	(3.218)	(3.420)	(2.418)	(2.520)
Upfires-Nonupfires	−0.216***	−0.235***	−0.217**	−0.236***
	(−3.284)	(−3.582)	(−2.217)	(−2.383)
Observations	6,700	6,700	6,700	6,700
R^2	0.476	0.526	0.444	0.490
Meteorological control variables	Y	Y	Y	Y
Individual control variables	N	Y	N	Y
Household FE	Y	Y	Y	Y
Province-Year FE	Y	Y	Y	Y

*Note: The numbers in parentheses are t-values clustered at the household level. *, **, and *** indicate significance at the 10%, 5%, and 1% levels, respectively. The same applies to the table below.*

TABLE 2 | Instrumental variables method (China. 2023).

	(1) Ventilation	(2) Wordtest	(3) Mathtest
Wildfire	0.026***	−0.149*	−0.248***
	(6.779)	(−1.867)	(−2.619)
Observations	6,700	6,700	6,700
Kleibergen-Paap rk Wald F statistic	70.785		
Meteorological control variables	Y	Y	Y
Individual control variables	Y	Y	Y
Household FE	Y	Y	Y
Province-Year FE	Y	Y	Y

TABLE 3 | Heterogeneous effects of wildfires on cognitive abilities (China. 2023).

Panel A	(1) Wordtest	(2) Mathtest	(3) Wordtest	(4) Mathtest
	Age ≤ 50 years old		**Age > 50 years old**	
Upfires	−0.174***	−0.227***	0.053	0.200
	(−4.032)	(−3.044)	(0.825)	(1.365)
Nonupfires	0.151***	0.234**	−0.013	−0.187
	(3.044)	(2.466)	(−0.153)	(−1.051)
Upfires-Nonupfires	−0.325***	−0.461***	0.0657	0.387
	(−3.611)	(−2.750)	(0.455)	(1.201)
Observations	3,844	3,844	2,856	2,856
R^2	0.581	0.538	0.740	0.893
Panl B	**Low defensive expenditure**		**High defensive expenditure**	
Upfires	−0.332***	−0.454***	−0.016	−0.054
	(−3.347)	(−4.074)	(−0.215)	(−0.991)
Nonupfires	0.380***	0.554***	0.091	0.107*
	(3.334)	(4.202)	(0.945)	(1.946)
Upfires-Nonupfires	−0.712***	−1.008***	−0.107	−0.161
	(−3.368)	(−4.178)	(−0.719)	(−1.555)
Observations	2,930	2,930	3,770	3,770
R^2	0.580	0.542	0.956	0.496
Meteorological control variables	Y	Y	Y	Y
Individual control variables	Y	Y	Y	Y
Household FE	Y	Y	Y	Y
Province-Year FE	Y	Y	Y	Y

are significant differences in attention and memory capacity, executive functioning, and abstract thinking across ages, which can affect an individual's ability to perceive and cope with the environment. Thus, the effect of wildfires on an individual's cognitive ability can be influenced by individual age heterogeneity. Second, defensive spending can reduce the duration and extent of an individual's exposure to contaminants, thereby reducing the risk of mental illness. At the same time, defensive behaviors can help individuals improve their ability to cope with disasters, which can help individuals reduce their sense of maladjustment and improve their quality of life in environments that are more contaminated by wildfire, thus protecting their cognitive health. Thus, defensive spending is an effective way to constrain the health costs of wildfire pollution. Therefore, we also explored the heterogeneous effects in terms of individual defensive expenditures.

This article analyzes two aspects of heterogeneity: the age of the respondents and their defensive spending. **Table 3** demonstrates the results of the heterogeneity test. All respondents were divided into middle-aged and elderly people over 50 years old and other non-middle-aged and elderly respondents according to age differences. The study found that wildfires had a greater negative impact on the cognitive abilities of young people, with each 10th upwind wildfire resulting in a 0.325 and 0.461 standard deviation reduction in young people's scores on word and math tests, respectively. This finding is consistent with He [45]. The possible reasons are that, firstly, individuals under 50 years old spend more time outdoors, thus increasing the risk of direct and indirect harm from wildfire, secondly, older people have longer life spans and richer experiences, making them better able to adapt to the impact of natural disasters, finally, in the rapidly developing information age, young people can obtain disaster information more timely, thus easily generating stronger negative emotional pressure [46].

TABLE 4 | Mechanism test of the impact of wildfire disaster on cognitive abilities (China. 2023).

	(1)	(2)	(3)	(4)	(5)	(6)
	Air pollution					
	PM2.5	PM10	AQI	NO_2	Black_carbon	Organic_carbon
Upfires	0.097***	0.108***	0.073***	0.134***	0.051***	0.044***
	(13.450)	(24.103)	(20.303)	(4.663)	(13.474)	(16.982)
Nonupfires	−0.098***	−0.103***	−0.074***	−0.087**	−0.059***	−0.050***
	(−10.358)	(−17.098)	(−15.438)	(−2.234)	(−10.881)	(−13.889)
Upfires-Nonupfires	0.195***	0.211***	0.147***	0.222***	0.110***	0.094***
	(11.75)	(20.37)	(17.72)	93.269)	(11.98)	(15.24)
Observations	6,700	6,700	6,700	6,700	6,700	6,700
R^2	0.997	0.998	0.998	0.992	0.999	0.999
Meteorological control variables	Y	Y	Y	Y	Y	Y
Individual control variables	Y	Y	Y	Y	Y	Y
Household FE	Y	Y	Y	Y	Y	Y
Province-Year FE	Y	Y	Y	Y	Y	Y

Notes: PM2.5 refers to particulate matter in the atmosphere with a diameter less than or equal to 2.5 μm. PM10 is particulate matter with a diameter equal to less than 10 μm. The Air Quality Index (AQI) is a non-linear dimensionless index that quantitatively describes air quality conditions. The larger the value, the more serious the air pollution condition and the greater the health hazard to human beings. Nitrogen dioxide (NO_2) is one of the oxides of nitrogen, a reddish-brown gas with an irritating odor at room temperature.

The database's investigators conduct healthcare expenditures surveys by asking respondents to answer the question, "In the past 12 months, how much did your household spend on expenditures that included fitness and exercise and the purchase of related product equipment and healthcare products?". We divide respondents into different defensive expenditure groups according to their health expenditures. If a respondent's health expenditure is greater than or equal to the average level of health expenditure, the individual is classified as a s high defensive expenditure group, and *vice versa* for the low defensive spending group. The results are shown in Panel B in **Table 3**. Relative to non-upwind wildfires, every 10th increase in upwind wildfires will lead to a significant decrease of 0.712 and 1.008 standard deviations in word and math test scores, respectively, for the low-defense spending group. This effect is greater for individuals with low defensive expenditures than for individuals with high defensive expenditures. The government and society should pay attention to and emphasize the group with low defensive expenditures, and guide and encourage this group to take active disaster prevention measures.

Mechanism Analysis

We suggest that wildfire hazards may affect individuals' cognitive abilities through the influence channel of air pollution. This is because smoke emitted by wildfires contains a substantial quantity of hazardous particles, including PM2.5 and nitrogen oxides. Primary pollutants can react in the atmosphere to form secondary pollutants like ozone, affecting regional air quality and public health [18]. Furthermore, previous studies have highlighted the potential neurotoxicity of air pollutants, which can harm the central and peripheral nervous systems, contribute to respiratory and cardiovascular ailments, and lead to a decline in cognitive ability. Therefore, we suggest that wildfire hazards can in turn affect the cognitive abilities of individuals by producing air pollution.

This article still uses a setting similar to Eq. **1** and replaces the explained variable with an air pollution index. The results are shown in **Table 4**. Specifically, compared with non-upwind wildfires, for every 10 additional upwind wildfires, PM2.5, PM10, AQI, and NO_2 increased by 19.5%, 21.1%, 14.7%, and 22.2%, respectively.

In addition, Akagi found that incomplete combustion of biomass fires produces a large amount of black carbon and organic carbon, which are the main components of air pollution particles, such as PM2.5, and aggravate air pollution levels [47]. This article further studies the impact of wildfire disasters on black carbon and organic carbon, for which raw data are obtained from the M2T1NXAER dataset. The results are shown in columns (5) and (6) of **Table 4**. Black carbon and organic carbon increased by 11.0% and 9.4%, respectively, for every 10th increase in upwind wildfires compared to non-upwind wildfires. The results all suggest that wildfires can affect human cognitive abilities by producing air pollution. The finding underscores the public health risks associated with wildfires and air pollution. Understanding the effect of wildfires on cognitive abilities highlights the need for measures to protect public health during and after wildfire events.

DISCUSSION

Conclusion

In the context of global climate change, it is essential to effectively address the adverse economic and social impacts of climate disasters. We investigate the effects of wildfire disasters on cognitive abilities using satellite-monitored wildfire data and cognitive ability survey data. The results show that exposure to wildfires leads to a significant reduction in the cognitive abilities of individuals. This finding underscores the serious public health implications of wildfires. The observed negative outcomes align with previous research on the adverse health effects of climate

change and disasters [17, 21, 48–50]. Our research has also shown that wildfires produce large amounts of air pollution particles that can affect an individual's cognitive abilities. Wildfires release a complex mixture of air pollutants, including particulate matter, volatile organic compounds, and solid particulate matter. The harmful pollutants can deeply penetrate the respiratory system, entering the bloodstream and potentially reaching the brain, which can have an impact on cognitive function [51]. Particulate matter, especially ultrafine particles (PM2.5), can have significant neurotoxic effects, impacting respiratory and cardiovascular health, as well as cognitive function. The cognitive impacts of wildfires have far-reaching consequences, affecting not only immediate wellbeing but also long-term health outcomes and community resilience in the face of natural disasters. Understanding these impacts is crucial for developing effective public health policies, and disaster response strategies, and enhancing community resilience in light of the disasters caused by climate change.

The results of our heterogeneity analysis indicate that younger individuals are more susceptible to the negative effects of wildfires on cognitive health. This could be attributed to factors such as still-developing physiological systems, longer life expectancy post-exposure, and increased time spent outdoors. Understanding age-specific vulnerabilities is crucial for designing effective public health interventions and policies aimed at protecting vulnerable populations from the health impacts of climate hazards. Moreover, our study underscores the role of socioeconomic factors in determining vulnerability to the health impacts of wildfires. Individuals with lower defensive expenditures, likely reflecting lower socioeconomic status, experienced more severe impacts on their cognitive and other health. Socioeconomic factors such as income and access to healthcare and resources play a critical role in determining an individual's ability to mitigate and recover from the health impacts of climate hazards [52, 53]. Therefore, policies aimed at reducing vulnerability to the health impacts of wildfires should address underlying socioeconomic inequalities.

Implications

Our study has dual policy implications. First, the findings highlight the importance and urgency of climate disaster governance. Given the substantial negative externalities that wildfire disasters can impose on individuals and society as a whole, governments need to enhance their early warning and response capabilities in the face of climate disasters and adopt proactive measures to mitigate their impacts. These measures may include but are not limited to, strengthening regulations pertaining to climate disasters and increasing investment in the research and development of adaptive technologies. Additionally, both individuals and the government should enhance their awareness of precautionary measures and defensive expenditure protection to minimize damage caused by wildfires. Second, developing economies like China are at a critical stage of transitioning to high-quality development. Cognitive ability, as a crucial component of human capital, plays a key role in enhancing individual and societal productivity and innovation capacity, thereby driving technological advancement and economic growth. However, climate disasters have had a significant impact on human capital, hindering economic transformation and upgrading. It is therefore imperative to fully embrace the principles of green development, effectively respond to climate disasters, actively pursue low-carbon development pathways, and mitigate the detrimental effects of climate change. By doing so, we can unleash the potential and value of human capital and promote long-term stable economic development.

Compared to previous studies, our study used satellite remote sensing to monitor wildfire data, including small-scale, nighttime, and away-from-urban-areas wildfires, allowing for a more accurate measure of episodic or short-duration wildfire events and more comprehensive and detailed data. The research shortcoming is that we used VIIRS 375-meter fire monitoring data, which may be affected by inversion accuracy, transit time points, and external factors such as lightning and cloudiness to include fire points from planned fires such as agricultural waste. Therefore, future research needs to further employ higher resolution remote sensing imagery with higher accuracy and more detailed land use classification data to extract wildfire ignition point data to improve the accuracy of the data samples. In addition, the cognitive ability survey data we used was limited to 2 years of data, 2014 and 2018, and future research could consider using survey data from a longer period.

DATA AVAILABILITY STATEMENT

All authors ensure that all data and materials as well as software application or custom code support their published claims and comply with field standards.

ETHICS STATEMENT

Ethical approval for the China Family Panel Studies was granted by the Institutional Review Board (IRB) of Peking University. The IRB approval review lot number is IRB00001052-14010. Written informed consent for participation was not required for this study in accordance with the national legislation and the institutional requirements.

AUTHOR CONTRIBUTIONS

All authors contributed to the study's conception and design. Material preparation, data collection, and analysis were performed by RD, KL, DZ, and QF. The first draft of the manuscript was written by RD and all authors commented on previous versions of the manuscript. KL and DZ made significant contributions to the revised manuscript. All authors read and approved the final manuscript.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2024.1607128/full#supplementary-material

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The Influence of Climate, Atmospheric Pollution, and Natural Disasters on Cardiovascular Diseases and Diabetes Mellitus in Drylands: A Scoping Review

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Objectives: In the face of escalating global aridification, this study examines the complex relationship between climate variability, air pollution, natural disasters, and the prevalence of cardiovascular disease (CVD) and diabetes mellitus (DM) in arid regions.

Methods: The study conducted a scoping review of multiple databases using JBI guidelines and included 74 studies.

Results: The results show that acute myocardial infarction (n = 20) and stroke (n = 13) are the primary CVDs affected by these factors, particularly affecting older adults (n = 34) and persons with hypertension (n = 3). Elevated air temperature and heat waves emerge as critical risk factors for CVD, exacerbating various cardiovascular mechanisms. Atmospheric pollutants and natural disasters increase this risk. Indirect effects of disasters amplify risk factors such as socioeconomic vulnerability (n = 4), inadequate medical care (n = 3), stress (n = 3), and poor diet (n = 2), increasing CVD and DM risk.

Conclusion: The study underscores the need for nations to adhere to the Paris Agreement, advocating for reduced air pollutants, resilient environments, and collaborative, multidisciplinary research to develop targeted health interventions to mitigate the adverse effects of climate, pollution, and natural disasters.

Keywords: climate change, atmospheric pollution, environmental resilience, cardiovascular diseases, diabetes mellitus

INTRODUCTION

Climate change is characterized by long-term increase in temperature, changes in the geographical distribution of precipitation, and an increase in the magnitude and frequency of extreme weather events such as floods, droughts, and heatwaves [1, 2]. These changes in weather patterns can influence people's health and lead to the development of Climate-Sensitive Diseases (CSD) [3, 4].

Climate change represents one of the most significant threats to human wellbeing [5], making the global population more vulnerable to CSDs such as cardiovascular diseases (CVD) and diabetes mellitus (DM) [6–9].

In the face of climate change, climate projections indicate an increase of drylands worldwide over the coming decades [10–12]. Drylands (arid, semi-arid, and dry sub-humid lands) are characterized by natural water scarcity, where the annual ratio between precipitation and evapotranspiration, or aridity index, is greater than 0.05 and less than 0.65. Drylands cover 41% of the land surface, produce 44% of the crops, and contain over 2 billion people and half of the world's livestock [13].

In dry regions, extreme weather events such as droughts [14], dust or sandstorms [15], heatwaves [16], and/or fires are frequent [12, 17, 18]. These weather events can occur in combination [19]. Additionally, other natural disasters such as earthquakes and hurricanes may also be recurrent and affected by climate change [20]. Populations in drylands, constantly affected by natural disasters, are more vulnerable to subsistence crises [21], poverty, economic and political marginalization [22], and health problems [23].

Recent studies highlight the effects of climate on cardiovascular diseases [24] and diabetes mellitus [25], where extreme temperatures, changes in relative humidity, and wind intensity were determining factors. Furthermore, the role of global climate phenomena such as El Niño in the development and/or exacerbation of CVD is emphasized [24–26].

Air pollution, combined with climatic effects, poses an additional risk factor for mortality from cardiovascular diseases and influences the increase in hospitalizations due to diabetes mellitus [27, 28]. Furthermore, the contribution of increased air pollution to the retention of greenhouse gases, responsible for warming the Earth's surface and raising temperatures globally [1], highlights its role in the long-term effects of climate change on CVD.

Thus, in addition to established risk factors for CVD and DM, known as non-modifiable (ethnicity, age, family history) and modifiable (sedentary lifestyle, poor diet, alcoholism, smoking, dyslipidemia, obesity) [29, 30], it is necessary to map the risk factors for CVD and DM related to climate variability, air pollution, and natural disasters. In this context, it is also relevant to identify populations living in dry regions that are most vulnerable to developing cardiovascular diseases and diabetes mellitus.

The general objective of this scoping review was to map the influence of climate variability, air pollution, and natural disasters on cardiovascular diseases and diabetes mellitus in drylands, aiming to identify the main cardiovascular diseases, the most vulnerable populations, the socio-environmental factors related to physiological mechanisms for the development and/or exacerbation of these diseases, and the main risk factors intensified by natural disasters.

It is expected that the results of this research will be useful for the development of public health protocols that can guide the implementation of effective multidisciplinary interventions for the prevention of CVD and DM and their complications resulting from climate variability, air pollution, and natural disasters in dry regions, especially in populations identified as most vulnerable in a context of climate change.

METHODS

A scoping review was conducted following the Joanna Briggs Institute (JBI) approach for scoping reviews, the PRISMA Extension for Scoping Reviews (PRISMA-ScR) guidelines, and the JBI Evidence Synthesis Manual. The protocol was registered in the Open Science Framework (OSF). Registration DOI.

Review Question

The Population, Concept, and Context (PCC) framework was adopted to formulate the research questions:

Population

Individuals with cardiovascular diseases: Group of heart and blood vessel diseases, including: coronary artery disease, acute myocardial infarction; cerebrovascular disease: peripheral artery disease; rheumatic heart disease; congenital heart disease; deep vein thrombosis and pulmonary embolism [31]; diabetes: Chronic metabolic disease characterized by high blood glucose levels, leading over time to serious damage to the heart, blood vessels, eyes, kidneys, and nerves [31].

Concept

Climate variability: Variations in climate compared to its average, resulting in changes in air pressure, temperature, precipitation, humidity, and other climate variables [32]. The climate variables included in this study are: air temperature, precipitation, air humidity, wind speed, and phenomena such as El Niño; Air pollution: Refers to contamination of the indoor or outdoor environment resulting in the modification of the atmosphere's natural characteristics. This contamination can occur due to chemical, physical, or biological agents [20]; Natural disasters: Severe weather conditions, including floods, tornadoes, hurricanes, wildfires, droughts, earthquakes, or a combination of these extreme events. They represent a major threat to infrastructure, health, property, and human security [33].

Context

Drylands characterized by water scarcity (a ratio between average annual precipitation and potential evapotranspiration, also known as aridity index, greater than 0.05 and less than 0.65). They can be classified as arid, semi-arid, and dry sub-humid lands [34].

Based on the aforementioned strategy, the following research question was formulated: 1) What is the influence of climate variability, air pollution, and natural disasters on cardiovascular diseases and diabetes mellitus in drylands? In this context, the following auxiliary questions were identified: 1) What are the most prevalent cardiovascular diseases and which populations are most vulnerable? 2) What are the effects of exposure to climate variability, air pollution, and natural disasters on hospitalizations and deaths from cardiovascular diseases? 3) What are the socio-environmental factors related to physiological mechanisms for

the development and/or exacerbation of cardiovascular diseases? 4) What are the main risk factors for cardiovascular diseases and diabetes mellitus intensified by natural disasters?

Eligibility Criteria

Inclusion: Studies that addressed the research questions, formulated based on the PCC framework, were included. Multinational studies that included any dry climate region were also included in this review.

Exclusion: Descriptive studies without identification of influencing factors, duplicate studies (only one of the studies was considered for analysis), and studies not available in full text.

Study Designs

We included studies using various designs: experimental and quasi-experimental studies (randomized and non-randomized controlled trials), before-after and interrupted time series studies, and analytical observational studies (prospective and retrospective cohort studies, case-control studies, and cross-sectional analytical studies), as well as descriptive observational studies including case series and reports of individual cases, qualitative studies, and systematic reviews. No language or time restrictions were applied.

Search Strategy

The search strategies were developed by the research team in collaboration with a librarian, utilizing the PCC components. Search terms were identified from controlled vocabularies such as Health Sciences Descriptors (DeCS), Medical Subject Headings (MeSH), and Embase Subject Headings (Emtree).

The search involved three steps. Firstly, a preliminary search in PubMed, Cochrane Library, OSF, and JBI Synthesis identified keywords and terms for the search strategy. Secondly, this strategy was applied to all chosen databases. A third search checked reference lists for additional sources. The detailed search strategies are in **Supplementary Appendix Table S1**. Searches were conducted on 04 September 2023, across various databases and gray literature sources, including Agris, Virtual Health Library, Academic Search Premier, CINAHL, GreenFILE, SocINDEX, CAB Direct, Cochrane Library, Embase, Engineering Village, Epistemonikos, PubMed Central, PubMed, Scielo, Scopus, and Web of Science.

Descriptors

Cardiovascular diseases; Cardiopathies; Diabetes Mellitus; Stroke; Coronary Disease; Coronary Artery Disease; Droughts; Dryland; Arid Season; Arid Zone; Semi-Arid Zone; "atmosphere pollution"; Natural Disasters.

Study Selection

After completing the bibliographic search, all results obtained from the databases were grouped and then exported to Rayyan CRI from Qatar, specifically for blinded document selection. Duplicates were removed, and titles and abstracts were independently assessed by two pairs of blinded reviewers based on predefined inclusion criteria. Potentially relevant sources were retrieved in full, and citation details were imported into the JBI System for unified management, assessment, and information review. The full text of selected citations was evaluated according to the inclusion criteria by two pairs of independent reviewers. Reasons for excluding full-text articles were recorded and reported. Any discrepancies among reviewers at each stage of the selection process were resolved through discussion or involvement of a third reviewer—the responsible researcher. Screening was only completed when the agreement proportion among reviewers reached or exceeded 75% [35].

Methodological Quality Assessment

As this study is a scoping review aiming to map available evidence, no bias risk assessment or quality assessment of included studies was conducted. However, we emphasize that the study remains consistent with the methodology proposed for scoping reviews [35].

Graphs, Data Extraction, and Synthesis of Results

Data extraction included the following elements: database, title, year, country, authorship, objective, study design, cardiovascular diseases/diabetes mellitus, risk factors, gender, age, and climatic variable. Results were mapped, organized into tables/diagrams/figures, and subjected to thematic analysis and narrative synthesis based on full-text article reading. Labels reflecting content were created for passages that addressed research questions, and similar passages were subsequently grouped [36], resulting in the construction of three thematic categories: climate variability, air pollution, and natural disasters. Figures were created to present thematic categories and associated risk factors influencing the development of CVD or exacerbation of DM, aiming to synthesize the findings of this review. Tables are provided in **Supplementary Appendix S1**.

Role of Funding Source

The funding sources had no involvement in study design; in the collection, analysis, and interpretation of data; in the writing of the report; and in the decision to submit the paper for publication.

RESULTS

The search process is summarized in a PRISMA flow diagram in **Figure 1**. Initially, a total of 5,660 studies were identified. Following title and abstract screening, 2,180 studies were selected for further consideration. Subsequently, after full-text screening, 228 studies remained. After a second full-text screening, 74 studies were ultimately selected for data extraction as they met the inclusion criteria. A synthesis of the selected studies can be found in **Supplementary Appendix S2**.

The articles identified in the review are notably recent, with 43 having been published within the last 5 years (2018–2023). The studies were conducted in 12 countries, predominantly high-income (n = 17) and upper-middle-income (n = 16) countries. Only

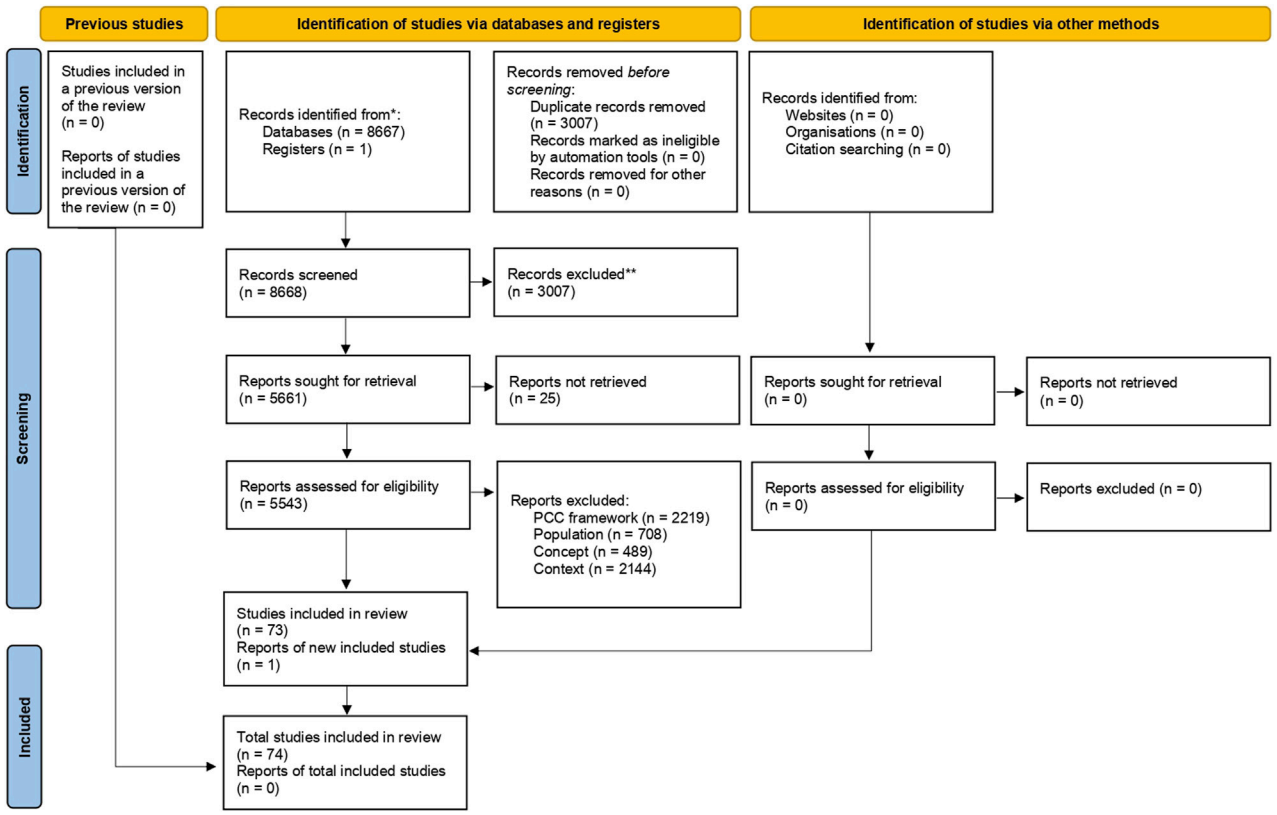

FIGURE 1 | Flowchart of study selection based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (2023, Brazil).

2 studies were conducted in low-income countries. The income levels of countries were based on the World Bank classification (World Bank Group, 2024). The four countries with the highest number of studies were the United States (n = 12), Iran (n = 12), and China (n = 11). The geographical distribution of the number of publications for each country is depicted in **Figure 2** and detailed in **Supplementary Appendix Table S2**.

A variety of study designs were identified, including time series (n = 14), retrospective (n = 7), systematic reviews (n = 7), narrative reviews (n = 6), ecological (n = 5), literature reviews (n = 4), clinical studies (n = 3), cross-sectional (n = 2), longitudinal (n = 2), cohort (n = 1), cross-sectional case-control (n = 1), regression analysis (n = 1), and report (n = 1). Some studies were categorized by researchers as quantitative (n = 19) and qualitative (n = 4) without specification of study design (**Supplementary Appendix Table S3**). The studies were retrieved from databases and portals including PubMed/Medline (n = 28), Scopus (n = 24), EBSCO (n = 17), Scielo (n = 2), BVS (n = 1), Embase (n = 1), and Institute of Electric and Electronic Engineers (n = 1) (**Supplementary Appendix Table S4**; **Supplementary Appendix Figure S1**).

The cardiovascular diseases identified included acute myocardial infarction (AMI) (n = 20), stroke (n = 13), systemic arterial hypertension (SAH) (n = 8), and heart failure (HF) (n = 3). In addition, diabetes mellitus was identified (n = 12) (**Supplementary Appendix Table S5**). The most vulnerable populations for CVD and diabetes mellitus in the dry regions were the older adults (n = 34), women (n = 9), and children aged 0–5 years (n = 5). Among the most affected were older adults aged 65–94 years with arterial hypertension (n = 3) (**Supplementary Appendix Tables S6, S7**; **Supplementary Appendix Figure S2**).

In this research, three central thematic categories were developed from data analysis: climate variability, atmospheric pollution, and natural disasters (**Figure 3** and **Supplementary Appendix Tables S8–S11**). These categories are interconnected in influencing the development of cardiovascular diseases and the exacerbation of diabetes mellitus in dry regions, as we will discuss below.

The variation of climate variables (precipitation, air temperature, air humidity, and wind speed) and El Niño were understood as part of the climate variability category (n = 71). Within this category, studies were distributed as follows: air temperature (n = 42), relative air humidity (n = 20), wind speed (n = 7), precipitation (n = 3), and El Niño (n = 1). Additionally, 22 studies mentioned climate variability, but did not specify the variable or phenomenon itself. In the atmospheric pollution category (n = 32), pollution by particulate matter (PM10, PM2.5), O_3, NO_2, SO_2, CO, and CO_2 were included. Studies focused on each pollutant were distributed as follows: PM10 (n = 15), PM2.5 (n = 15), O_3 (n = 9), NO_2 (n = 9), SO_2 (n =

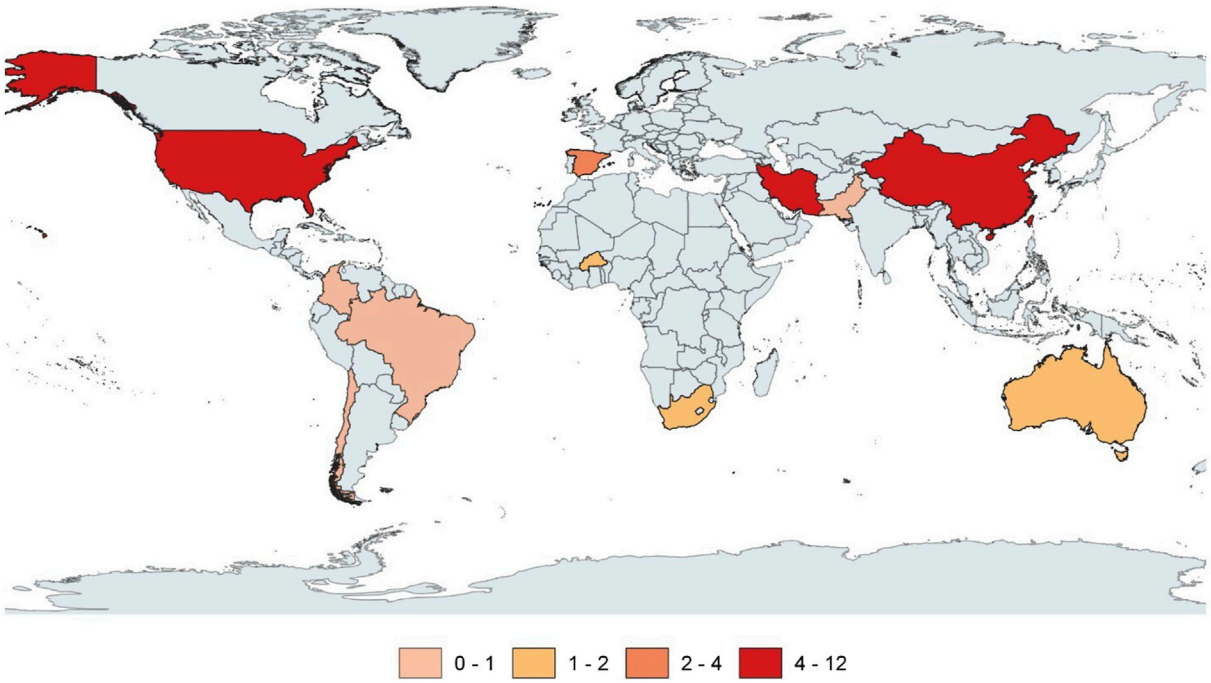

FIGURE 2 | Geographical distribution of publications by country (2023, Brazil). **(A)** Thematic categories. **(B)** Climate variability. **(C)** Atmospheric pollution. **(D)** Natural disasters.

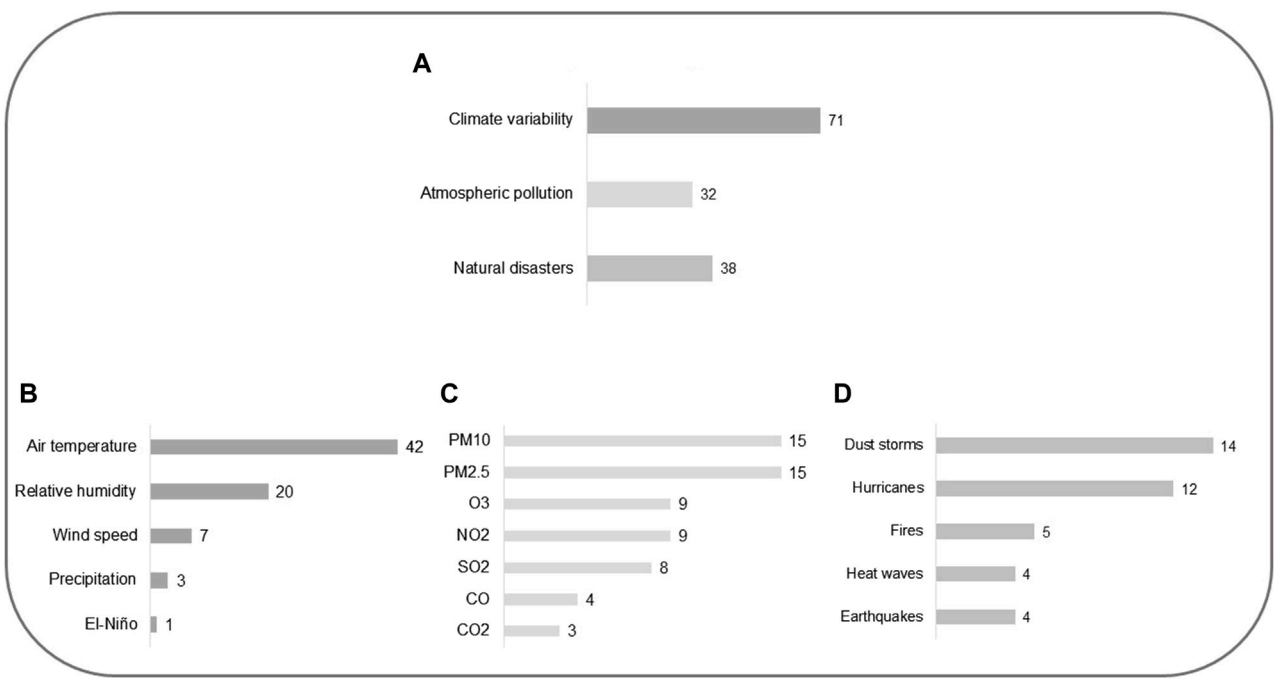

FIGURE 3 | Central thematic categories emerging from data analysis: climate variability, atmospheric pollution, and natural disasters (2023, Brazil).

8), CO (n = 4), and CO_2 (n = 3). Extreme natural events, whether climatic or not, were categorized as natural disasters (earthquake, hurricane, fire, heatwaves, and dust storms). Studies in the natural disasters category (n = 38) were distributed as follows: earthquake (n = 4), hurricane (n = 12), dust storms (n = 14), fire (n = 5), and heatwaves (n = 4). Some studies mentioned more than one

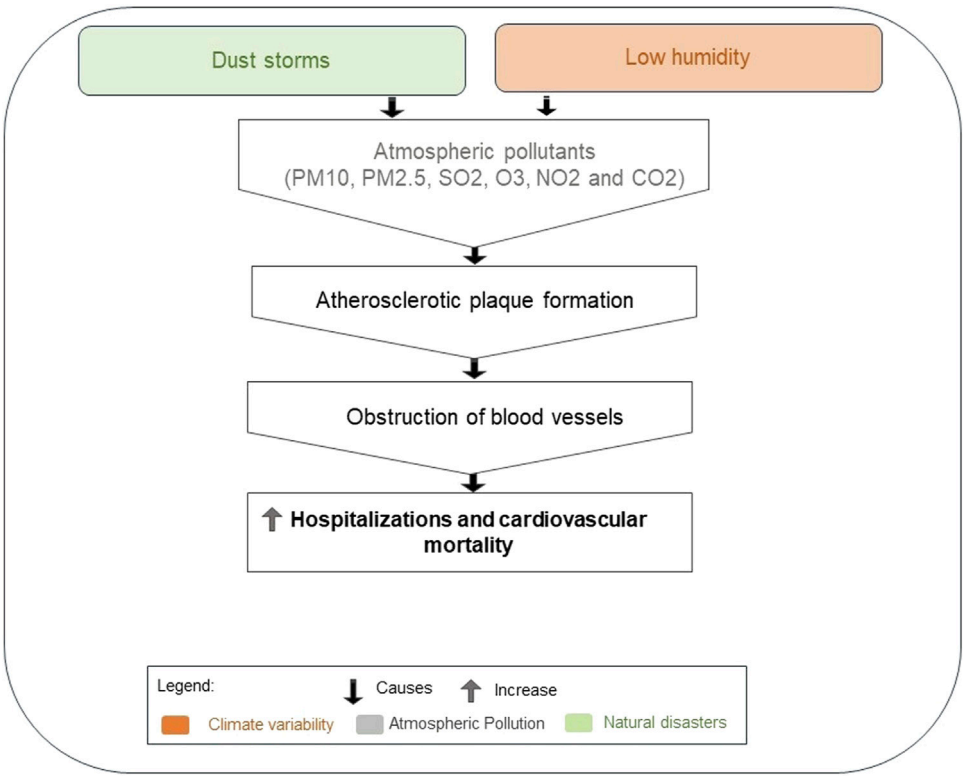

FIGURE 4 | Effect of climate variables, atmospheric pollution, and natural disasters on increased hospitalizations and cardiovascular mortality (2023, Brazil).

climate variable, pollutant, and/or natural disaster, as detailed in **Supplementary Appendix Tables S9–S11**.

In studies focusing on the influence of climatic components, it was observed that high precipitation was associated with more cases of CVD [37]. Air temperature significantly above or below historical averages is linked to increased CVD mortality [38]. The extreme heat characteristic of drought episodes is considered an important risk factor related to CVD [39]. Heatwaves are a causative factor of stress and exhaustion, posing risks to individuals with CVD [40]. Conversely, extreme decreases in temperature compared to historical averages can also lead to cardiovascular problems such as AMI and stroke [41].

The rise in air temperature, decrease in relative air humidity, and increase in wind speed can exacerbate the harmful effects of air pollutants on cardiovascular health. Increased temperature influences the concentration of air pollutants such as SO_2, O_3, NO_2, PM10, and PM2.5 [42].

Dust storms, characterized by strong winds, elevate the concentration of air pollutants of natural or anthropogenic origin, such as SO_2, O_3, NO_2, PM10, and PM2.5 [41–43]. These pollutants, along with CO_2, have been associated with the formation of atherosclerotic plaques, leading to blood vessel obstruction [44].

Studies indicate that days with low relative air humidity have higher levels of air pollutants [45]. Additionally, dust storms also occur during periods of low relative air humidity, leading to increased hospital admissions for CVD [46].

The influence of the El Niño phenomenon on cardiovascular diseases is noteworthy. Meteorological droughts caused by El Niño in certain regions of the planet can intensify the risk of forest fires. These fires, in turn, emit gases and increase the concentration of air pollutants. Thus, a higher number of deaths and hospital admissions due to stroke are associated with El Niño occurrences [47].

The main effects mentioned in studies relating climatic variables, atmospheric pollution, and natural disasters to the development of CVD are summarized in **Figures 4**, **5**.

Natural disasters such as heatwaves, dust storms, and wildfires are risk factors and have a direct impact on the development of cardiovascular diseases, as discussed above. However, there are disasters like earthquakes and hurricanes that have an indirect impact (**Supplementary Appendix Table S11**). Exposure to these disasters (earthquakes and hurricanes) contributes to exacerbating the effect of other risk factors in people with CVD and DM, such as: stress (n = 3), inadequate diet (n = 2), socioeconomic vulnerability (n = 4); medication unavailability, non-adherence, and treatment interruption (n = 3); increased smoking (n = 3); unstable blood sugar levels (n = 2); increased alcohol consumption (n = 2); and difficulty accessing healthcare services (n = 2), as shown in **Supplementary Appendix Figure S3**. These risk factors are further explored in **Supplementary Appendix Table S12** and **Supplementary Appendix S2**.

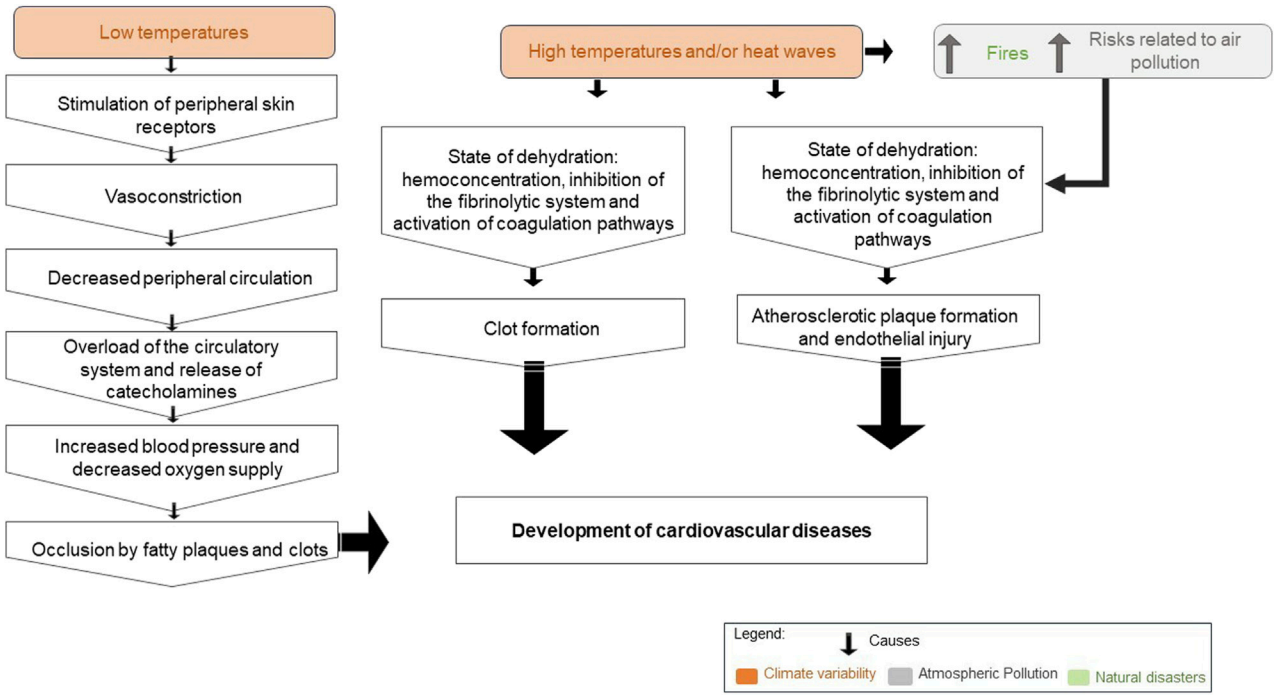

FIGURE 5 | Effect of climate variables, atmospheric pollution, and natural disasters on the development of cardiovascular diseases (2023, Brazil).

Due to disasters such as earthquakes or hurricanes, individuals residing in affected areas need to relocate to refuge locations. In this process, many people are unable to bring the necessary medications for the treatment of chronic diseases such as diabetes mellitus and hypertension, discontinuing treatment [48], which can lead to alterations in blood glucose and/or blood pressure levels. Additionally, the food offered in shelters is often restricted and inadequate for people with CVD and DM, posing another risk factor for individuals to experience episodes of hyperglycemia, severe hypoglycemia, or hypertensive crises [49].

DISCUSSION

This scoping review allowed us to map the influence of variations in climatic variables (precipitation, air temperature, air humidity, and wind speed), El Niño, atmospheric pollution (PM10, PM2.5, CO_2, O_3, SO_2, and NO_2), and natural disasters (earthquake, hurricane, fire, heatwaves, and dust storms) on cardiovascular diseases and diabetes mellitus in dry regions. The most frequent diseases addressed in the studies were AMI and stroke. Exposure to extreme temperatures and atmospheric pollutants were the main risk factors with direct impacts on CVD, while exposure to natural disasters was an important risk factor for amplifying other known risk factors (inadequate diet, alcohol consumption, smoking, and stress), thus considered a risk factor with indirect impact on CVD and DM.

When analyzing the category of climatic variability, one of the studies included in this review related increased precipitation to increased CVD [37]. Similarly, an ecological study conducted in China identified an increase in hospitalizations due to ischemic stroke associated with increased precipitation, especially in men and older adults (>65 years) [50]. Other researchers observed in a cohort study a higher risk of incidence of stroke (ischemic and hemorrhagic) when rainfall was higher [51].

Additionally, the risk of stroke may increase when precipitation is associated with other climatic variables such as air humidity, as in environments with very high precipitation and higher humidity, the body's decreased ability to sweat and the blockage of chloride and sodium discharge can lead to stroke [52]. On the other hand, low precipitation is observed in dry periods [53] and has been considered a risk factor for CVD, such as stroke [39]. In summary, it is known that extremes of high or low precipitation can increase the risk of stroke, even though there is no consensus in the literature on the type of stroke.

Regarding temperature variations, it was observed that, isolated or associated with other climatic variables, it was the one that most influenced the development or worsening of CVD. In the studies, we observed that the increase or decrease in temperature reference values was associated with CVD in the region where each study was conducted, with the association between increased temperature and heatwave being more frequent with the worsening or development of any cardiovascular disease [40].

In China, on days when heatwaves were present, there was an increased risk of various CVDs: chronic ischemic heart disease (32.2%), acute (27.3%), cerebrovascular disease (26.7%), and myocardial infarction (25.2%) [54]. According to the literature,

the main pathophysiological mechanisms that can explain the relationship between increased temperature and CVD are dehydration, hemoconcentration, hypercoagulable state, and electrolyte disturbances [55]. Moreover, the formation of clots from hypercoagulation can result in acute coronary events or stroke [26]. We found in this research that heat stress and exhaustion resulting from heatwaves generated by the rise in temperature can pose risks for people with CVD [40]. According to Coates et al. [56], heatwaves already cause more deaths than all other natural disasters combined.

Similar to our research, other studies have also linked decreases in temperature to an increased incidence of myocardial infarction [57] and stroke [58]. The impact of low temperatures on these cardiovascular events may be connected to vasoconstriction—a natural response of the human body to cold. Vasoconstriction aims to reduce heat loss by narrowing blood vessels. However, this narrowing can raise the risk of myocardial infarction by reducing peripheral blood circulation. Additionally, it may promote the occlusion of arteries due to fat plaques and blood clots. Furthermore, cold temperatures can lead to elevated blood pressure and decreased oxygen supply [59, 60], further contributing to cardiovascular risks.

In addition to the isolated influence of climate variability on CVD, some of the studies included in this review also highlighted the effects of these climatic variables on the concentration of air pollutants in the development of CVD. A higher concentration of air pollutants was observed during periods of low air humidity in dry seasons, contributing to increased cardiovascular hospitalizations and mortality [46]. Also, low humidity, combined with the high temperatures typical of dry seasons, provides favorable conditions for dust storms [61] and fires [62]. During dust storms, hot air masses can intensively concentrate local pollutants [63], besides favoring the transport and condensation of gaseous pollutants such as SO_2 [64].

Just like dust storms, temperature variation, and heatwaves influence the increase in concentration of air pollutants harmful to cardiovascular health, such as greenhouse gases [42], which can accentuate CVD mortality. Particulate matter along with CO_2 has been associated with the formation of atherosclerotic plaques, stemming from blood hypercoagulability due to endothelial dysfunction [44], exposing individuals to the risk of myocardial infarction and heart failure [39, 41].

The pathophysiological mechanisms by which exposure to air pollution negatively affects cardiovascular diseases are not yet fully understood; however, studies have highlighted possible explanations such as systemic inflammatory response [28], oxidative stress [65], genetic and epigenetic factors, impact on the central nervous system and autonomic dysfunction, as well as prothrombotic response, vascular dysfunction, and remodeling [66].

The last category presented in this study was that of natural disasters, being the only one where studies directed at people with DM were identified. Natural disasters, such as hurricanes [49] and earthquakes [48, 67], can be risk factors that cause indirect impacts, as they lead to the development or intensification of other risk factors, such as behavioral factors (tobacco and alcohol use, sedentary lifestyle, among others) and/or hypertension, which can trigger and/or exacerbate cardiovascular problems and diabetes mellitus.

After a disaster situation, a person may experience a hypertensive crisis due to sudden stress. Also, a gradual increase in blood pressure values is common due to the immediate and unplanned need for lifestyle changes, such as inadequate meals leading to weight gain, and the possibility of increased alcohol consumption. This finding is supported by a study conducted in the city of Fukushima, Japan, on the evacuation experience of individuals after a hurricane, which found an increase in blood pressure among these individuals [68]. After a disaster, in addition to changes in blood pressure values, alterations in HbA1c levels in people with DM are common, increasing the risk of hospitalizations [69].

Dietary habits may change after a natural disaster, for example, individuals in temporary shelters are restricted to the meals provided there [49, 67, 70]. Another influencing factor may be the distance from supermarkets and fast-food outlets when individuals are relocated to areas farther away from these establishments [71], reducing their opportunities to obtain the foods that were part of their diet.

Changes in dietary patterns can also occur due to mental illness, such as symptoms of post-traumatic stress disorder (PTSD) and depression [72], thereby increasing the risk of CVD and DM. The occurrence of late-onset post-traumatic stress disorder among survivors of natural disasters may be associated with impaired self-control [73]. A study conducted in Japan after the major earthquake and tsunami in 2011 suggested that the increased risks of cardiometabolic diseases may result from changes in diet associated with PTSD and depression. There was an association between reduced healthy eating patterns and depressive and/or PTSD symptoms, leading to increased unhealthy eating habits such as higher consumption of processed foods rich in carbohydrates and proteins, reduced intake of fruits and vegetables, and increased alcohol consumption, especially among males [74].

The likelihood of using toxic substances among survivors of natural disasters was also identified in our study. The main concerns of survivors were directed towards potential family or material losses, which can lead individuals to high levels of physical and emotional stress [49, 67, 75], favoring increased cigarette smoking [38, 70, 75] or alcohol consumption [38]. This finding may be associated with psychological distress resulting from decreased self-efficacy perception in coping, leading to increased substance use post-natural disaster [76]. Alcohol use as a temporary relief for stress is also common [77].

Other conditions reported in studies and related to increased hospitalization or mortality from CVD or DM in individuals affected by natural disasters include interruption of routine healthcare services [78] and lack of access to medications and treatments [48, 49, 67, 79] due to increased difficulty in accessing services [70]. All of this may be related to difficulty in self-managing some chronic diseases post-natural disaster [80].

The destruction of facilities, infrastructure, and significant changes in living conditions caused by natural disasters can increase difficulty, especially in older people, in maintaining healthy practices [77]. In addition to causing the destruction of health facilities, natural disasters can also reduce the number of professionals and interfere with the quality and effectiveness of health services provided [81, 82]. Furthermore, in circumstances

of natural disaster, health actions often focus on patients with acute conditions such as trauma or infectious diseases, even though inadequate control of chronic diseases is considered a major threat to people's health [82].

The most vulnerable groups identified in this review are similar to other research, with a focus on older adults, women, and children, who are most affected by climate influence [83]. This association may occur due to the greater susceptibility of older adults to retain more heat when exposed to hot and dry conditions than younger individuals [84]. The presence of comorbidities, such as hypertension, may further increase this vulnerability of older adults to heat exposure [85].

Women were also indicated in the studies as one of the vulnerable groups. This result may be associated with the progression of atherosclerotic disease. In women, the progression of atheroma plaques is slower but more severe [86] and may be exacerbated by climate change. Children were also considered vulnerable in the analyzed studies. This relationship may be related to the physiological development of children being different from adults. Furthermore, it is worth noting that children are exposed to long-term extreme weather events [87], as recent studies indicate that children born in 2020 will be more exposed to heatwaves (7 times more) and wildfires (2 times more) than previous generations in recent decades [88].

Exposure to climatic variability, pollution, and natural disasters in drylands is linked to cardiovascular diseases. Natural disasters also indirectly worsen diabetes mellitus. Vulnerability is particularly pronounced among older adults, women, and children. These factors often interact rather than act independently, highlighting the importance of nations adhering to Paris Agreement targets to decrease air pollutants and enhance resilience against disasters. Further research is imperative for tailored health interventions, necessitating interdisciplinary teams to alleviate the health impacts of climate, pollution, and disasters on these conditions.

Study Limitations

The study has limitations due to variability in population size and composition across the studies analyzed. Moreover, factors like public policies (such as early warning systems or green spaces) and socioeconomic status (income) could influence the results but were not addressed in this study.

AUTHOR CONTRIBUTIONS

RM and AC contributed with conceptualization, formal analysis, funding acquisition, investigation, supervision, and writing. CdS contributed with conceptualization, formal analysis, investigation, and writing. TdS and FL contributed with formal analysis, investigation, and writing. HM and AdO contributed with formal analysis, visualization, and writing. GD-C, MG, and TC contributed with conceptualization, formal analysis, visualization, and writing. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/phrs.2024.1607300/full#supplementary-material

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Risk, Attributable Fraction and Attributable Number of Cause-Specific Heat-Related Emergency Hospital Admissions in Switzerland

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Objectives: We assessed the relationship between heat and emergency hospital admissions (EHAs) in Switzerland using clinically relevant metrics.

Methods: Applying distributed lag non-linear models, we investigated temperature-admission associations between May and September 1998–2019 for various disease groups, by age class and gender. We estimated the relative risk (RR) for moderate (29°C) and extreme (34°C) daily maximum temperatures relative to disease-specific optimum temperature, and calculated attributable fractions (AFs) for hot days and the following week. We also calculated the total number of heat-related EHAs.

Results: We attributed 31,387 (95% confidence interval: 21,567–40,408) EHAs to above-optimal temperatures, 1.1% (0.7%–1.4%) of the total. Extreme temperatures increased the EHA risk for mental, infectious and neurological diseases. We observed particularly high AFs due to extreme heat for dehydration (85.9%, 95% CI: 82.4%–88.8%) and acute kidney injury (AKI, 56.1%, 95% CI: 45.3%–64.7%). While EHA risk generally increased with age, we also found high RRs for infectious diseases in children (0–15 years) and AKI in young adults (15–64 years).

Conclusion: Hot weather increases the EHA risk in Switzerland. Therefore a comprehensive clinical and public health response is needed.

Keywords: hot weather, morbidity, emergency hospital admissions, attributable risk, heat-related diseases

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INTRODUCTION

Exposure to high ambient temperature is an important public health hazard. Globally, about 490,000 deaths per year, or about 0.9% of the total, are attributable to heat [1]. It has been estimated that every third heat-related death between 1991 and 2018 was due to man-made climate change [2]. The most frequently documented heat-related health impacts are mortality increases attributed to cardiovascular and respiratory disease, especially among the elderly and the chronically ill [2–8].

Although heat effects on morbidity are somewhat less studied, there is a growing body of literature on this topic. Previous studies from various global regions documented increased hospital admissions [9–17], visits at emergency departments [12, 18–22] and ambulance call-outs [23–26] during periods of heat. Adverse heat effects have been found for various disease groups

such as mental, respiratory, gastrointestinal or kidney diseases. The effect varies depending on local climate, age structure and the characterisation of heat exposure [4, 27–29].

In Switzerland, a small number of studies assessed the effects of hot weather on morbidity. Ragettli et al. reported an excess rate of 2.4% for emergency hospital admissions (EHAs) for non-external causes during the warm summer of 2015 [15]. For certain cardiovascular diseases such as hypertension and hear failure, however, a decrease in the risk for EHA was observed [30]. A study in the city of Bern found an increased risk for mental health hospitalisations associated with increasing temperature [14].

Most studies on heat-related morbidity do not report disease-specific attributable fractions (AFs) or absolute attributable numbers (ANs). The AFs and ANs are relevant to improve the detection of heat-related diseases in clinical settings and for public health planning. Temperature-specific AFs for relevant disease groups may assist medical teams to assess how likely heat may have caused or mimicked an emergency patient's suspected diagnosis [31], thereby improving quality of care and informing the design of public health interventions.

This study offers a comprehensive examination of the relationship between heat and EHAs in Switzerland, employing a range of relevant metrics over a period of 22 years. We provide the attributable fraction (AF) of heat-related EHAs on a hot day and the following week, along with the total number of heat-attributable EHAs (AN) for various diagnoses and disease groups. Furthermore, we calculated the relative risk (RR) by age group and gender to identify vulnerable population groups. We also investigated whether an age group may be more susceptible for EHAs from a specific disease due to exposure to moderate or extreme heat.

METHODS

Study Setting and Health Data

We obtained anonymized EHA data on diagnosis, age group and gender from the medical statistics of Swiss hospitals provided by the Federal Statistical Office [32]. The data set includes all emergency admissions to an emergency department of a Swiss hospital between May and September of the years 1998–2019 in the nine Swiss cantons Basel-Stadt, Basel-Land, Berne, Geneva, Lucerne, St. Gallen, Ticino, Vaud and Zurich. The area comprises the largest cities of Switzerland and the areas with the highest (urban) population density, representing 60% of the total census population in 2021. All diagnosis coding is based on the 10th revision of the International Classification of Diseases (ICD-10). The WHO version of the ICD-10 [33] was used between 1998 and 2009, and the slightly modified German version (ICD-10-GM) [34] between 2010 and 2019. The recorded ICD-10 code is aligned with the hospital discharge diagnosis, which is entered into the system by the attending physician and the hospital's coding specialist. A high correlation between the hospital discharge diagnosis and the emergency diagnosis has been reported in high-income settings [35, 36].

We grouped data into the following disease groups (ICD-10 codes in brackets): Total EHAs (I-XXII), total non-external causes (I-XVIII excl. T67.0), certain infectious and parasitic diseases (I, A00-B99), mental and behavioural disorders (V, F00-F99), diseases of the nervous system (VI, G00-G99), diseases of the respiratory system (X, J00-J99), diseases of the digestive system (XI, K00-K93), diseases of the genitourinary system (XIV, N00-N99) and external causes (XIX-XXII & T67.0). In addition, we examined the effect of heat on the following specific renal diseases and conditions: Dehydration (E86, R39.2), urinary tract infections (N10, N13.6, N30 excl. N30.4, N39.0, N41), acute kidney Injury (N17), chronic kidney disease (N18) and kidney stones (N20-N23). Cardiovascular diseases were investigated in a previous Swiss study [30] and therefore not separately analysed. We aggregated the disease-specific EHAs among Swiss residents by canton, age group (0–14, 15–64, 65–75, 75–84 and ≥85 years), and gender (male, female).

Temperature Data

Supplementary Table A1 shows the representative monitoring stations for each canton that was used to collect daily maximum temperature (Tmax), daily minimum temperature (Tmin) and daily mean temperature (Tmean). The temperature data was obtained from the IDAweb database, a service provided by the Swiss Federal Office of Meteorology and Climatology (MeteoSwiss) [37].

Statistical Analysis

We explored the association between temperature and EHAs using distributed lag non-linear models (DLNMs) with conditional Poisson regression [38, 39]. DLNMs are used to describe the non-linear association between the predictor, the outcome and the lag dimension (delayed effect) by including a so-called cross-basis function in the Poisson regression model. All cantons were pooled into one data set and a stratum variable for each combination of year, month, weekday and canton was included in the model. This approach yields results equivalent to a case-control study, but can account for overdispersion and auto-correlation [39], and eliminates the need to calculate canton-specific relative risks.

Exposure-Response Functions

We modelled the exposure dimension of the cross-basis function using a quadratic B-spline with one internal knot at the median, and boundary knots at the minimum and maximum of the warm season temperature distribution across all cantons and years. For the lag dimension of the cross-basis, we used a natural cubic spline with two internal knots equally spaced at the log scale. The maximum lag was set to 7 days, because initial analyses showed that most of the heat impact on EHAs occurs on a hot day and during the following week. We also performed an analysis with 10 days of lag for comparison. As in prior studies, the selection of the model parameters, such as knot positions, degrees of freedom and lag was based on previous research [7, 22] and preliminary analysis. To assess the robustness of our results, we performed a sensitivity analysis for total EHA risk and by diagnosis, age and gender using different temperature metrics, knots and degrees of freedom.

TABLE 1 | Descriptive statistic of the investigated emergency hospital admissions in eight Swiss Cantons during the warm season (May-September) 1998–2019 (Risk, attributable fraction and attributable number of cause-specific heat-related emergency hospital admissions in Switzerland, Switzerland, 1998–2019).

Disease	All	0–14 years	15–64 years	65–74 years	75–84 years	≥85 years	Women	Men
Total*	2,884,489	211,143 (7.3%)	1,427,326 (49.5%)	393,317 (13.6%)	510,491 (17.7%)	342,212 (11.9%)	1,557,787 (54.0%)	1,326,702 (46.0%)
Non-external Causes*	2,309,035	140,392 (6.1%)	1,170,848 (50.7%)	326,545 (14.1%)	414,839 (18.0%)	256,411 (11.1%)	1,262,685 (54.7%)	1,046,350 (45.3%)
External Causes	575,454	70,751 (12.3%)	256,478 (44.6%)	66,772 (11.6%)	95,652 (16.6%)	85,801 (14.9%)	295,102 (51.3%)	280,352 (48.7%)
Diseases of the digestive system	315,076	18,386 (5.8%)	165,176 (52.4%)	48,276 (15.3%)	52,886 (16.8%)	30,352 (9.6%)	157,880 (50.1%)	157,196 (49.9%)
Mental and behavioural disorders	238,596	4,744 (2.0%)	186,853 (78.3%)	17,232 (7.2%)	17,927 (7.5%)	11,840 (5.0%)	123,986 (52.0%)	114,610 (48.0%)
Diseases of the respiratory system	177,345	31,512 (17.8%)	56,341 (31.8%)	28,515 (16.1%)	37,514 (21.2%)	23,463 (13.2%)	75,987 (42.8%)	101,358 (57.2%)
Diseases of the genitourinary system	148,210	8,114 (5.5%)	79,356 (53.5%)	20,168 (13.6%)	24,633 (16.6%)	15,939 (10.8%)	72,537 (48.9%)	75,673 (51.1%)
Certain infectious and parasitic diseases	136,197	20,453 (15.0%)	56,504 (41.5%)	19,501 (14.3%)	24,753 (18.2%)	14,986 (11.0%)	65,986 (48.4%)	70,211 (51.6%)
Diseases of the nervous system	84,007	4,979 (5.9%)	36,332 (43.2%)	14,411 (17.2%)	18,741 (22.3%)	9,544 (11.4%)	42,286 (50.3%)	41,721 (49.7%)
Urinary Tract Infection	31,290	2,142 (6.8%)	7,209 (23.0%)	5,255 (16.8%)	9,185 (29.4%)	7,499 (24.0%)	17,190 (54.9%)	14,100 (45.1%)
Kidney Stones	30,612	147 (0.5%)	25,292 (82.6%)	3,288 (10.7%)	1,519 (5.0%)	366 (1.2%)	8,139 (26.6%)	22,473 (73.4%)
Acute kidney injury	7,627	25 (0.3%)	1,746 (22.9%)	1,625 (21.3%)	2,616 (34.3%)	1,615 (21.2%)	3,246 (42.6%)	4,381 (57.4%)
Dehydration	5,852	557 (9.5%)	826 (14.1%)	709 (12.1%)	1,695 (29.0%)	2,065 (35.3%)	3,468 (59.3%)	2,384 (40.7%)
Chronic Kidney Disease	4,876	52 (1.1%)	1,366 (28.0%)	989 (20.3%)	1,562 (32.0%)	907 (18.6%)	2,089 (42.8%)	2,787 (57.2%)

For each disease group, the absolute number of emergency hospital admissions and its proportion in % of the disease-specific total is shown by age group and gender.
**includes cardiovascular diseases which were not the focus of this study and are studied in relation to temperature elsewhere [30].*

We run separate models by age group and gender for each disease group. Based on these models, we estimated the cumulative relative risk (RR) for EHA. The RR compares the number of EHAs on a hot day and the following week with the number of EHAs on a less hot day and the following week. We used the following temperature cut-offs: For overall heat, we compared the 99th percentile of the warm-season temperature distribution (p99) to the disease-specific reference temperature (tref). For moderate and extreme heat, we compared the 90th percentile (p90) with tref, and p99 with p90, respectively. The temperature threshold at which mortality begins to increase may vary between different disease groups and depend on age- or gender specific vulnerabilities. Therefore, we calculated separate reference temperatures for each disease-gender and disease-age group combination by identifying the minimum of the respective exposure-response function between the 25th and the 90th percentile of the warm season temperature distribution. We also calculated lag-specific RR values for each age group, gender and disease.

EHAs Attributable to Heat

We quantified the cause-specific EHAs attributable to heat using the observed daily EHAs and the cumulative risk estimate of the exposure-response association corresponding to the observed Tmax on each day [2]. We applied this procedure to each canton-specific time series. The number of heat-related EHAs corresponds to the sum of all EHAs attributed to heat on days with Tmax above the disease-specific reference temperature over the entire observation period.

Temperature Specific Attributable Fractions

Assuming that the whole population is directly or indirectly exposed to ambient temperature, the temperature specific RR was converted into an attributable fraction (AF) using the formula AF = (RR-1)/RR. We present the AF corresponding to the RR comparing a day with a temperature at the 99th or 90th percentile with a day with disease-specific reference temperature. In this definition, the AF represents the proportion of heat-related emergency hospital admissions on a given day with a specific temperature and the following week (lag 0–7) among all patients with the same diagnosis.

All analyses were conducted with the statistical software R (version 4.2.2), relying on the dlnm package [38].

RESULTS

Table 1 shows a descriptive statistic of the daily EHAs in the nine Swiss cantons during the study period 1998 to 2019 by disease, age and gender. In total, 2,884,489 EHAs were registered during the study period. Most of them (2,309,035, 80%) were due to non-external causes, especially digestive (315,076, 11%), mental (238,596, 8%) and respiratory (177,345, 6%) diseases. A considerable number of EHAs was due to external causes (575,454, 20%). Kidney stones (30,612, 1%) and urinary tract infections (31,290, 1%) made up the largest part of the examined specific kidney diseases. Most patients were female (54%) and below 65 years old (56%). Half (50%) of the EHAs were observed in the age group 15–64 years. In all age groups, external causes were the most frequent cause of EHA, followed by respiratory diseases in children 0–14 years, mental diseases in adults 15–64 years, or digestive diseases in all of the older age groups above the age of 65 years.

Over all cantons, the average Tmean, Tmin and Tmax during the study period was 22.7°C, 3.2°C and 39.7°C, respectively. The populations in different cantons were exposed to similar temperatures, with canton-specific maximum Tmax ranging from 33.3°C in St. Gallen to 39.7°C in Geneva. More detailed information on the measured temperature levels in each canton is presented in **Supplementary Table A1**.

Figure 1 shows the exposure-response functions for all examined disease groups. On a hot day with 34°C and the following week, the risk for EHA increased by 5% (RR = 1.05, 95% CI: 1.03–1.06) compared to a day with the disease-specific reference temperature and the following week. Specifically, we observed an increase in RR with temperature for external causes,

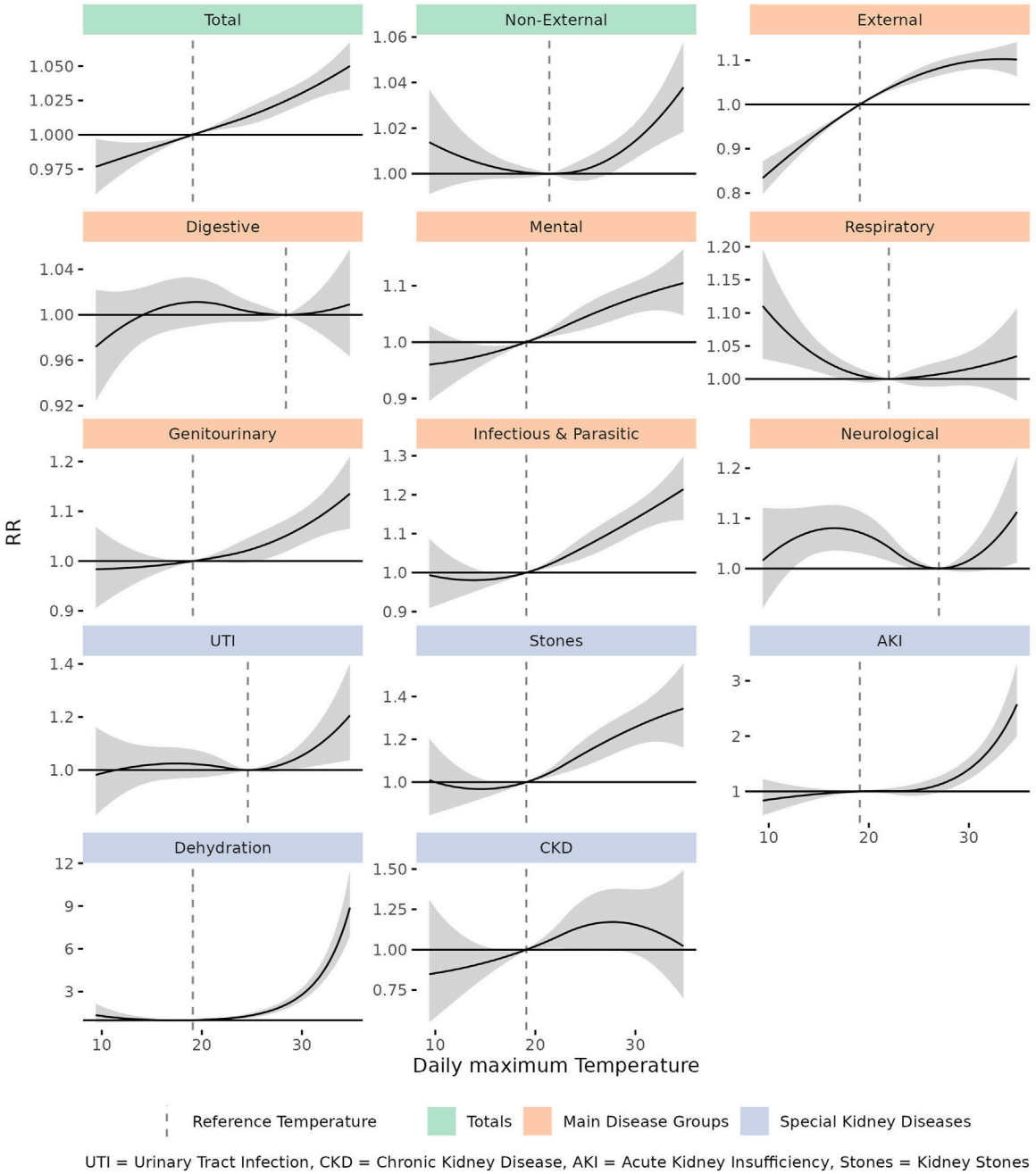

FIGURE 1 | Cumulative (lag 0–7) relative risk (RR) with 95% confidence interval between daily maximum temperature and emergency hospital admissions for examined diseases during the warm season. Dashed vertical lines show the disease-specific reference temperature (Risk, attributable fraction and attributable number of cause-specific heat-related emergency hospital admissions in Switzerland, Switzerland, 1998–2019).

mental diseases, genitourinary diseases, infectious diseases and neurological diseases, and for all examined specific kidney diseases except for chronic kidney disease. The highest RRs were observed for dehydration (7.1, 95% CI: 5.67–8.9), acute kidney injury (2.28, 95% CI: 1.83–2.83) and kidney stones (1.33, 95% CI: 1.18–1.51).

Disease-specific RR also varied by lag. For external causes, infectious diseases and dehydration, we observed the strongest impact on lag 0. For mental diseases, AKI and kidney stones, we observed the strongest effects on lag 1–4, 1–5 and 1–3, respectively. All lag-specific RRs and attributable fractions are shown in **Supplementary Figure A1**.

Table 2 displays the age- and gender specific cumulative RR for all examined diseases, comparing the warm-season P99 of Tmax with the disease-specific reference temperature. In general terms, the risk increase was higher for women (6% [96% CI: 4%–8%]) than for

TABLE 2 | Cumulative (lag 0–7) relative risk for emergency hospital admission with 95% confidence interval by disease group, specified by age class and gender (Risk, attributable fraction and attributable number of cause-specific heat-related emergency hospital admissions in Switzerland, Switzerland, 1998–2019).

Disease	All	0–14 years	15–64 years	65–74 years	75–84 years	≥85 years	Women	Men
Total	**1.05 (1.03–1.06)**	1.01 (0.96–1.06)	**1.05 (1.03–1.07)**	**1.05 (1.02–1.09)**	**1.04 (1–1.07)**	**1.09 (1.04–1.13)**	**1.06 (1.04–1.08)**	**1.03 (1.01–1.05)**
Non-external Causes	**1.03 (1.02–1.05)**	1.03 (0.96–1.09)	1.02 (1–1.04)	1.02 (0.98–1.07)	1.04 (1–1.08)	**1.12 (1.07–1.17)**	**1.05 (1.03–1.08)**	1.01 (0.99–1.04)
External Causes	**1.1 (1.07–1.14)**	0.98 (0.89–1.07)	**1.18 (1.13–1.23)**	**1.27 (1.17–1.38)**	1.05 (0.98–1.13)	1.02 (0.95–1.08)	**1.1 (1.05–1.14)**	**1.11 (1.06–1.16)**
Diseases of the digestive system	1.01 (0.97–1.05)	1.01 (0.86–1.19)	1.02 (0.96–1.08)	1.07 (0.97–1.19)	0.97 (0.89–1.05)	0.97 (0.85–1.1)	1.05 (0.98–1.11)	0.98 (0.93–1.03)
Mental and behavioural disorders	**1.1 (1.05–1.15)**	0.9 (0.67–1.2)	**1.09 (1.03–1.14)**	1.18 (1–1.41)	**1.2 (1.03–1.4)**	1.2 (1–1.43)	**1.08 (1.02–1.15)**	**1.12 (1.05–1.19)**
Diseases of the respiratory system	1.03 (0.97–1.09)	**0.72 (0.63–0.82)**	1.04 (0.95–1.14)	1.14 (0.99–1.32)	**1.19 (1.05–1.33)**	1.15 (0.98–1.34)	1.01 (0.92–1.1)	1.05 (0.97–1.13)
Diseases of the genitourinary system	**1.12 (1.06–1.19)**	0.95 (0.77–1.17)	**1.1 (1.01–1.18)**	0.98 (0.86–1.11)	**1.18 (1.03–1.34)**	**1.54 (1.3–1.82)**	1.08 (0.99–1.18)	**1.18 (1.09–1.27)**
Certain infectious and parasitic diseases	**1.2 (1.13–1.27)**	**1.38 (1.18–1.6)**	**1.13 (1.03–1.24)**	1.16 (1–1.34)	**1.3 (1.14–1.48)**	1.16 (0.98–1.37)	**1.26 (1.16–1.36)**	**1.15 (1.06–1.25)**
Diseases of the nervous system	**1.09 (1.01–1.18)**	**1.42 (1.01–2)**	0.97 (0.87–1.07)	1.18 (0.97–1.44)	**1.21 (1.03–1.43)**	1.11 (0.9–1.37)	**1.18 (1.05–1.32)**	1.01 (0.93–1.11)
Urinary Tract Infection	**1.17 (1.03–1.33)**	0.97 (0.61–1.54)	0.97 (0.76–1.24)	1.14 (0.83–1.55)	1.12 (0.9–1.39)	**1.62 (1.26–2.06)**	**1.36 (1.15–1.62)**	1 (0.84–1.18)
Kidney Stones	**1.33 (1.18–1.51)**	2.5 (0.4–15.76)	**1.34 (1.16–1.54)**	1.08 (0.73–1.59)	1.34 (0.79–2.27)	**6.9 (2.38–20.03)**	1.22 (0.96–1.55)	**1.37 (1.19–1.59)**
Acute kidney injury	**2.28 (1.83–2.83)**	<100 cases	**3.27 (2.08–5.13)**	1.49 (0.92–2.4)	**2.52 (1.67–3.81)**	**2.35 (1.42–3.89)**	**1.85 (1.29–2.64)**	**2.67 (2–3.57)**
Dehydration	**7.1 (5.67–8.9)**	**3.63 (1.49–8.85)**	**4.85 (2.37–9.95)**	**9.48 (5.06–17.74)**	**6.97 (4.56–10.66)**	**8.76 (6.15–12.5)**	**8.02 (6–10.71)**	**5.92 (4.14–8.45)**
Chronic Kidney Disease	1.05 (0.76–1.45)	<100 cases	1.01 (0.54–1.9)	0.97 (0.47–2.01)	0.96 (0.59–1.54)	1.13 (0.55–2.33)	1.21 (0.74–1.98)	0.94 (0.61–1.43)

Comparison between the 99th percentile of the daily maximum temperature distribution (p99, 34°C) and the reference temperature (specific for disease and demographic group). Significant values in bold.

men (3% [95% CI 1%–5%) and particularly pronounced in the very old ≥85 years (9% [95% CI: 4%–13%]). Children were most affected by heat-related EHAs classified as infectious diseases. Adults and young pensioners were often admitted for external causes during periods of heat. In the elderly, heat was associated with a considerable increase in EHA risk for dehydration and acute kidney injury. Specifically, we also observed an increase in EHAs due to urinary tract infections (UTI) in old women, and due to kidney stones in old men.

Effects for moderate and extreme heat by age are presented in **Figure 2**. Moderate heat was associated with an increase in EHA risk for total, non-external, external, mental, genitourinary and infectious diseases in various age groups. Especially the increase for external causes was mainly attributable to moderate heat, which corresponds to the flattening shape of the respective E/R-curve. Extreme heat was associated with an increasing EHA risk for total and non-external causes, especially in the oldest age group. A particularly striking additional effect of extreme heat was detectable for dehydration and acute kidney injury across age groups, consistent with the exponential shape of the respective E/R curves (**Supplementary Figure A2**).

Table 3 shows the estimated number of heat-related EHAs in Switzerland between 1998 and 2019 by diagnosis. According to our model, 31,387 (95% CI: 21,567–40,408) out of the total 2,884,489 EHAs were attributable to heat. Most cases were observed for external causes, mental and behavioural disorders, infectious diseases and diseases of the genitourinary system. Among the examined specific kidney diseases, kidney stones accounted for the largest number of heat-related EHAs.

Alongside, **Table 3** shows the disease-specific attributable fractions on a moderately (29.3°C, p90) or extremely (34°C, p99) hot day and the following week, compared with a day with disease-specific reference temperature and the following week. Following an extreme heat event (p99, 34°C), 4.4% (95% CI: 3.1%–5.8%) of all EHAs were statistically attributable to heat. Particularly high attributable fractions were observed for dehydration (85.9%, 95% CI: 82.4%–88.8%), acute kidney injury (56.1%, 95% CI: 45.3%–64.7%) and kidney stones (24.9%, 95% CI: 14.9%–33.7%) after extreme heat events, which corresponds to the marked RR increase with temperature for these diseases.

Sensitivity analyses assessing the impact of model choices on our results did not change the shape of the exposure-response functions. The exposure-response functions also looked similar for Tmin and Tmean. The results for overall (p99/tref), moderate (p90/tref) and extreme (p99/p90) heat were similar across models. Detailed plots are presented in the **Supplementary Figures A3–A5**.

DISCUSSION

Our study shows that both moderate and extreme heat is associated with an increased EHA risk in Switzerland. Overall, we estimated that 31,387 (95% CI) all-cause EHAs can be attributed to heat during the warm season 1998–2019, representing 1.1% (95% CI) of the total EHAs during the period. In absolute terms, most heat-related EHAs were diagnosed as external causes (23,962, 95% CI: 19,901–27,688), mental diseases (7,104, 95% CI: 4,653–9,743), and infectious diseases (6,374, 95% CI: 4,478–8,140). On a hot day of 34°C and the following week, 4.4% of all EHAs can be attributed to heat exposure, as well as 86% of the dehydration cases, 56% of the acute kidney injury cases and 25% of the kidney stone cases. The risk of EHA mainly increased for infectious diseases in children, for external causes in adults up to 64 years of age, and for dehydration, kidney stones and UTI in the elderly.

External causes made up the largest number of heat-attributable EHAs. The RR for EHA due to external causes increased mainly on lag 0 in the age groups 15–64 and 65–74, and was most pronounced in moderate heat. Similar to previous studies, we assume that the most likely explanation for this finding are outdoor leisure time and occupational

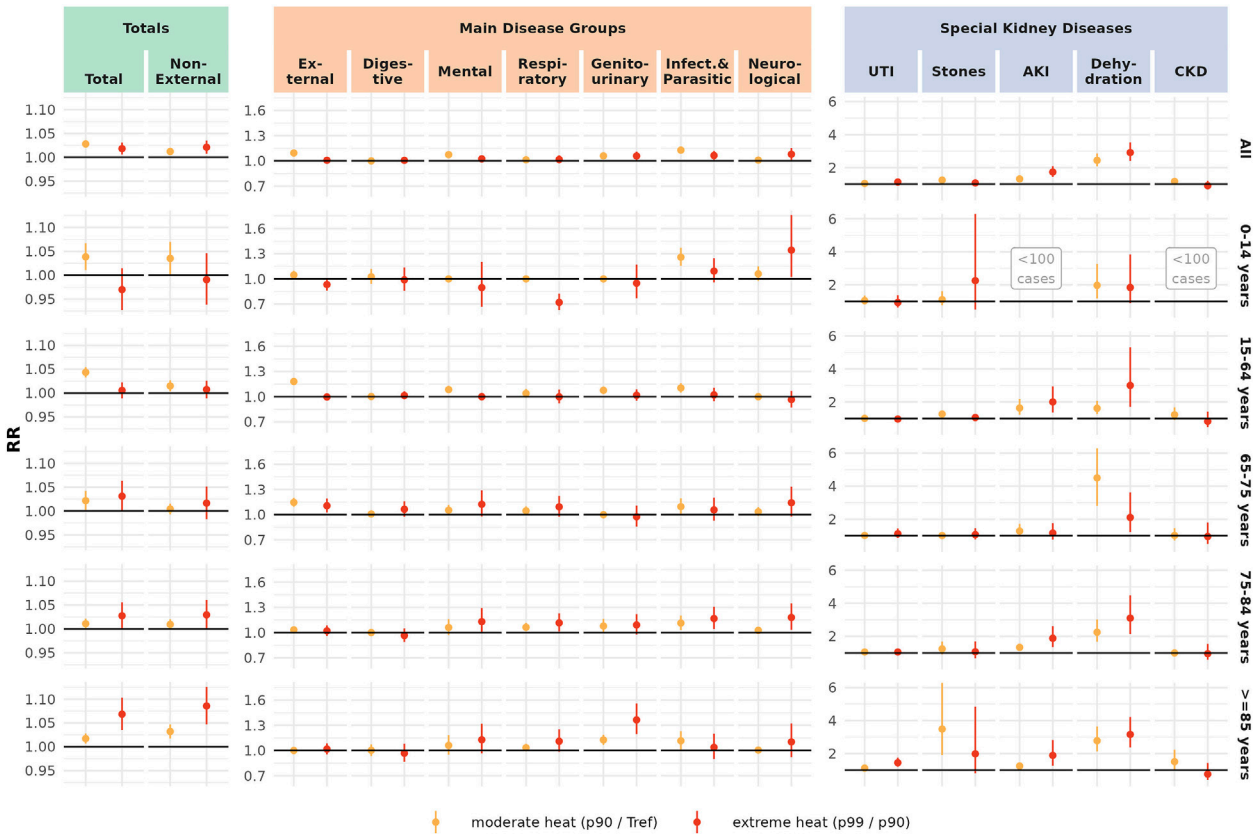

FIGURE 2 | Cumulative (lag 0–7) relative risk with 95% confidence interval comparing moderate heat (p90, 29.3°C) with the reference temperature, and extreme heat (p99, 34°C) with moderate heat (Risk, attributable fraction and attributable number of cause-specific heat-related emergency hospital admissions in Switzerland, Switzerland, 1998–2019).

accidents during warm summer weather, although reduced cognitive or motor function under heat stress may also contribute [15, 26, 40, 41]. Our results differ from some previous research that identified heat-related fractures mainly in the elderly [20].

For mental and behavioural disorders, there was a significant increase of the EHA risk with Tmax at lag 1–4. The effect is well described and the lag structure is well in line with similar studies from Bern, Switzerland and Toronto, Canada. The risk increase can be explained by specific heat effects, such as altered neurotransmitter levels, interference of heat with psychiatric drugs, impaired cognitive function or sleep deprivation [11, 14, 42].

Heat-related EHAs for infectious diseases increased across age groups, with children (0–14 years) most affected. Previous studies described a higher risk for gastroenteritis with heat that may account for some of these cases [12, 43]. Another study by Bobb et al. suggested that heat-related illness may mimic sepsis, which could lead to a false increase of EHAs for supposed infectious diseases [44]. There are indications that such misdiagnosis may explain some of the risk increase for infectious diseases that we observed, both in children and adults. First, heat exhaustion and heat stroke ("heat illness") are generally overlooked. The limited available research shows low detection rates (0%–3%) especially in Europe, which means that most cases falsely receive a different diagnosis [45, 46]. Second, the symptoms of heat illness and infectious diseases overlap considerably: Hemoconcentration due to heat-induced dehydration can mimic leukocytosis, while hyperthermia, hypotension, tachycardia and impaired consciousness are characteristic for both heat illness and severe infections, particularly sepsis [47, 48]. This favours the misdiagnosis of heat-related illnesses as an infectious disease, especially sepsis. And third, we observed a similar lag pattern between dehydration, which is a direct heat effect, and infectious diseases: Both peak on day 0, with little effect on the consecutive days. This may indicate that both observations in fact describe the same underlying event. Future research may address this finding by examining patient level data, e.g., with a similar approach as used by Oberlin et al. [45].

For dehydration, acute kidney injury (AKI) and kidney stones, our results showed a particularly strong association of heat and EHAs. The affected patients were usually 85 years and older or of working age (15–64 years). The observed effect was consistent with literature [10, 12, 28, 44, 49–52] and followed an exponential (dehydration, AKI) or near-linear (kidney stones) exposure-response curve. A causal pathway from heat over sweating to dehydration and acute kidney injury has been widely described in literature and experimentally

TABLE 3 | Left part: Absolute and relative heat-attributable emergency hospital admissions with 95% confidence interval by disease group. Right part: Heat attributable fractions on a hot day with 34°C and the following week with 95% confidence interval by disease group (Risk, attributable fraction and attributable number of cause-specific heat-related emergency hospital admissions in Switzerland, Switzerland, 1998–2019).

Disease	Ref. Temp	Heat-related EHA, May-September 1998–2019 on days with tmax > Ref. Temp		Fraction of heat-related emergency hospital admissions (EHA) on a hot day with 34°C and the following week after a heat event with a temperature of…	
		Heat-attributable EHA	Share on summer EHA 1998–2019	29.3°C (p90)	34°C (p99)
Total	19.1°C	**31,387 (21,567–40,408)**	**1.1% (0.7%–1.4%)**	**2.7% (2.0%–3.5%)**	**4.4% (3.1%–5.8%)**
Non-external Causes	21.4°C	**7,906 (1,760–13,849)**	**0.3% (0.1%–0.6%)**	**1.2% (0.5%–1.9%)**	**3.2% (1.6%–4.8%)**
External Causes	19.1°C	**23,962 (19,901–27,688)**	**4.2% (3.5%–4.8%)**	**8.6% (7.1%–10.1%)**	**9.3% (6.5%–12.0%)**
Diseases of the Digestive system	28.4°C	76 (–415–591)	0.0% (–0.1%–0.2%)	0.0% (–0.4%–0.4%)	0.7% (–3.2%–4.5%)
Mental and behavioural disorders	19.1°C	**7,104 (4,653–9,743)**	**3.0% (2.0%–4.1%)**	**6.9% (4.5%–9.3%)**	**9.2% (4.9%–13.2%)**
Diseases of the respiratory system	22°C	672 (–682–2,014)	0.4% (–0.4%–1.1%)	1.3% (–1.0%–3.5%)	3.0% (–2.8%–8.4%)
Diseases of the genitourinary system	19.1°C	**3,157 (1,104–5,016)**	**2.1% (0.7%–3.4%)**	**5.6% (2.7%–8.5%)**	**10.9% (5.9%–15.7%)**
Certain infectious and parasitic diseases	19.1°C	**6,374 (4,478–8,140)**	**4.7% (3.3%–6.0%)**	**11.4% (8.4%–14.2%)**	**16.7% (11.8%–21.4%)**
Diseases of the nervous system	27°C	336 (–42–697)	**0.4% (0.0%–0.8%)**	0.9% (–0.6%–2.5%)	**8.2% (0.6%–15.3%)**
Urinary Tract Infection	24.6°C	**387 (67–716)**	**1.2% (0.2%–2.3%)**	**3.9% (0.3%–7.4%)**	**14.7% (3.1%-24.9%)**
Kidney Stones	19.1°C	**2,548 (1,711–3,280)**	**8.3% (5.6%–10.7%)**	**19.5% (13.8%–24.8%)**	**24.9% (14.9%–33.7%)**
Acute kidney injury	19.1°C	**624 (154–1,006)**	**8.2% (2.0%–13.2%)**	**24.0% (12.8%–33.7%)**	**56.1% (45.3%–64.7%)**
Dehydration	19.1°C	**1,735 (1,453–1,973)**	**29.7% (24.8%–33.7%)**	**59.0% (52.0%–65.0%)**	**85.9% (82.4%–88.8%)**
Chronic Kidney Disease	19.1°C	**345 (11–617)**	**7.1% (0.2%–12.7%)**	14.0% (–1.6%–27.3%)	4.9% (–31.3%–31.1%)

Significant values in bold.

confirmed [40, 53, 54]. Similarly, the accumulation of minerals in concentrated urine can lead to kidney stones [40, 51]. With all applicable Bradford Hill criteria for causality [55] fulfilled, our results suggest that on a hot day with 34°C and in the following week, more than 4/5th of the dehydration cases, more than half of the acute kidney injury cases, and a quarter of the kidney stone cases are likely caused by heat exposure. The risk increase also affected the working-age population between 15 and 64, which could justify extending heat protection measures to this age group to reduce exposure.

We also found a heat-related increase for urinary tract infections (UTI), specifically in the very old (≥85) and in women. The risk group is unsurprising: Younger patients with (suspected) UTI would likely receive outpatient treatment and not be included in the EHA statistic, and UTI are uncommon in men. We suggest two plausible explanations for increasing EHAs due to UTI with heat. On one hand, dehydration has been described as a risk factor for UTI, especially in care-dependent individuals [56]. Several pathophysiological pathways have been proposed for this effect, although with inconsistent evidence [57]. On the other hand, missed cases of heat emergencies may also contribute, similar as for infectious diseases: Heat-induced hyperthermia may be misinterpreted as fever, while an inconclusive urine sample due to low urine output may remain the only pathological finding after diagnostic work-up for suspected infection, leading to hospitalization for UTI.

Our study provides a comprehensive assessment of the effects of heat on EHAs for different causes, subgroups and temperature ranges over an extended period of time. By quantifying the effect in the form of attributable numbers and attributable fractions, we provide relevant results for public health professionals and clinicians that may help to improve the detection of heat-related diseases. For instance, emergency medical teams can use the AF to estimate the risk that the condition of a specific emergency patient is heat-related under current meteorological conditions. We could show that heat events are associated with a substantial increase in EHAs in Switzerland. The effect already occurs in moderate heat and causes the majority of EHAs for some diseases (dehydration, acute kidney injury) on a hot day with 34°C and the following week.

Our results demonstrate the potential of primary prevention for vulnerable population groups. This could be achieved by appropriate heat protection measures, such as sufficient thermal insulation and passive cooling of buildings [58] like nursing homes, heat-resilient urban planning, and workplace safety measures such as cooling clothes and adapted working hours for outdoor workers during hot spells [59]. Further, secondary prevention should include the training of healthcare professionals in the detection and management of heat-related diseases by appropriate measures. Such measures include the inclusion of heat exhaustion and heat stroke in common differential diagnostic schemes for dizziness, elevated body temperature and altered level of consciousness. Furthermore, physical cooling should be made available as a standard practice in emergency and non-intensive care settings to improve the treatment of heat exhaustion and heat stroke. The study also identified a substantial number of EHAs due to external causes that is probably caused by behavioural changes on hot days, although the physiological effects of heat may amplify the risk. This finding should be further investigated and may require entirely different prevention measures, such as accident prevention programs.

To facilitate the implementation of prevention measures such as heat health action plans, a multi-stakeholder approach is needed, where scientific institutions, medical or nursing organizations, health governments, civil defence authorities, municipalities and occupational safety organizations collaborate with each other [40, 60]. In such a manner, feasible and acceptable solutions can be developed [61], which efficiently reduce the heat-related health burden.

However, some limitations have to be acknowledged. Inevitably, first diagnoses in hospital records may be optimized for changes in insurance reimbursement schemes,

such as the introduction of diagnosis related groups (DRGs) in Switzerland in 2012 [62, 63]. However, such long-term changes do not correlate with short-term weather fluctuation and are therefore unlikely to cause bias. As in previous studies on the temperature-morbidity relationship [15], we used temperature data from only one station per canton. Thus, within-canton variability of temperature could not be accounted for. By including only the cantons with the largest urban areas, choosing representative monitoring stations and excluding the mountain area, we tried to minimize exposure misclassification. We did not account for possible confounders and effect modifiers such as air pollution or humidity. While prior research showed an independent effect of temperature on health outcomes, the additional effect of air pollution has been found to be small [4]. Heat can affect air pollution levels, in particular ozone. This implies that air pollution is on the pathway and serves as a potential mediator for heat-related health effects. Consequently, adjusting for air pollutants such as ozone would have potentially removed these indirect heat effects, leading to an underestimation of heat-related morbidity [64]. Previous research has demonstrated that heat metrics incorporating humidity, such as apparent temperature, yield comparable outcomes to tmax [7, 65, 66]. A recent large scale analysis has confirmed this for cities with a robust negative correlation between temperature and humidity [67], which is the case for Switzerland. Therefore, we selected the more accessible and comprehensible measurement to facilitate the utilisation of the study results in clinical practice.

Conclusion

Heat accounts for a considerable amount of emergency hospital admissions (EHAs) in Switzerland. External causes, mental and behavioural disorders and infectious diseases are the most frequent heat-related diagnoses. Our findings suggest that the majority of EHAs for dehydration and acute kidney injury on a hot day with 34°C and the following week can be attributed to heat exposure, especially in the elderly and working ages. A multi-stakeholder approach is needed to develop and implement feasible and acceptable prevention measures for risk groups to reduce heat exposure and improve the detection of heat-related diseases.

AVAILABILITY OF R-CODE AND DATA

The health data used for this study are available under license from the Federal Statistical Office, Switzerland. The R code is available on request from the authors.

ETHICS STATEMENT

There were no patients involved. All analysis was done on aggregated data, for which no ethical approval is required in Switzerland.

AUTHOR CONTRIBUTIONS

FS: Conceptualization, Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing–original draft, Writing–review and editing. MR: Conceptualization, Resources, Writing–review and editing. MR: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Supervision, Writing–review and editing. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2024.1607349/full#supplementary-material

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REVIEW
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Understanding the Risk Factors, Burden, and Interventions for Chronic Respiratory Diseases in Low- and Middle-Income Countries: A Scoping Review

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Objective: This scoping review aims to identify risk factors for COPD and asthma, examine the burden and intervention measures, and clarify the findings in the context of climate change, with a particular focus on LMICs.

Methods: Following the PRISMA-ScR guidelines, we conducted a scoping review using PubMed, Embase, and Scopus, focusing on studies published from 2011 to 2024.

Results: Our review included 52 studies that encompassed 244,004 participants. Predominantly conducted in SSA (n = 43, 83%) and Asia (n = 16, 31%), they address indoor and ambient air pollution, occupational hazards, and environmental conditions. Climate change exacerbates risks, varying regionally. SSA faces severe household and occupational exposures, while other LMICs deal with industrial and urban pollution. Stigma, social exclusion and economic burden underscore the necessity for intervention strategies (e.g., educational programs, pulmonary rehabilitation, low-emission cookstoves).

Abbreviations: CAPTURE, COPD Assessment in Primary Care to Identify Undiagnosed Respiratory Disease and Exacerbation Risk; COLA-6, COPD in LMICs Assessment; COPD, Chronic obstructive pulmonary disease; CRD, Chronic Respiratory Disease; ECRHS, European Community Respiratory Health Survey; FEV1, Forced Expiratory Volume in 1 s; FVC, Forced Vital Capacity; GARD, Global Alliance Against Chronic Respiratory Diseases; HIV, Human Immunodeficiency Virus; ISAAC, International Study of Asthma and Allergies in Childhood; LAMAs, Long-acting muscarinic antagonists; LFQ, Lung Function Questionnaire; LMICs, Low-and middle-income countries; MCID, Minimum Clinically Important Difference; MRC, Medical Research Council; NCD, Non-communicable disease; PEFR, Peak Expiratory Flow Rate; PEO, Population-Exposure-Outcome; PM, Particulate Matter; PRISMA-ScR, Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews; RCT, Randomized Control Trial; SpCO, Carboxyhemoglobin saturation; SSA, Sub-Saharan Africa; WHO, World Health Organization; WMO, World Meteorological Organization.

Conclusion: Our research shows a strong link between air pollution, occupational and environmental exposures, and the prevalence of COPD and asthma in LMICs. It suggests that targeted interventions are effective ways to mitigate these diseases and also highlights the significant impact of climate change on respiratory health.

Keywords: COPD, asthma, low-and middle-income countries, sub-Saharan Africa, climate change

INTRODUCTION

Chronic respiratory diseases like chronic obstructive pulmonary disease (COPD) and asthma have a significant impact on low- and middle-income countries (LMICs) due to environmental and socio-economic factors. Globally, COPD affects 4.1% of the population, while asthma affects 3.7% [1]. Asthma is characterized by chronic lower respiratory inflammation triggered by various factors like smoke, pollutants, and allergens [2], while COPD involves irreversible airway obstruction from chronic inflammation [3]. In 2019, out of the 391.9 million individuals aged 30–79 years affected by COPD worldwide, 315.5 million resided in LMICs [4]. Furthermore, LMICs account for over 80% of asthma-related deaths [3] and 90% of COPD-related deaths [5].

In LMICs, COPD accounts for approximately 1,000 disability-adjusted life years (DALYs) per 100,000 individuals [6]. In Sub-Saharan Africa (SSA), the rate is slightly lower at 715 DALYs per 100,000 individuals [7]. Furthermore, both COPD and asthma are often underserved diseases, exacerbated by the limited availability and cost-effectiveness of asthma medications and diagnostic procedures [3]. Limited access to healthcare, exposure to pollutants, and inadequate public health policies exacerbate these conditions in LMICs [3]. Asthma medications like long-acting muscarinic antagonists (LAMAs) are often scarce and costly in LMICs, impacting treatment availability [8–10]. Prioritizing preventive interventions, early diagnosis, and improving access to essential medications is crucial in reducing the burden of these diseases in LMICs [11].

In addition to the high prevalence, climate change, characterized by rising temperatures, increased heat exposure, and varying humidity levels, is emerging as a potentially under-explored risk factor that exacerbates respiratory diseases [12]. Elevated temperatures and weather variability, linked to climate change, may increase the frequency and concentration of airborne pollutants, allergens, and ozone, potentially worsening respiratory conditions [13]. Additionally, climate change-induced weather extremes may increase dust exposure [14], whereby inhaling dust particles may cause or worsen inflammation and irritation in the airways, leading to acute respiratory reactions such as bronchoconstriction, excess mucus production, and increased inflammation. Dust often contains allergens and microbes, introducing further respiratory irritants [15]. High humidity can increase airway resistance because of its high water content and raise the physiological demand for oxygen, resulting in heightened breathlessness [16]. Additionally, high humidity may promote mold growth, posing an additional risk to both healthy individuals and those with asthma and COPD who already have sensitive airways [17]. The World Meteorological Organization (WMO) predicts a 66% chance of global temperatures rising by at least 1.5° above pre-industrial levels between 2023 and 2027, potentially leading to a significant increase in the exacerbation of respiratory diseases [18]. SSA is already established as a highly vulnerable region to the impacts of climate change and extreme weather events [19, 20], experiencing the sharpest increases in temperature and changes in rainfall patterns [21].

However, research on obstructive lung diseases, notably COPD and asthma, is both limited and unevenly distributed worldwide [22]. In the literature, we identified five systematic reviews focusing on COPD in SSA [23–27], primarily examining the prevalence of the disease [23, 25–27], inadequate supply and quality of spirometry tests and equipment [23, 24, 27], risk factors [26], and the lack of non-communicable disease (NCD) healthcare plans [23, 24]. These studies primarily focused on countries such as South Africa, Nigeria, Tanzania, Malawi, Uganda, and Ethiopia, leaving many other low- and middle-income countries (LMICs) unexplored. Asthma research in SSA is scant and primarily centered on South Africa, while studies from high-income countries often lack relevance for SSA and other LMICs due to distinct population and environmental factors [26, 28, 29]. Key knowledge gaps regarding the impact of various risk factors and climate change on the health of individuals with COPD and asthma, as well as the evaluation of the effectiveness of current interventions, remain unexplored in LMICs.

To address these knowledge gaps, we conducted a scoping review and interpreted the findings in the context of climate change. This review was guided by the following research objectives:

1. To identify major risk factors of obstructive lung diseases, specifically COPD and asthma,
2. To elucidate the burden of disease of living with COPD and asthma and,
3. To determine intervention approaches and their effectiveness in managing and preventing COPD and asthma

METHODS

The scoping review adhered to the methodological framework by Arksey and O'Malley [30], refined by Levac et al. [31], following defined steps like defining research questions, selecting studies, charting data, and reporting findings in line with Preferred Reporting Items for Systematic Reviews and Meta Analyses for Scoping Reviews (PRISMA-ScR) guidelines [32].

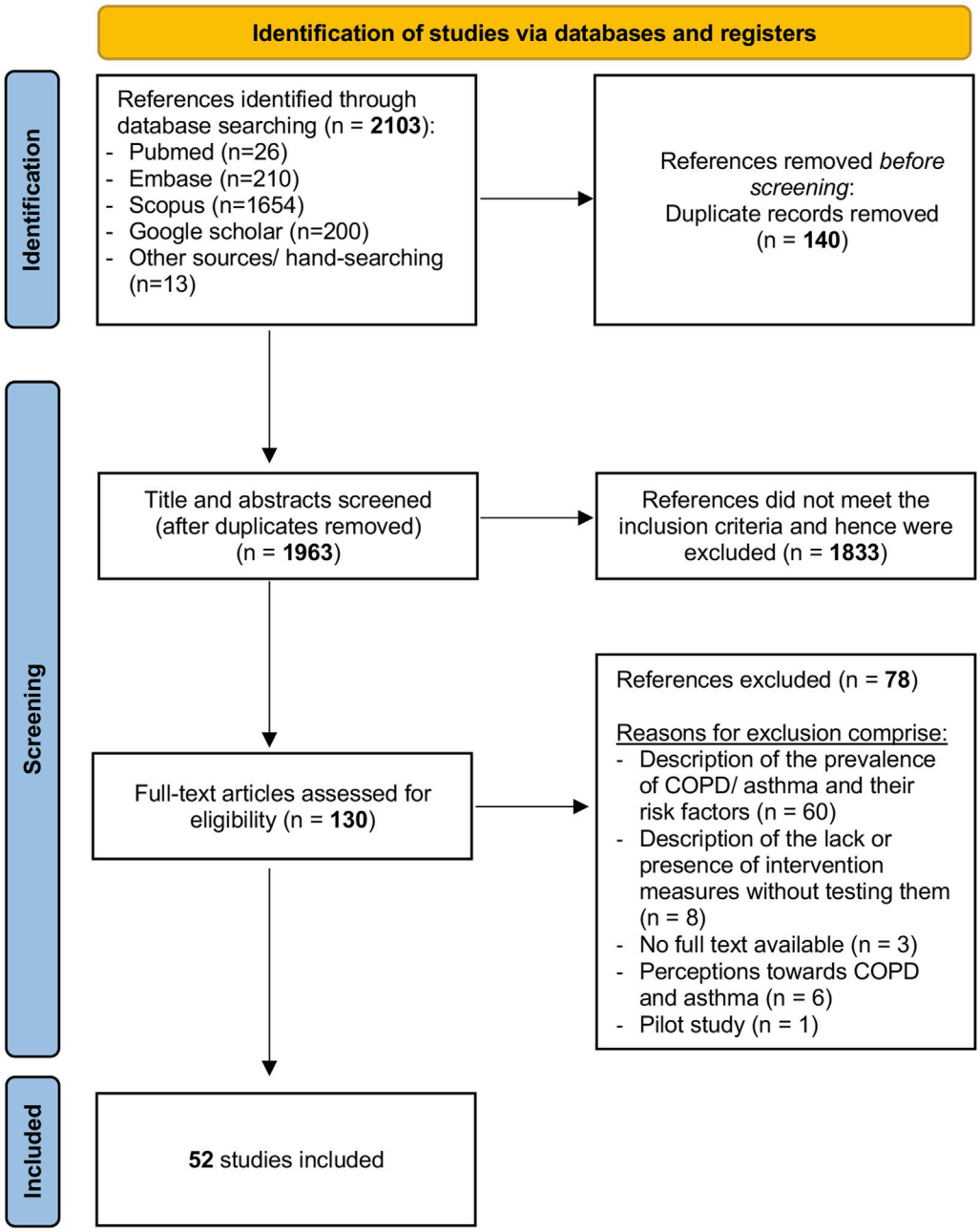

FIGURE 1 | Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews flowchart (scoping review, low- and middle-income countries, 2022–2024).

Inclusion and Exclusion Criteria

The study employed the Population-Exposure-Outcome (PEO) framework (see **Supplementary Table S1**), refining screening criteria and focusing on English primary research articles post-1st January 2011. This aligns with van Gemert et al.'s seminal work in 2011, evaluating asthma and COPD risk factors, impacts in SSA, and suggesting intervention strategies [26].

Our review encompassed studies from LMICs [33] exploring COPD and asthma as exposures, assessing risk factors, interventions for prevention and management, and challenges faced by affected individuals. Excluded were studies solely focusing on disease prevalence.

Search Strategy

We searched electronic databases, including PubMed, Embase, and Scopus. Additionally, we examined grey literature via Google Scholar, focusing on the first 200 search results. Reference lists of relevant articles were hand-searched to

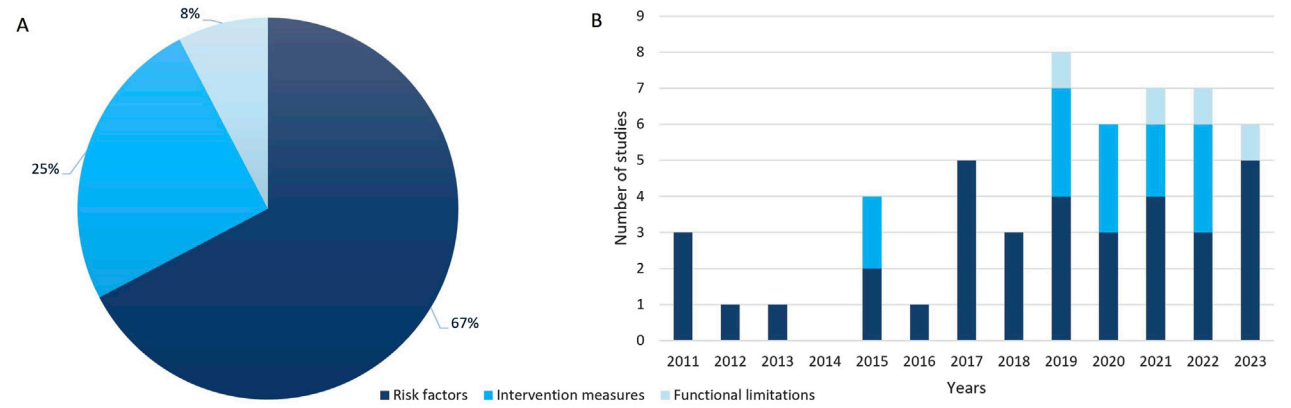

FIGURE 2 | Distribution **(A)** and trend **(B)** of publications in low- and middle-income countries from 2011 to 2023 highlighting key areas: risk factors, intervention measures and functional limitations (scoping review, low- and middle-income countries, 2022–2024).

manually identify and include relevant studies. Our search strategy incorporated index terms (e.g., MeSH, Emtree) and relevant keywords specific to the topic and context (see **Supplementary Table S2**).

Study Selection

Articles identified from the databases were imported into Rayyan software [34], which removed duplicates. Two independent reviewers (PB, NK) evaluated the studies in a two-step process, using the predefined inclusion and exclusion criteria. Initially, titles and abstracts were screened. If either reviewer deemed a study potentially relevant, a full-text review was undertaken. A study was excluded only if both reviewers agreed on its irrelevance.

Data Charting

Relevant data were extracted and organized in a Microsoft Excel spreadsheet. The charting process included parameters of title, author, publication year, country of origin, study objectives, target population, sample size (if provided), research design, analytical methods, gender distribution, age range, and primary findings.

Reporting the Results

A narrative synthesis was conducted to provide an overview of the primary emerging themes from the included studies.

RESULTS

Overview

The initial database search was conducted on August 9th, 2022, and updated on 4th January 2024. The results of the latter search are presented in the PRISMA-ScR flowchart (refer to **Figure 1**). After deduplication and incorporating 13 manually searched references from relevant studies, a total of 2,103 studies were considered. After screening titles, abstracts and full texts, n = 130 full-text articles were reviewed, of which n = 52 studies met the inclusion criteria and were subsequently included into the scoping review.

Study Characteristics

In this review, we analyzed data from a total study population of n = 244,004 participants covered in n = 52 studies (see **Supplementary Table S3**). The largest study, conducted in India in 2012, included n = 156,316 (64%) participants. From 2011 to 2022, publications on interventions for obstructive lung diseases in LMICs (see **Figure 2**) increased. Six studies (12%) were multinational in scope [35–40]. Specifically, n = 43 studies (83%) were conducted in SSA, representing n = 76,481 participants (31%), with Nigeria and Uganda contributing twelve (23%) and ten (19%) studies, respectively. The distribution of studies per country is depicted in **Figure 3**. The methodologies varied, with n = 38 (73%) being cross-sectional, n = 7 (13%) experimental longitudinal, n = 4 (8%) observational longitudinal, n = 2 (4%) randomized controlled trials, and n = 1 (2%) non-randomized controlled trials. Of the 52 studies, n = 7 (13%) exclusively involved women, n = 9 (17%) focused on children, n = 1 (2%) included both women and children, and n = 2 (4%) was focusing on men. Fourteen studies (27%) included participants diagnosed with asthma or COPD, whereas n = 38 studies (73%) focused on participants exposed to risk factors for obstructive lung diseases (**Table 1**).

Risk Factors for COPD and Asthma

Thirty-five studies (67%) [39, 41–74] reviewed the association between various risk factors and the incidence or severity of obstructive lung diseases, respiratory symptoms, and spirometry outcomes (see **Figure 4**). Disease status was determined using self-reports, hospital records, or spirometry results. Questionnaires were utilized to collect data on respiratory symptoms, and spirometry tests (see **Supplementary Table S4**) were used to measure lung function.

The questionnaires, designed to capture respiratory symptoms such as cough, sputum production, wheezing, and shortness of

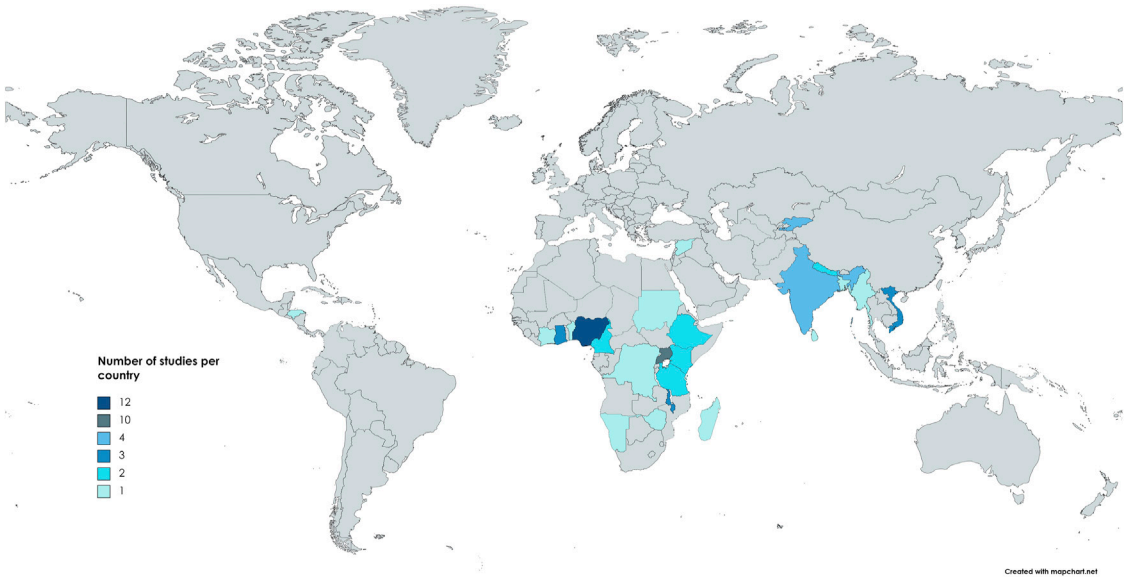

FIGURE 3 | Distribution of included studies per country (scoping review, low- and middle-income countries, 2022–2024).

breath, were either developed by the researchers or adapted from established, validated instruments. These instruments include The Bold Core questionnaire, the Medical Research Council (MRC) questionnaire on respiratory symptoms, the Global Alliance Against Chronic Respiratory Diseases (GARD) World Health Organization (WHO) survey, the International Study of Asthma and Allergies in Childhood (ISAAC) questionnaire, and the European Community Respiratory Health Survey (ECRHS) questionnaire.

Indoor Air Quality Degradation

Eighteen (35%) studies [39, 41, 44, 47, 48, 50, 51, 52, 54, 57, 58, 59, 60, 61, 62, 63, 72, 74] explored the link between Indoor Air Quality degradation and lung diseases, respiratory symptoms, lung function tests, and disease severity (see **Supplementary Table S5**).

Outdoor Air Quality Degradation

Six (12%) studies [47, 51, 52, 56, 57, 73] assessed the relationship between outdoor air quality degradation and respiratory symptoms, as well as lung function outcomes (see **Supplementary Table S6**).

Occupational Exposures

Eleven (21%) studies [42, 43, 45, 46, 47, 64, 67, 68, 69, 70, 71] investigated the connection between occupational exposure and respiratory health outcomes (see **Supplementary Table S7**).

Environmental Exposures

Weather data was obtained through direct measurement, sourced from meteorological agencies, or inferred based on seasonal patterns (see **Supplementary Table S8**). Seven (13%) studies [46, 49, 53–55, 65, 66] investigated the relationship between environmental exposures and respiratory diseases (see **Supplementary Table S9**).

Burden of Living With an Obstructive Lung Disease in Low-Resource Countries

Four (8%) studies [35, 40, 75, 76] estimated the personal and socioeconomic burden of living with an obstructive lung disease in low-resource settings. In a cross-sectional study conducted by Zoller et al. in Tanzania from 2015 to 2016, it was found that non-smokers refrained from taking a job due to shortness of breath. This condition was linked to high carboxyhemoglobin (SpCO) levels, living in rural areas, and the use of wood for cooking on open fires [75]. Brakema et al. found that asthma and COPD patients across Uganda, Vietnam, and Kyrgyzstan experienced low work absenteeism but significant activity impairment at work due to breathlessness, smoking, and solid fuel use [35]. In a qualitative study conducted by Tamire et al. in Addis Ababa, Ethiopia, it was found that COPD patients suffered from work impairment, decreased productivity, and limitations in physical activities due to their respiratory symptoms [35, 76]. These symptoms extended to financial, psychological, and social challenges, such as medication affordability issues, stress, helplessness, and reduced participation in social and religious events [76]. Similarly, Egere et al. explored challenges faced by chronic respiratory disease (CRD) patients - including asthma, COPD, occupational lung diseases, pulmonary hypertension, and cystic fibrosis - in Sudan and Tanzania. CRD resulted in reduced work capacity, economic hardship, and additional social and psychological burdens, including challenges in

TABLE 1 | Overview of study characteristics of included studies (scoping review, low- and middle-income countries, 2022–2024).

Studies (n = 52, of which 6 multinational)				
Countries			**Participants**	
	n	**%**	**n**	**%**
Total	**61**	**100**	**244,004**	**100**
Sub-Saharan Africa	43	70.5	76,481	31.3
Nigeria	12	19.7	9,268	3.8
Uganda	10	16.4	19,905	8.2
Ghana	3	4.9	21,237	8.7
Malawi	3	4.9	2,256	0.9
Cameroon	2	3.3	4,646	1.9
Ethiopia	2	3.3	557	0.2
Tanzania	2	3.3	815	0.3
Kenya	2	3.3	2,398	1
Benin	1	1.6	13,589	5.6
Ivory Coast	1	1.6	104	<0.1
Namibia	1	1.6	107	<0.1
Sudan	1	1.6	5	<0.1
Democratic Republic of the Congo	1	1.6	247	0.1
Madagascar	1	1.6	661	0.3
Zimbabwe	1	1.6	686	0.3
Central America				
Honduras	1	1.6	137	<0.1
Asia	16	26.2	166,598	68.3
Kyrgyzstan	4	6.6	1,332	0.5
India	4	6.6	156,823	64.3
Vietnam	3	4.9	1,080	0.4
Nepal	2	3.3	3,620	1.4
Bangladesh	1	1.6	3,496	1.5
Myanmar	1	1.6	207	<0.1
Sri Lanka	1	1.6	40	<0.1
Middle East				
Syria	1	1.6	788	0.3
Study design			**Participants**	
Total	**n**	**%**	**n**	**%**
Cross-sectional	38	73	233,808	96
Longitudinal interventional	7	13	3,259	1.3
Longitudinal observational	4	8	6,699	2.7
Randomized controlled trial	2	4	198	<0.1
Non-randomized controlled trial	1	2	40	<0.1

education expenses and caregiving for older relatives [40]. Healthcare-related costs, such as diagnostic tests and transportation, further burdened participants. Routine personal and community activities were severely impacted, leading to feelings of exclusion. Additionally, CRD patients faced stigmatization, often being wrongly associated with human immunodeficiency virus (HIV) or tuberculosis due to chronic cough, resulting in community isolation, limitations in sexual activities, and challenges in marital pursuits [40].

Intervention Measures

Thirteen (25%) studies [36–38, 77–86] assessed various COPD and asthma intervention measures in low-resource settings, focusing on knowledge of the diseases and their risk factors, disease screening and control, treatment adherence, behavioral changes, and the use of improved indoor cookstoves (see **Table 2**).

Knowledge Transmission

Four (8%) studies [36, 77, 78, 80] investigated educational interventions to enhance awareness of obstructive lung diseases and risk factors using tools like posters, flip charts, brochures, and local radio broadcasts (see **Supplementary Table S10**). In Uganda, a successful train-the-trainer program improved healthcare and community health workers' understanding of tobacco and biomass smoke's impact on lung health, resulting in increased questionnaire scores. This knowledge was effectively communicated to villagers, particularly regarding the dangers of tobacco smoke [77]. The program, adapted for Kyrgyzstan and Vietnam, led to a significant increase in correct responses on knowledge questionnaires, indicating sustained behavioral changes such as greater acceptance and proper use of lower-emission cookstoves [78]. Robertson et al. observed improved COPD knowledge in Nepal, Peru, and Uganda after distributing a COPD-specific educational package by community health workers [36]. Furthermore, educational sessions conducted by midwives in Uganda not only increased pregnant women's knowledge about biomass smoke as an asthma risk factor by 45% but also motivated them to switch to safer fuel types and enhance kitchen ventilation [80].

Approaches to disease Management and Policy Interventions

Five (10%) studies [38, 79, 81, 82, 86] focused on interventions that improved COPD screening, asthma management, new respiratory health policy implementation and, rehabilitation and treatment of COPD in LMICs (see **Supplementary Table S11**).

COPD Screening

In these settings, three screening questionnaires - the COPD Assessment in Primary Care to Identify Undiagnosed Respiratory Disease and Exacerbation Risk (CAPTURE), the Lung Function Questionnaire (LFQ), and the COPD in LMICs Assessment (COLA-6) - were evaluated for their efficacy in identifying individuals diagnosed with COPD who would benefit from further spirometry testing [38]. The study found that participants diagnosed with COPD often had severe obstruction and were mostly unaware of their condition, despite experiencing a low quality of life. Those with false-positive results typically had a history of asthma or chronic bronchitis and were currently exposed to biomass smoke [38].

Asthma Management

In a randomized control trial (RCT), non-physicians delivered an enhanced asthma care package, including clinical assessment, optimized inhaled treatments, and customized asthma education, while the control group received standard physician care [81]. The intervention group showed fewer school absences, reduced emergency visits, and improved asthma control and medication adherence [81]. Another RCT assessed a pharmacist-led asthma education intervention [82], delivering information on triggers, control methods, and inhalers through clinic visits, mobile phone

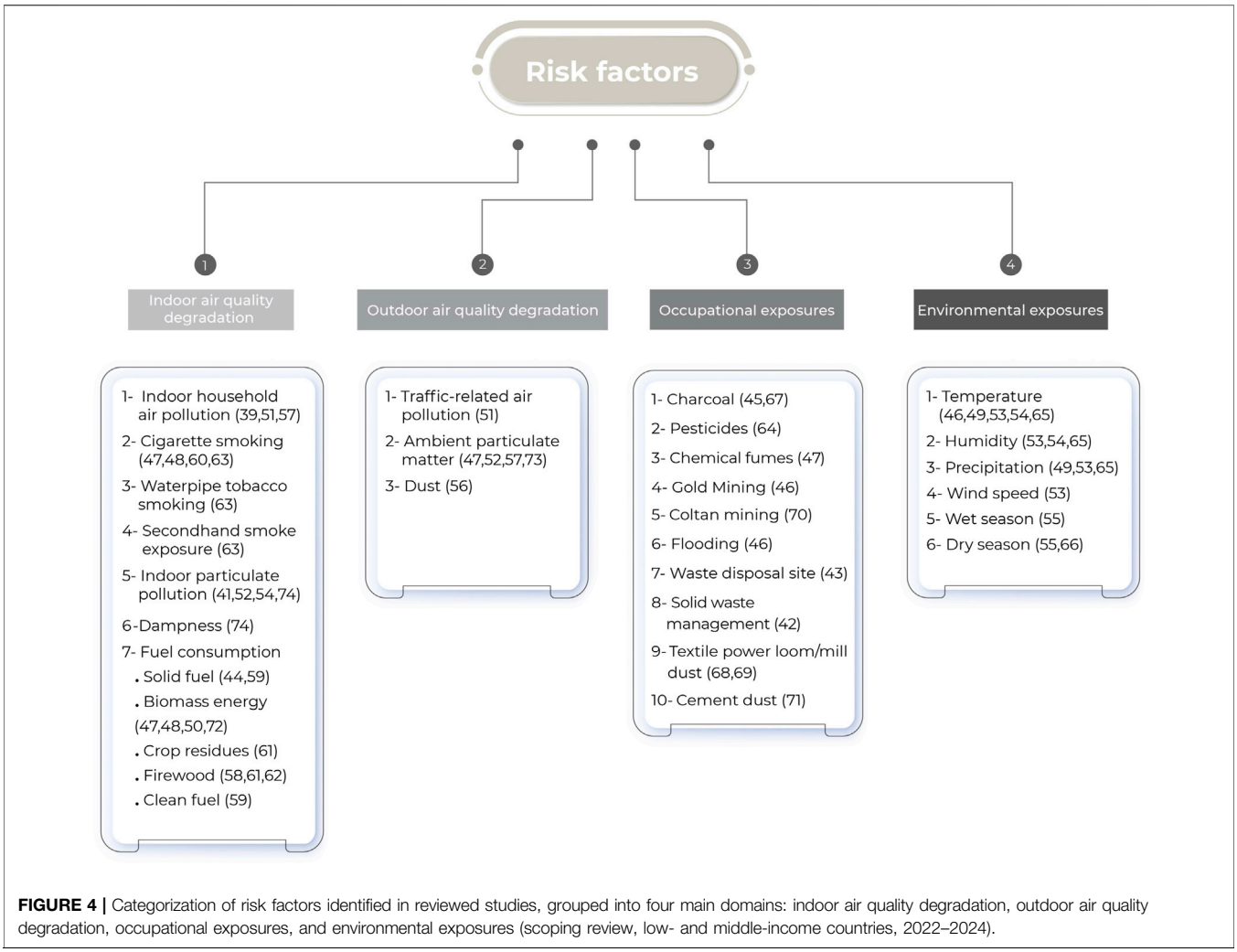

FIGURE 4 | Categorization of risk factors identified in reviewed studies, grouped into four main domains: indoor air quality degradation, outdoor air quality degradation, occupational exposures, and environmental exposures (scoping review, low- and middle-income countries, 2022–2024).

calls, and texts, compared to standard hospital care for the control group. The intervention resulted in improved asthma control and medication adherence [82].

Educational and Policy Interventions on Respiratory Health

Cartwright et al. evaluated the long-term effects of educational sessions on biomass smoke, initially investigated by Nantanda et al. [80], which were conducted by midwives for pregnant women and mothers [79]. The study observed that participants made modifications in their cooking areas, enhanced kitchen ventilation, and reduced children's proximity to smoke while cooking [79]. Furthermore, a reduction in expenses for wood and medical care associated with smoke exposure was also noted [79].

Rehabilitation and Treatments in Low-Resource Settings

In Sri Lanka, a non-randomized controlled trial adapted the University Hospital of Leicester's pulmonary rehabilitation protocol for COPD individuals in low-resource settings. The 6-week program included supervised and home-based exercises such as walking, stretching and strength training using simple equipment like water-filled bottles. Significant improvements were noted in respiratory symptoms, dyspnea, and exercise performance, with the intervention group surpassing the Minimum Clinically Important Difference (MCID) [86].

Low Emission Cookstoves

Four (8%) studies [37, 83–85] investigated the impact of introducing low-emission cookstoves indoors (see **Supplementary Table S12**). These stoves, utilizing cleaner fuels or enhancements like chimneys, combustion chambers and solar-powered stove-fan batteries led to reduced indoor particulate matter (PM2.5) [37, 85] and decreased self-reported respiratory symptoms [37, 84]. However, one study observed no change in cough or clinic visits after adoption [83]. Another study reported an increase in respiratory symptoms, attributed to altered reporting methods rather than a true increase [85]. Spirometry tests demonstrated improved lung function in Honduras and Kenya [83, 84], but no significant changes were noted in Malawi [85]. Improved cookstoves were well-received in rural communities across Uganda, Vietnam, and Kyrgyzstan [37], providing additional benefits such as reduced fuel costs and less time spent gathering firewood [84].

TABLE 2 | Intervention measures for chronic obstructive pulmonary disease and asthma in low-resource contexts based on included studies (scoping review, low- and middle-income countries, 2022–2024).

	Interventions	Outcomes	Study
Knowledge transmission	- COPD-specific education package [36]	- Increased knowledge about COPD: risk factors, management, prevention, etc.	[36]
	- A train-the-trainer lung health educational program [77]	- Improved knowledge about tobacco and biomass smoke	[77]
	- A train-the-trainer lung health educational program [78]	- Improved knowledge about tobacco and biomass smoke - Higher acceptability and adequate use of improved single and multiple pot stoves instead of open fire	[78]
	- Health education sessions on biomass smoke [80]	- Improved knowledge about tobacco and biomass smoke - Higher motivation for behavioral changes: reducing smoke emissions by using dry wood and improving kitchen ventilation	[80]
Disease and policy interventions	- COPD screening questionnaires in LMIC [38]	- Possible use of COPD screening questionnaires as a primary tool prior to spirometry	[38]
	- Health education sessions on biomass smoke [79]	- Modifications in cooking area, kitchen ventilation, and distance of children from smoke - Reduced expenditure on firewood and medical care related to smoke exposure	[79]
	- Enhanced asthma care package [81]	- Improved asthma management and adherence to medication - Decline in school absenteeism and emergency medical visits	[81]
	- Pharmacist-led asthma education [82]	- Improved asthma management and adherence to medication	[82]
	- Pulmonary rehabilitation sessions [86]	- Improved respiratory symptoms and exercise capacity	[86]
Improved cookstoves	- Implemented stoves using cleaner fuels and equipped with either chimneys, a combustion chamber, or a solar panel to charge the stove-fan battery [37, 83–85]	- High acceptance of the new cookstoves - Decreased self-reported respiratory symptoms - Decreased particulate matter concentration and air quality indoors	[37]
		- Unchanged self-reported respiratory symptoms - Improved spirometry test results	[83]
		- Decreased self-reported respiratory symptoms - Unchanged particulate matter concentration and air quality indoors - Improved spirometry test results - Reduced expenditure on additional fuel and decreased time spent collecting firewood	[84]
		- Increased self-reported respiratory symptoms - Decreased particulate matter concentration and air quality indoors - Unchanged spirometry test results	[85]

DISCUSSION

This review examines COPD and asthma in SSA and other LMICs, with a particular focus on the impact of climate change. It highlights key risk factors such as indoor and ambient air pollution, occupational hazards, and environmental allergens, impacting disease severity and exacerbations. Individuals with these conditions face multifaceted challenges including reduced work capacity, limited access to healthcare, social stigma, financial strain and psychological stress [87, 88]. Biomass fuel use for cooking exacerbates COPD in LMICs [87], particularly affecting women and children in rural areas [89]. Additionally, cultural practices such as burning incense, using kerosene lamps, and lighting mosquito coils contribute to higher levels of indoor pollution [89]. Interventions such as educational programs, non-physician-led treatments, and improved cookstove initiatives aim to mitigate indoor air pollution and improve respiratory outcomes. Aging also appears to significantly contribute to the prevalence of COPD in SSA. Between 1990 and 2019, the overall prevalence of COPD cases in SSA increased by 117%. However, during the same period, the age-standardized COPD prevalence rate declined by 3.3% [7]. The decline in the age-standardized COPD prevalence rate in SSA, amidst an overall case increase, might result from improved healthcare, public health policies, and a younger population.

Greenhouse gas concentrations have increased rapidly since 1850, in parallel with a 1.1°C increase in global surface temperature by 2011–2020 compared to 1850–1900 [90]. The

regions that have generally contributed the least to CO2 emissions and climate change are considered to be the most vulnerable [91] and are mainly located in East, Central and West Africa, with some other regions in South Asia and Central and South America [90]. Climate change can have direct and indirect effects on health; for example, exposure to extreme heat can have indirect effects through increased transmission of food- and waterborne diseases, and direct effects through dehydration, heat stroke, and increased hospitalization and mortality from respiratory and cardiovascular diseases [92].

Although no study in the literature has explicitly examined the relationship between climate change and chronic respiratory diseases in SSA and other LMICs, it can be argued that some of the risk factors exacerbating COPD and asthma developed in this review may serve as mediators between climate change and chronic respiratory diseases. Thus, a hypothesized link between both entities in SSA and other LMICs can be deduced.

Weather variables like temperature, humidity, and precipitation play a significant role in obstructive lung diseases. Studies exhibit inconsistent outcomes, potentially attributable to climate variations or differing methodologies and settings; for example, a study conducted in Sudan's dry Savanna region revealed an inverse correlation between temperature and asthma severity [53]. This contrasts with the common understanding that high temperatures worsen respiratory conditions [93]. The wet season with low temperatures and high humidity has been associated with increased asthma cases owing to a greater prevalence of viral infections and indoor triggers [54], which is consistent with previous research, highlighting the role of humidity and the presence of allergens and pollutants in indoor environments [94]. The combination of low temperature and humidity can cause bronchoconstriction, underscoring the importance of maintaining suitable indoor climates [95]. High humidity can exacerbate asthma by releasing allergens, highlighting the importance of indoor air quality management [95]. Although wind can increase long-range transport of pollen and pollutants [96], increased outdoor wind speed can help disperse pollutants, potentially providing protective benefits that require further investigation [95]. Human-induced climate change associated with increased greenhouse gas emissions affects weather variables, leading to heat waves, heavy precipitation and droughts in some regions [90]. Climate change may therefore have direct and indirect effects on respiratory health [97]. The included studies in this review however focused on variations of climate factors rather than extreme weather events caused by climate change. Further investigation should therefore be implemented, particularly in highly affected areas such as SSA, to study the complex relationship between climate change and chronic respiratory diseases.

In this review, other risk factors listed in **Figure 4** have been shown to be associated with reduced lung function.

Ambient air pollution, divided into gaseous and particulate matter (PM) pollutants, affects both indoor and outdoor air quality. Gaseous pollutants include nitrogen dioxide (NO2), sulfur dioxide (SO2), ozone (O3), carbon monoxide (CO), carbon dioxide (CO2), and volatile organic compounds (VOCs). PM pollutants, on the other hand, are classified by size and are formed from gases such as nitrogen oxides, ammonia, SO2, and VOCs [97]. In this review, studies have shown that indoor biomass and coal burning for cooking and heating in SSA and other LMICs has led to an increase in indoor gaseous and PM pollutants, and therefore to a degradation of indoor air quality. Exposure to dust and traffic-related air pollution has led to an increase in outdoor PM pollutants, resulting in poor outdoor air quality. PM pollutants have been shown to vary seasonally, with higher levels in winter due to increased dust particles and biomass burning [97]. Specifically, in SSA, excessive heat and heavy rainfall during the rainy season make outdoor cooking impractical, leading people to burn biomass indoors more frequently, resulting in poorer indoor air quality. In addition, future intense heat waves caused by climate change will lead to more wildfires, which will increase particulate matter and harmful greenhouse gases and lead to deterioration of outdoor air quality [98]. Dry and hot conditions and reduced precipitation can also lead to increased air pollution, especially ozone [97, 98], due to increased photochemical production [98]. Climate change and air pollution have also been shown to be interrelated, as PM pollutants and greenhouse gases are often co-emitted [99]; burning fossil fuels not only increases air pollution but also produces greenhouse gases, which in turn lead to extreme weather events such as droughts, heat waves and floods, which can further affect respiratory health [97]. Charcoal production and climate change are also linked through a feedback loop rather than a direct cause and effect relationship. The process of charcoal production involves deforestation and the release of greenhouse gases such as CO2 and methane, which in turn contribute to global warming [100]. In some regions affected by climate change, particularly drought, farmers may be more likely to engage in charcoal production during the dry season. In Tanzania, farmers rely on charcoal production as an alternative source of income after crop failure during the dry season [101]. This cyclical relationship will lead to poorer respiratory health. Pesticide use and climate change have also been shown to be interconnected. Rising temperatures allow for severe pest outbreaks because such conditions allow pests to survive in regions where they were previously unable to thrive [102]. In addition, the lengthening of the growing season due to higher temperatures exposes plants to pests for longer periods of time [103]. This leads to increased use of pesticides to control pest infestations. Pesticides, in turn, contribute to CO2 emissions and can disrupt soil health by killing microorganisms that play a beneficial role in carbon sequestration [104], resulting in the release of more CO2 into the atmosphere and exacerbating climate change.

Implementing cookstoves that use cleaner fuels and are equipped with a solar panel to charge the stove-fan battery [85] is an effective way that allows individuals to cook indoors during extreme heat and heavy rainfall while maintaining a good indoor air quality and generating less CO2 emissions. On the other hand, cookstoves with chimneys or a combustion chamber may reduce indoor air pollution but will still contribute to greenhouse gas emissions [83, 84]. In addition, the introduction of educational programs to increase knowledge

about biomass smoke [77, 78, 80] can play a key role in reducing the burning of indoor biomass fuel but does not offer an established long-term alternative that can be afforded by the general population. These solutions can then be considered as important intermediate steps in LMICs, where resources are scarce and the use of clean energy and electric stoves is not always feasible.

Sustainable agricultural practices and predominantly plant-based diets decrease emission of greenhouse gases [98]. Adopting diets rich in antioxidants and vitamins, characteristic of Mediterranean or "prudent" diets, can significantly improve pulmonary function and reduce asthma and COPD risks [105–108]. However, over two million people suffer micronutrient deficiencies [109], especially in SSA [110]. Educational initiatives in LMICs promoting healthy diets typically utilize printed and digital materials, often based on behavior change models, and aim to engage both women and men, reflecting their distinct roles in food preparation and decision-making [111–113]. Climate change is likely to exacerbate nutrient deficiency in LMICs by affecting food security, namely accessibility, availability and food stability [114, 115]. However, other key factors contribute to food insecurity in LMICs, including limited access to modern agricultural technologies, reliance on subsistence farming, and political and economic instability in conflict zones, which disrupt agricultural production and reduce access to food [116].

It is evident that climate change plays a pivotal role in the prevalence of chronic respiratory diseases in SSA and other LMICs. This impact can be achieved directly or indirectly through various mediators, including indoor and outdoor air pollution, charcoal production, pesticide use, and nutrient deficiency. However, additional factors unique to SSA contribute to the heightened burden of chronic respiratory diseases and impede their prevention.

In certain regions in SSA where targeted asthma management protocols are lacking, managing risk factors and promoting lifestyle changes are prioritized [117]. The shortage of trained medical professionals, particularly in remote areas, poses a challenge for diagnosing and managing obstructive lung diseases. Community-based screening, technology utilization, and awareness initiatives are crucial for enhancing primary healthcare [89]. Spirometry plays a vital role in diagnosing obstructive lung diseases, but inconsistencies in diagnosis can arise from varying cutoff measures [7]. In countries like South Africa and Nigeria, spirometry use is largely confined to specialized hospitals and research settings, despite being recommended for asthma diagnosis. In Tanzania, asthma diagnosis relies mainly on clinical history and findings, while Zimbabwe lacks specific asthma diagnostic guidelines [117]. Challenges in asthma diagnosis encompass not only spirometry availability and clinician training but also equipment maintenance, electricity access, technical support, and the use of outdated equipment, necessitating comprehensive training and guidelines for healthcare workers [89, 118]. Implementing tailored pulmonary rehabilitation programs and national strategies can alleviate the burden of lung diseases in low-resource settings [89, 118, 119], although challenges like infrastructure limitations, budget constraints, political instability and healthcare workforce shortages persist in implementing WHO's NCD management framework [11, 120].

Enhanced research, screening, and interventions are crucial for obstructive respiratory diseases in LMICs, especially in SSA, where the need is intensified by the disproportionate impact of climate change-induced global warming [119].

Limitations

In our review, we focused exclusively on studies from LMIC contexts, a deliberate choice that, while limiting comparative insights from high-resource settings, was aimed at a specific analysis. The included studies varied in their definitions of certain risk factors and were influenced by multiple confounders, necessitating cautious interpretation of direct comparisons. Additionally, we omitted studies that described but did not empirically test intervention measures, which could have offered a wider view on potential intervention strategies despite their lack of practical outcome data.

Conclusion

This review examines the impact of different risk factors on the health of individuals with COPD and asthma in LMICs. Climate change plays an indirect but pivotal role in the exacerbation of the burden of chronic respiratory diseases by impacting some risk factors specific to SSA and other LMICs.

This research highlights the need for comprehensive strategies that encompass educational programs, low-emission cookstoves and the implementation of targeted healthcare policy to mitigate the effects of climate change on respiratory health. Furthermore, it emphasizes the urgent necessity for further interventions that are tailored to the specific environmental and socio-economic context. In order to address these challenges, it is essential that there is urgent global collaboration and investment in research and infrastructure with the aim of improving public health resilience against climate-related exacerbations of respiratory conditions in LMICs.

AUTHOR CONTRIBUTIONS

The research question was formulated by PB and SB; title, abstract, full-text screening, and data extraction were performed by PB and NK; PB wrote the manuscript draft with significant contributions from all authors in editing and revisions. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/phrs.2024.1607339/full#supplementary-material

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The Urgency of Climate-Resilient Health Systems in Pakistan: Lessons From the 2022 Floods

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The catastrophic floods that struck Pakistan in 2022 brought unprecedented devastation, revealing deep vulnerabilities in the country's infrastructure and public health systems. As the waters receded, the full extent of the disaster became clear: 1700 people died, and one in seven Pakistanis, or around 33 million people, were directly impacted, including 8 million who were displaced from their homes [1]. Given the probability of future floods of similar severity [2], urgent action is necessary to ensure that Pakistan doesn't experience the same disastrous consequences again. In this commentary, we review the impact of the 2022 floods and outline the importance of sustained investment in climate-responsive health systems in Pakistan and across East Asia.

Between June and October 2022, Pakistan experienced a sequence of unusually intense monsoon rainfall. The extreme rainfall caused widespread landslides along the Indus River basin, resulting in flooding across one-third of the country [3]. Beyond the immediate impact of flooding on lives and livelihoods, the floods also had a profound impact on access to healthcare services for the most vulnerable populations—children, the elderly, and those with chronic conditions. The floods destroyed 13% of the country's medical facilities and left 15% of the population across all provinces without access to primary and secondary healthcare [1]. In addition, incident malaria increased fivefold to 2.6 million in the immediate aftermath of the floods [4]. Moreover, more than 41,000 dengue cases were reported later that year, mostly in Sindh and Balochistan, the disaster's most severely affected districts [5]. Over 5.4 million people were dependent on contaminated water from ponds and wells as a result of the floods damaging the majority of the water systems in the areas that were affected. This led to a severe cholera outbreak, with almost 2,000 confirmed cases by the end of 2022 in all four provinces of Pakistan [6].

Economically, the impact was also profound. It is estimated that floods cost the Pakistan economy $15.2 billion in economic losses [7]. The agricultural sector, which forms the backbone of Pakistan's economy, was devastated. Vast areas of farmland were submerged, leading to immediate food shortages and threatening long-term economic stability for farmers and rural communities. Malnutrition, which was already dangerously high in the country, was substantively increased. According to a survey by the UN's Children's Fund in 15 flood-affected districts released in May 2023 revealed that "one-third of children aged 6–23 months had suffered from moderate acute malnutrition, and 14% suffer from severe acute malnutrition, a life-threatening form of malnutrition [8].

Unfortunately, the initial public health response in the affected regions was undermined by logistic and administrative challenges, and health systems were quickly overwhelmed [9]. Rebuilding and reinforcing health infrastructure to be resilient against future climate shocks is imperative. Leveraging technology, like Sehat Kahani's telemedicine platform, to provide remote healthcare access in disaster-affected areas [10] or using AI-powered predictive analytics and satellite data enhance flood risk assessment and early warning systems could enable rapid response to future climate-shocks. Lessons can also be learned from other climate-affected countries, such as Sri Lanka,

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which established a Climate Change and Health Unit within the Ministry of Health in 2016. This unit is vital in coordinating national efforts to address climate-related health risks, including conducting research, collecting data, and implementing climate adaptation strategies. A similar unit in Pakistan could serve as a centralized body to lead research initiatives, monitor climate-related health trends, and coordinate national adaptation strategies.

Given the limited domestic funding available for climate-related health adaptations and the burden of substantial sovereign debt, international donors and the private sector can play a critical role in helping governments build climate resilience. Facilitating access to climate financing mechanisms, including the World Bank's Strategic Climate Fund, could enable Pakistan to undertake large-scale adaptation and mitigation projects that could protect against future climate-related disasters. The private sector also has a vital role to play in this effort. For example, Engro Corporation, one of Pakistan's largest conglomerates, with diversified businesses spanning several key sectors, could promote renewable energy projects to reduce rural vulnerability to climate shocks; And K-Electric, Pakistan's largest providers of electricity, could support the development of climate-resilient energy grids to ensure healthcare facilities remain operational during extreme weather events.

The catastrophic floods in Pakistan in 2022 underscore the urgent need for comprehensive, coordinated policy responses that addressed both immediate relief and long-term resilience. To avoid repeating the same mistakes again, it's essential for government, donors, and international partners to work together to secure a safer, more sustainable future for Pakistan, turning this crisis into an opportunity to build back better and stronger. Bold and decisive action is needed to ensure that Pakistan could withstand future challenges and protect its people and economy from the devastating impacts of such disasters.

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Both authors were involved with conceptualization, drafting and final review of the paper. TM also undertook background literature review. All authors contributed to the article and approved the submitted version.

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The authors declare that they do not have any conflicts of interest.

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Gaps in Heat-Related Knowledge, Practices and Adaptation Strategies Among Coaches in German Outdoor Sports

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Objectives: Climate change is increasing the risk of heat-related illness in outdoor sports. Coaches have a responsibility to protect the athletes in their care. In this study, the knowledge and practice of German coaches in heat prevention were evaluated nationwide.

Methods: Coaches (n = 1,200) from the ten largest outdoor sports in Germany were asked about their knowledge using the knowledge of heat-related illness symptoms index (KOSI, range [0–14]). Prevention measures currently implemented by coaches were analyzed in terms of relative compliance with specified recommendations (heat prevention score (HPS), range [0–100]).

Results: The KOSI averaged 10.31 ± 1.81 and pointed to clear knowledge deficits: the lowest score values were shown by coaches in skiing (9.85 ± 1.80), soccer (10.07 ± 2.33) and golf (10.09 ± 1.75; pANOVA = 0.015). Heat protection in training was also deficient: The HPS showed a mean value of 62.41 ± 14.89. The greatest deficits existed in tennis (57.71 ± 14.29), mountain sports (58.17 ± 13.08) and soccer (58.70 ± 13.86; pANOVA < 0.001). No correlation between theoretical knowledge and practical prevention was found.

Conclusion: In Germany, coaches are insufficiently prepared for the health hazards of heat. Promoting onsite educational programs seems essential to ensure safer sports environments.

Keywords: outdoor sports, coaches, health risks, heat stress disorders, heat illness

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INTRODUCTION

The significant increase in heatwaves is considered to be the most important health consequence of climate change. According to the World Health Organization (WHO), in addition to children, pregnant women and multimorbid seniors, athletes are particularly at risk in this context [1]. The reason is that in outdoor sports, unlike other risk groups, it is almost or even completely impossible to seek out air-conditioned rooms or avoid physical activity during a heatwave.

Doing sport in a hot environment is much more strenuous for the body than in cooler conditions [2]. Prolonged exposure to heat can lead to heat-related illnesses [3]. Heat-related illnesses include heat syncope, heat cramps, heat exhaustion and exertional heat stroke (EHS) [4]. Regarding EHS, a recent narrative review critizises that to date there is neither a register to record valid incidences nor

an internationally standardized definition [5]. Nevertheless, studies on long-distance road races found EHS incidences between 1.6 und 2.1 per 1,000 finishers (without mortality; 5). At least when ambient temperatures are above average (median start-time temperature 24°C/75°F), exertional heat strokes are even more common than non-heat-related cardiac events in endurance competitions [6]. Last but not least, exertional heat stroke is one of the leading causes of death among athletes [7].

Sports organizations, clubs and coaches have a responsibility to protect the athletes in their care from these risks. This applies first to competitive sports. Competitive athletes are particularly exposed to heat risks due to the long seasons, high training volumes and high competition density. However, the risks of heat-related illnesses should not be underestimated in amateur sports either due to recreational athletes generally having a less favorable fitness and acclimatization status, meaning that the risk of developing a heat-related illness ceteris paribus may even be higher compared to a competitive athlete [8]. Even with a lower training intensity, a less favorable movement economy (i.e., milliliters of oxygen per kilogram of total body mass per kilometer run) can lead to a comparatively higher heat production in this case [9]. Apart from this, the population of recreational athletes is significantly larger in number compared to competitive athletes and therefore the cumulative risk for an entire population is higher.

Following recent suggestions [10, 11], the present study examines knowledge of heat risk prevention, prevention practices, and opportunities for prevention among coaches working in German outdoor sports, as well as differences in knowledge and practices between various types of sports.

METHODS

Study Design and Setting

As part of the "C^3O study" (*C*limate *C*hange, *C*oaches and *O*utdoor Sports - *Study*) presented here for the first time, coaches were asked about prevention knowledge, practice and options for action in relation to heat stress in sport as part of a cross-sectional study. The survey was conducted nationwide and the ten largest outdoor sports associations in Germany were included. We followed the definition of Dee et al. [12], according to which it is an outdoor sport if the competitions take place outdoors. According to the official membership statistics of the umbrella organization, the German Olympic Sports Confederation (DOSB), these were the German Football Association (DFB), the German Tennis Association (DTB), the German Alpine Association (DAV), the German Athletics Association (DLV), the German Equestrian Federation (FN), the German Golf Association (DGV), the German Life Saving Association (DLRG), the German Ski Association (DSV), the German Sailing Association (DSV) and the German Cyclists' Federation (BDR). With a total membership of 14 million people, 16% of the German population are organized in these associations (as of 01/2023) [13, 14]. Examples of specific heat exposure include the German Athletics Association (DLV), which represents all athletics disciplines, the German Life Saving Association (DLRG), which is responsible for swimming training throughout Germany, and the German Sailing Association (DSV), where infrared and UV exposure is amplified by water reflection.

To reach as many coaches of these sports as possible, the national and local sports associations were contacted, numerous study calls were published online and in the printed association notices and further participants were recruited via e-mail and telephone directories of the sports associations. All participants were informed in advance via an online link about the study content and procedure. Informed consent was obtained from all individual participants included in the study. The survey took place as an asynchronous written online survey using computer aided web interview (CAWI) with the help of a standardized questionnaire using the Lime-Survey software package from May 2022 to June 2023. Before the start of the survey phase, the online questionnaire was subjected to an expert review (n = 4) and a standard pre-test (n = 8 coaches excluded from final sample). Suggestions and ideas from the expert reviews and the pretest were then incorporated into the final questionnaire (e.g., the suggestion to ask the coaches from skiing the knowledge questions, but not the questions on prevention behavior, which is irrelevant for them in practice). All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional committee (ethics committee of the Medical Faculty Mannheim of the University of Heidelberg) and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards: The STROBE Statement [15] on standardized reporting of cross-sectional studies were met. An unreservedly positive vote of the responsible ethics committee of the Medical Faculty Mannheim of the University of Heidelberg was available in advance (AZ 2021-653, 16 November 2021). The study was preregistered in the German Clinical Trials Registry on 18 January 2022 (registration number DRKS00027815; https://drks.de/search/de/trial/DRKS00027815).

Participants

In addition to being of legal age (≥18 years) and a German resident, the central inclusion criterion was a coaching activity in competitive or popular sports in one of the above-mentioned outdoor sports. The study participants were recruited by means of quota sampling, a systematic, non-probabilistic sampling procedure, according to type of sport and federal state. The minimum sample size of n = 600 originally envisaged in the study protocol was far exceeded by the actual participation (n = 1,200). Using a standard weighting procedure (so-called standard redressment on number of respondents), each of the above-mentioned outdoor sports was represented with 120 respondents (disproportionate quotas by type of sport) and the sample was representative nationwide in terms of distribution across the 16 federal states (proportional quota by federal state; for details see **Supplementary 1**, [16]).

Variables and Measurement

In addition to descriptive information (e.g., to check the inclusion criteria such as age, license level, type of sport, federal state of the

club location), the research questions were operationalized as follows in the questionnaire:

Expected impact of climate change: all coaches were first asked in general terms how likely they thought climate change would have an impact on the health of outdoor athletes within the next 10 years (in %).

Prevention knowledge (Knowledge of heat-related illness symptoms index - KOSI): Whether trainers know the typical symptoms of heat-related illnesses was recorded using a battery of items. This was developed by Smith et al. [17] based on recommendations of the National Institute for Occupational Safety and Health [18] and was kindly made available to us by the authors. This list of symptoms largely coincides with relevant reviews and expert reports [4, 19]. The question "Which of the following happens to a person who is sick from heat exposure?", ten applicable symptoms (headache, dizziness, heavy sweating, irritability, nausea and vomiting, slurred speech, seizures, confusion, fainting, very high body temperature) and four non-applicable symptoms (blisters on skin, pain while urinating, rash on hands, lower back pain) were asked. A sum index with the value range [0–14] was calculated from all correct answers. The operationalization of the KOSI together with the original questionnaire and the validation results can be found in detail as a supplement by Smith et al. [17].

Prevention practice and options for action (heat prevention score): The survey of prevention measures currently implemented by coaches when training in hot weather was based on the recommendations "Exercise in the Heat" [20] published by the German Society for Sports Medicine and Prevention (DGSP). Essentially, these ten DGSP recommendations concretize the guidelines of the German Society for General Medicine [21] and the WHO guidelines [22] for the sports context. The trainers were asked to imagine a "cloudless, sunny summer day with an outside temperature of over 30°C" (=86°F) and to indicate on a 100-point Likert scale with the poles 0 = "never" vs. 100 = "always" how often the respective measure is currently implemented in a typical training session under these conditions (prevention practice) and how easy it is or would be to implement in principle (options for action). The ten individual measures were also summarized in two sum indices (heat prevention scores HPS; range [0–100]) according to the general calculation formula:

$$HPS = (LV_{RA} + LV_{RB} + LV_{RC} + LV_{RD} + LV_{RE} + LV_{RF} + LV_{RG} + LV_{RH} + LV_{RI} + LV_{RJ})/10$$

with:

LV = Likert scale value.

$_{R(A\text{-}J)}$ = Recommendation A-J.

A = Movement of training to the morning or evening hours.

B = Reduction of exercise intensity and duration.

C = Drinking sufficient fluids before training.

D = Drinking sufficient fluids during training.

E = Drinking sufficient fluids after training.

F = Application of external cooling methods during and after training.

G = Wearing of suitable, light and airy clothing.

H = Wearing of headgear during training breaks.

I = Observation of athletes for heat symptoms during training.

J = Presence of medical personnel at organised competitions.

Bias and Quality Control

The online survey method enabled plausibility checks to be carried out during entry, for example, by blocking unauthorized values and incompletely filled out questionnaires. Multiple participations from the same IP address were also not permitted. In addition, plausibility checks were carried out in the data set after the data base lock (30 June 2023). They did not reveal any systematic anomalies. The average processing time was 24 min and over 95% of the respondents took between ten and 60 min to complete the questionnaire. The original questionnaire can be obtained from the corresponding author.

Statistical Analysis

The C^3O study was analyzed using classical descriptive and inferential methods. The metric scores were approximately normally distributed. Arithmetic mean and median were less than 0.2 standard deviations apart. Group differences were analyzed using unpaired t-tests and one-way ANOVA, bivariate correlations of the scores using Pearson's r^2. The analyses were performed using the program IBM SPSS Statistics 29.0.0 (IBM Corp., Armonk, United States). All tests were exploratory and two-sided with a significance threshold of $p \leq 0.05$.

RESULTS

The sample of coaches had an average age of 44 (±14, range [18–81]) years and was 68% male. On average, the participants could look back on 15 (±11) years of experience as trainers. The training group comprised an average of 11 (±8) people and consisted of children in 26% of the cases, adolescents in 40% and adults in 34%. Gender was missing in two cases and age was missing in three cases. All other variables had no missing values.

Overall, the trainers estimated the probability of climate change having an impact on the health of outdoor athletes at an average of 62% (±29.29). The KOSI scores, which measures knowledge of typical heat-related illness symptoms, averaged 10.31 (±1.81, range [3–14]). The least known was that symptoms such as heavy sweating, slurred articulation, seizures and irritability can be symptoms of heat-related illness. Only 61.7%, 50.3%, 39.8% and 33.4% of all trainers were aware of this in relation to the individual symptoms. There were also significant differences in heat-related health knowledge between the sports (**Figure 1**, ANOVA: F-value: 2.29, df = 9, $p = 0.015$): The least favorable values were shown by coaches in skiing and soccer, the best values by coaches in mountain sports and equestrian sports.

The coaches stated that on a cloudless summer day with temperatures above 30°C, their athletes were most likely to pay

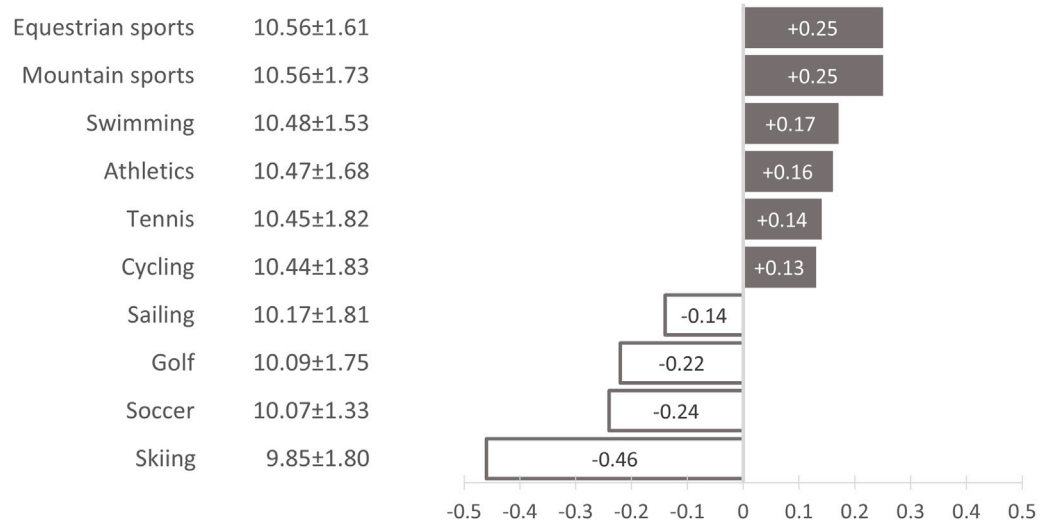

FIGURE 1 | Heat-related health knowledge in German outdoor sports by type of sport. Absolute deviation from the arithmetic mean of the knowledge of heat-related illness symptoms index (KOSI) by type of sport (arithmetic mean: 10.31 ± 1.81; ANOVA: F-value: 2.29, df = 9, $p = 0.015$); Climate Change, Coaches and Outdoor Sports – Study (C^3O study), Germany, 2022–2023. Grey = Positive deviation from the mean value. White = Negative deviation from the mean value.

attention to heat symptoms (83.31 ± 24.19), light, airy clothing (71.39 ± 28.10) and adapted training intensities (69.60 ± 28.19) (**Figure 2**). In contrast, the trainers stated that only around two-thirds of all training groups drank enough during training in accordance with the recommendations (67.38 ± 27.76). According to their reports, sufficient fluid intake before and after training was even less common (55.17 ± 30.20 and 66.19 ± 25.83). The additional question of how easy it would be to implement each individual measure during training provided an indication of the potential for improvement. **Figure 2** shows the percentage value for the possible implementation of the respective measures using the *y*-axis coordinate. The vertical lines illustrate that, in addition to wearing headgear, the provision of external per- and post-cooling measures (such as cool packs, spray bottles, ice for rubbing and moist towels) and a better supply of fluids before training have the greatest potential for improvement (**Figure 2**).

The current prevention practice (ANOVA: F-value: 10.59, df = 8, $p < 0.001$) and the possible options for action (ANOVA: F-value: 5.34, df = 8, $p < 0.001$) differed significantly between the sports. The most striking deficits in the preventive measures applied can be seen in tennis, mountain sports, soccer and swimming (**Figure 3**). If the coaches are asked about implementation possibilities, the greatest potential for improvement is also evident in these sports - except for mountain sports (with index values of 67.48 ± 14.29, 62.68 ± 14.95, 67.33 ± 17.62, and 69.10 ± 16.43; for differences see **Figure 3**).

Finally, the extent to which prevention knowledge, practice and options for action in outdoor sports correlate in the coaching staff was investigated (**Figure 4**). It was shown that the coaches' heat-specific knowledge does not appear to be reflected in their prevention behavior ($r^2 = 0.005$, n.s.).

DISCUSSION

Heat illnesses and in particular the medical emergency heat stroke are largely preventable. In organized sports, trainers are the key people for preventing such events. This applies to competitive sports as well as to amateur sports and to training with adults as well as with children and young people.

The C^3O study presented here shows clear deficits among German coaches in recognizing possible symptoms of heat illnesses. Our large, representative sample also enables the identification of sport-specific deficits: Unsurprisingly, coaches in skiing achieved the worst scores, as such phenomena are of marginal importance in alpine environments. Soccer coaches, on the other hand, were the second least knowledgeable.

With a mean score of 62 points and a maximum of 100 points, the measures currently implemented in training to protect against heat-related illnesses also showed implementation deficits and clear differences between the sports. From the coaches' point of view, improvements in tennis, swimming and soccer are particularly easy to achieve.

The final correlation analysis showed that pure education and information campaigns would not be sufficient for future adaptation strategies in sport: There was no correlation between theoretical knowledge of typical heat-related symptoms and the practical prevention of heat-related illnesses.

Limitations and Strengths of the Study

The weaknesses of this study include possible selection effects, fundamental objections to the official recommendations and limitations in transferability to other regions: Firstly, it cannot be ruled out that those trainers in particular were willing to participate who considered the topic to be more relevant and therefore also had more knowledge and a more mindful training

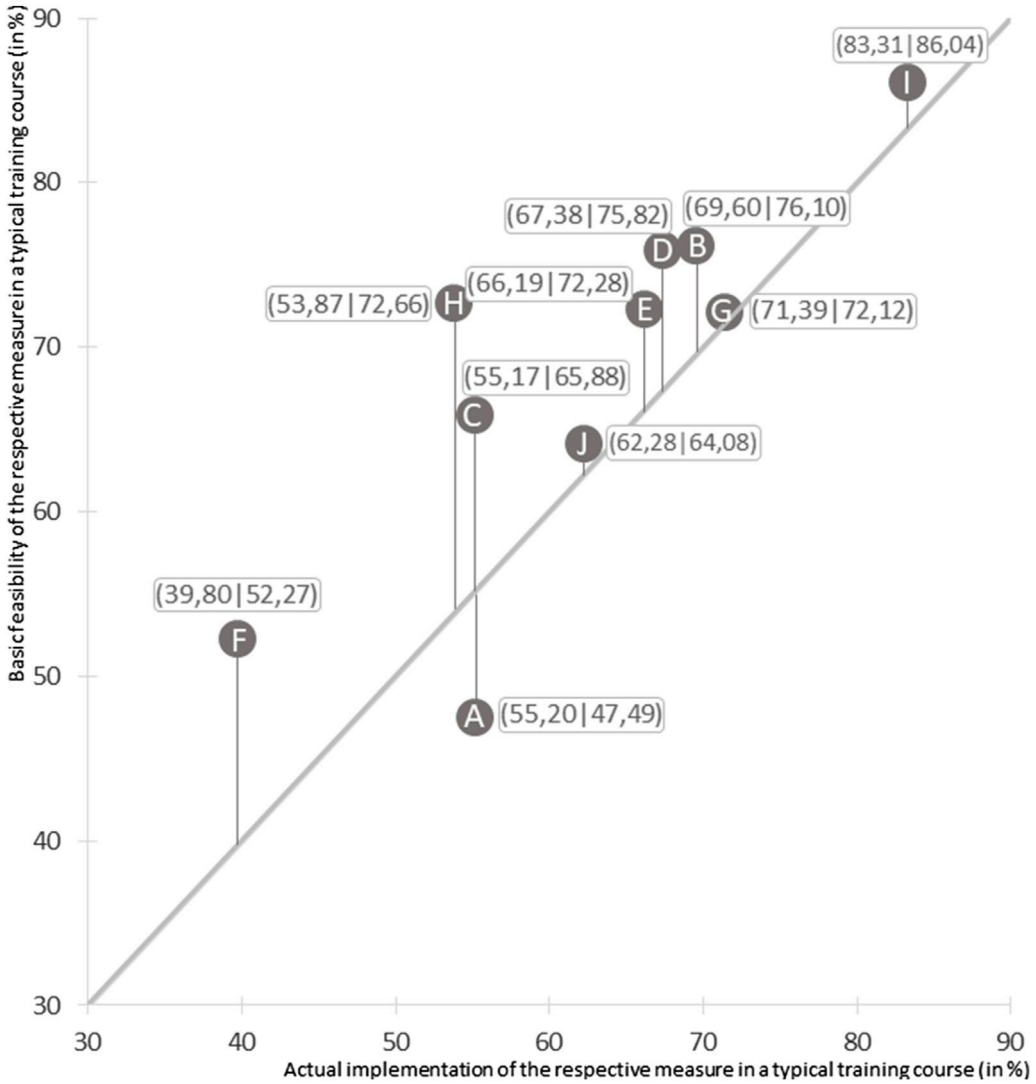

FIGURE 2 | Implemented and possible heat protection measures in German outdoor sports. Measures taken by "the majority of the training group on a cloudless, sunny summer day with an outside temperature of over 30°C" (=86°F); n = 1,080 (without the coaches in skiing). Climate Change, Coaches and Outdoor Sports – Study (C^3O study), Germany, 2022–2023. Prevention measures based on the recommendations of the German Society for Sports Medicine and Prevention: A = Movement of training to the morning or evening hours. B = Reduction of exercise intensity and duration. C = Drinking sufficient fluids before training. D = Drinking sufficient fluids during training. E = Drinking sufficient fluids after training. F = Application of external cooling methods during and after training. G = Wearing of suitable, light and airy clothing. H = Wearing of headgear during training breaks. I = Observation of athletes for heat symptoms during training. J = Presence of medical personnel at organised competitions.

practice. Secondly, isolated recommendations of the German Society for Sports Medicine and Prevention regarding heat protection should be critically examined. For example, one recommendation is to wear headgear at least during competition breaks to avoid sunstroke [20]. As long as athletes spend training and competition breaks in sufficient shade, we believe that headgear could be dispensed with so as not to hinder heat dissipation via the head during this time. A third limitation concerns the transferability of our results to other regions of the world. Comparable trainer surveys originate exclusively from the United States. In Germany, on average only 2 h of sport are taught per week in school. In addition, 49% of all German children and young people play sport in one of the 16 state sports associations in their free time [13]. Most club coaches work on a voluntary basis in a local club and usually only have a coaching license acquired on a part-time basis. For this reason, German coaches (especially in popular sports) are on average less qualified than, for example, in the United States, where sport takes place primarily in schools and usually under the direction of professionally trained coaches. These historical and political differences mean that our collective is significantly older and is active as a trainer for longer than the coaching collectives in the United States [7, 19, 23].

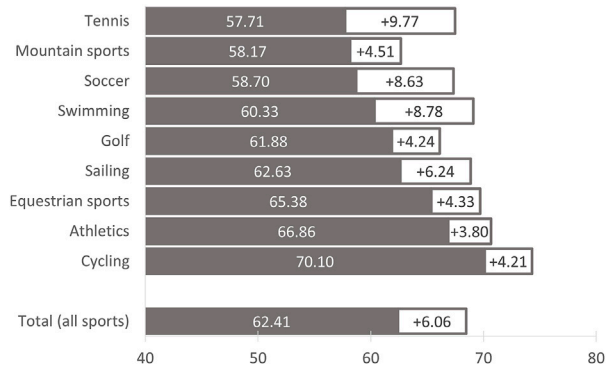

FIGURE 3 | Implementation and potential for improvement in heat protection measures in German outdoor sports by type of sport. Climate Change, Coaches and Outdoor Sports – Study (C^3O study), Germany, 2022–2023. n = 1,080 (without the coaches in skiing). Grey = Degree of implementation (%), sum index of the ten prevention measures based on the recommendations of the German Society for Sports Medicine and Prevention (for details see legend of **Figure 2** and Ref. [20]). White = Potential for improvement (%), difference between the sum index of possible heat protection measures and the sum index of measures implemented.

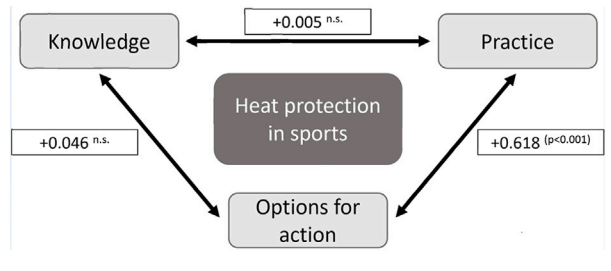

FIGURE 4 | Correlation of prevention knowledge, practice and options for action of coaches in German outdoor sports. Pearson's r^2, n = 1,080 (without the coaches in skiing). n.s. = Not significant. p = Significance level (Germany, 2022–2023).

The strengths of our study include the large sample size, its representativeness and the ability to differentiate between the most relevant sports in this context.

Relevance in the International Context

The prevention of heat-related illnesses in sport is particularly advanced in the United States [23, 24]. For example, the National Athletic Trainers' Association (NATA) has published a position statement on the prevention and treatment of external heat illnesses [25]. Their implementation has already been intensively evaluated in coaching associations [26], colleges [7, 12], middle schools [19] and high schools [12, 19, 27–29]. The clear focus was on the two most important measures for recognizing and treating the particularly dangerous heat stroke, namely, the measurement of rectal temperature, which is evidence-based on the one hand and practiced very differently among trainers on the other, and the cold-water immersion as an aggressive cooling measure, which is also controversially discussed among trainers [7, 23, 26, 29]. In addition, a task force in the USA has developed guidelines for preseason heat acclimatization for all secondary schools [30]. This includes precisely developed training plans and recommendations on clothing, such as not wearing helmets and shoulder protectors in American football during parts of the training.

In comparison, the preventive measures against heat stress published by the German Society for Sports Medicine and Prevention have a much broader approach (and have never been evaluated to date). They do not focus on diagnosis and intervention in the case of heat stroke as the heat-related illness with the highest mortality rate. Rather, they are primarily preventive, low-threshold and based on international recommendations such as postponing training [24, 31], reducing the training load [11, 24, 31], internal pre-, per- and post-cooling through specific guidelines on weight-adapted fluid intake [4, 24, 31, 32], the wearing of headgear and light, airy clothing [11, 31] as well as the use of external cooling methods [31, 32], the monitoring of heat symptoms [4, 11, 24, 31] and the presence of medical personnel during competitions [31, 32]. Most of the above-mentioned measures require little preparation in terms of time and monetary resources. Encouraging athletes to drink before, during and after training should be a training routine - not just in hot weather. Even the provision of external cooling methods can be realized with a water bucket with towels, spray bottles or reusable cool packs with little financial and time expenditure. It is therefore all the more surprising that even these simple measures are apparently not implemented in every training session and in every affected sport.

Conclusion

Our findings suggest that newly imparted knowledge (e.g., in coach training) should be flanked by structural measures on the part of the associations and clubs in order to support coaches in converting their training. There are elaborate and differentiated concepts for this in sport [31, 32]. Structural measures for heat protection include technical and constructional measures (e.g., artificial shading, installation of water dispensers) [31–33], organizational measures (e.g., rule changes, additional shade and drinking breaks, more frequent player changes, redesign of endurance competitions as night runs) [6, 31–33] and personal measures (e.g., provision of cooling vests) [31].

Studies from the USA show that heat-specific health risks are assessed very differently within the coaching community [19, 29]. In qualitative studies, some coaches expressed an attitude that no emergency had occurred to date and that there was therefore no need for precautions [34]. Such an opinion is highly sensitive, as coaches are role models and authority figures who, among other things, decide on starting places and nominations. Marshall [11] also pointed out that such an attitude on the part of the coach is particularly fatal for young athletes, as they often do not have the courage to interrupt their training - for example, during structured exercise drills - to take breaks for drinking or shade.

With regard to climate models, current forecasts assume that in around 60 years' time, the Summer Olympics will only be able to be held in 33 cities worldwide under medically acceptable temperature risks. At the beginning of the 22nd century, there will

only be four suitable cities on our planet. Considering that such forecasts relate to health risks for highly selected and more heat-resistant competitive athletes, the question arises: is the much larger amateur sports sector sufficiently prepared for future heat extremes [35]. According to the C^3O study, one possible starting point for improvements appears to be trainers as role models, authority figures, multipliers and managers.

ETHICS STATEMENT

The studies involving humans were approved by Ethics committee II of the Medical Faculty Mannheim of the Heidelberg University (AZ 2021-653, 16 November 2021). The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

Conceptualization, SS; methodology, SL and SS; resources, SS; writing—original draft preparation, SL, ZP, and SS; writing—review and editing, SL, ZP, and SS; visualization, SL and SS; translation, ZP; supervision, SS; project administration, SS; All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2024.1607928/full#supplementary-material

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The Health and Health Insurance Implications of Climate Change in Sub-Saharan Africa: A Narrative Review

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Objectives: This paper aims to provide a narrative review of the implications of climate change on health and health insurance in sub-Saharan Africa.

Methods: A comprehensive research was employed to carry out a complete narrative study on the subject. Thus, since September 2022 we searched for literature on the relationships between climate change, health, and health insurance on PubMed over an unbounded period. By updating the research method, the outputs cover the period 2009–2024.

Results: Based on 19 key articles that focused on the implications of climate change for health and health insurance in sub-Saharan Africa, we highlight that climate change directly affects population health through climate-related disease. Indirectly, climate change affects health through its disruption of food availability and agriculture and through demographic shifts.

Conclusion: Finally, this narrative review suggests appropriate strategies to combat the health consequences of climate change and to improve universal health insurance systems.

Keywords: climate change, implications, health, health insurance, review, sub-Saharan Africa

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INTRODUCTION

Climate change is currently one of the most pressing environmental concerns in sub-Saharan Africa (SSA), where profound climate-related stresses are expected in the coming years. Among these stresses and challenges are adverse health outcomes [1]. In anticipation of such negative health outcomes, countries in SSA are beginning to implement universal health insurance for the entire population. African countries already face special challenges in the field of healthcare provision, given the current "double burden" of decreasing effectiveness of tools against traditional tropical

Abbreviations: FAO, Food and Agricultural Organization; GDP, Gross domestic product; IPCC, Intergovernmental Panel on Climate Change; NCDs, Non-communicable diseases; NHI, National Health Insurance; PRISMA, Preferred Reporting Items for Reviews and Meta-Analyses; SSA, Sub-Saharan Africa; WHO, World Health Organization.

diseases and increased prevalence and incidence of noncommunicable diseases (NCDs) [2]. The development of universal health insurance systems in most African countries is one potential measure for addressing these health-system challenges. Concomitantly, global climate change, which affects various geographic regions at different levels, is also associated with a wide range of human health problems [1]. These pose a burden to health systems, with implications for access to care and emergency care service disruptions, especially in regions such as SSA [3]. Indeed, SSA has been identified by the Intergovernmental Panel on Climate Change (IPCC) as being the region most vulnerable to climate change impacts [4]. The African continent is particularly vulnerable to the effects of extreme weather events due to an already overburdened health system, a lack of early warning signs, poverty, inadequate infrastructure, and variable adaptive capacity [5]. Over the coming decades, SSA will face profound stresses and challenges from global climate change, many of which will manifest as adverse health outcomes [1]. Shezi et al. [6] highlight that vulnerable population groups in South Africa, especially people living in poverty, young children, women, the older population, and people with pre-existing diseases, are susceptible to new or exacerbated health threats resulting from climate change.

The intersection of health and climate change is often absent or under-represented in sub-national government strategies [7]. It is critical that impacts to health systems from climate change are well understood, especially in light of the plans to implement South Africa's National Health Insurance (NHI) program [8].

To this end, many challenges must be addressed in relation to an exhaustive list of health drivers related to climate change. Health has many drivers that can be classified based on demographic, socio-economic, and environmental factors. Like all environmental problems of global concern, climate change remains a reality that affects societies on a broad scale [9]. Moreover, it is widely accepted and increasingly recognized within the global scientific community that climate change is a fact and that it is having an impact on human health [10]. While climate change is adversely affecting the health of people around the world, the worst affected people are those in low-income countries [11, 12]. Wright et al. [13] highlight the risks to health due to several alterations in the climate of South Africa. These include an increase in ambient temperature, which has caused a significant rise in morbidity and mortality; heavy rainfall that has led to changes in the prevalence of vector-borne diseases; drought-associated malnutrition; and exposure to dust storms and air pollution that has led to the potential exacerbation of respiratory diseases.

Through its effects on the health of the population, climate change may also affect health insurance. Attention should therefore be focused on the role played by climate change when conceptualizing or analyzing health insurance systems across the world. Weather, climate, and climate change are affecting human health, with scientific evidence increasing substantially over the past two decades, but only very limited research has been conducted on low- and middle-income countries [14].

The specific aims of this review were to 1) search, select, appraise, and synthesize published research on the health and health insurance implications of climate change in SSA; 2) highlight the key channels or categories of the consequences of climate change for health and health insurance; and 3) make recommendations for efficient health provision for countries in SSA.

METHODS

The paper provides a review of the health and health insurance implications of climate change. This review primarily sought hard evidence of the implications of climate change on health and health insurance. Analyses of a causal effect between variables or indicators of climate change and health were not considered. We conducted our academic search on PubMed, with "climate change," "health," and "health insurance" serving as the key search terms.

RESULTS

Global Overview of the Health Impacts of Climate Change in SSA

Table 1 highlights some key examples of research focused on the implications of climate change on health and health insurance in sub-Saharan Africa. For each study, we indicate the manifestations of climate change and its potential impact pathways on health and health insurance.

The health impacts of climate change occur mainly as a result of increasing temperatures, rising sea levels, and an increased frequency of extreme weather events. These phenomena interact with demographic, socio-economic, and environmental factors, as well as access to and the quality of healthcare, to affect the magnitudes and patterns of risks [14]. We distinguished between direct and indirect climate change–induced health impacts. Direct effects can be further classified into two types of disease: 1) NCDs and 2) vector-borne diseases. Indirect effects occur via 3) water- or food-borne diseases. **Figure 1** summarizes the links between the main manifestations of climate change and the deterioration of population health. Climate change alters population health through the transmission of NDCs, vector-borne diseases, and water- or food-borne diseases. Specifically, we highlight how increased temperatures significantly contribute to the transmission of these three types of diseases. The evolution of precipitation as a possible manifestation of climate change also contributes to the spread of all three types of diseases. Moreover, sea-level rise was found to increase the transmission of vector-, water-, and food-borne diseases. The following section explains the mechanisms by which climate change causes these three main types of disease.

Mechanisms of the Health Impacts of Climate Change in SSA

Relationship Between NCDs and Climate Change in SSA

Research continues to highlight the link between climate change and health outcomes. There is, however, limited evidence of the

TABLE 1 | Some key research on climate change and its implications for health in sub-Saharan Africa (Ouagadougou, Burkina Faso. 2024).

Author and year	Region/country	Study design (data collection process)	Manifestations of climate change	Potential impact pathways of climate change on health and health insurance
Ramin et al. (2009) [1]	Sub-Saharan Africa	Five hypothetical cases	Discrete manifestations of climate change	Impacts on agriculture and food security, droughts, floods, malaria, and population displacement
Opoku et al. (2021) [3]	Six African countries (Ghana, Nigeria, South Africa, Namibia, Ethiopia, and Kenya)	Cross-sectional study	The study evaluated the levels of information, knowledge, and perceptions of public health professionals	Rise of vulnerabilities to climate change, focusing on its impacts on human health
Rother et al. (2020) [4]	Sub-Saharan Africa	Review	Increase in extreme weather events, such as storms, floods, droughts, heat waves, wildfires, and landslides	Mental health of children and adolescents
Theron et al. (2022) [5]	Africa	Scoping review	Climate change's global public health emergency	Implications for access to care and emergency care service disruptions
Shezi et al. (2019) [6]	South Africa	Cross-sectional survey	Not specified (climate change–related knowledge, practices, and perceptions)	Vulnerable population groups, especially people living in poverty, young children, women, the older population, and people with pre-existing diseases
Godsmark et al. (2019) [7]	Western Cape province of South Africa	Methodological framework	Local climatic projections (warmer and potentially drier future with increased frequency and intensity of extreme weather events)	Mental health, noncommunicable diseases, injuries, poisonings (e.g., pesticides), food and nutrition insecurity–related diseases, water- and food-borne diseases, and reproductive health
Dos Santos et al. (2022) [8]	South Africa	20 key expert interviews	Not specified	Previously poor communities are most at risk for the impacts of climate change on health, as well as those with underlying medical conditions; climate change may serve as a catalyst for improving the healthcare system overall (specifically health insurance)
Rother (2020) [12]	Urban areas of sub-Saharan Africa	Framework of climate-sensitive noncommunicable diseases and achieving the Sustainable Development Goals	Environmental risk factors (e.g., pollution, chemicals) for noncommunicable diseases linked to climate change	Impact of environmental factors on noncommunicable diseases
Wright et al. (2021) [13]	South Africa	Unspecified	Increase in ambient temperature, heavy rainfall, and exposure to dust storms and air pollution	Rise in morbidity and mortality, changes in the prevalence and occurrence of vector-borne diseases, drought-associated malnutrition, and exacerbation of respiratory diseases
Nilson et al. (2021) [14]	Sub-Saharan Africa and South Asia	Narrative review	Rising temperatures, rising sea levels, and an increase in extreme weather events	Health impacts of vulnerable regions and populations
Chaix et al. (2022) [15]	Unspecified	Multidisciplinary analysis	High temperatures and extreme climate events (increase in sea levels)	Increased mortality, accidents at work, suicides, domestic violence, and assaults; development of skin cancers; modification of geographic distribution of some vector-borne diseases and aquatic bacteria (e.g., cholera outbreaks)
Smith et al. (2014) [16]	Unspecified	Review	Shifts in weather patterns and other aspects of climate change (changes in temperature and precipitation and occurrence of heat waves, floods, droughts, and fires)	Ecological disruption brought on by climate change (e.g., crop failures, shifting patterns of disease vectors), social responses to climate change (e.g., displacement of populations following prolonged drought)
Dupar (2020) [17]	Africa	Special report	Extreme weather events, including heat waves, droughts, and precipitation	The distribution of land biodiversity, the mix of plant and animal species in ecosystems, the structure and productivity of vegetation, and nutrient and water cycles
Robineau (2019) [18]	Unspecified	Report (relationships between insurance and climate change)	Sea-level rise, rising temperatures, and desertification	Difficulties in identifying risks, difficulties related to the reversal of insurers' production cycles, and the rise of the normative power of insurers

(Continued on following page)

TABLE 1 | (*Continued*) Some key research on climate change and its implications for health in sub-Saharan Africa (Ouagadougou, Burkina Faso. 2024).

Author and year	Region/country	Study design (data collection process)	Manifestations of climate change	Potential impact pathways of climate change on health and health insurance
OMS (2022) [19]	World	Report (qualitative assessment of vulnerability and adaptation)	Extreme weather events (droughts, floods, heat waves), ecosystem changes, water scarcity, changes in food availability, and changes in the distributions of vectors	Climate-sensitive diseases: cardiovascular diseases, acute and chronic respiratory diseases, acute diarrhea, mental disorders, vector-borne diseases, malnutrition, and trauma
Andersen et al. (2021) [20]	Informal settlement (urban slum) of Mukuru in Nairobi, Kenya	Three focus group discussions and five in-depth interviews conducted with a total of 28 participants	Not specified (explored knowledge and perspectives on climate change and health-related issues, with a particular focus on noncommunicable diseases)	Climate change–related diseases, nutrition and access to clean water, environmental risk factors, urban planning and public infrastructure, economic risk factors, vulnerable groups, and adaptation strategies
Sorgho et al. (2021) [21]	West Africa (Burkina Faso)	35 semi-structured, qualitative, in-depth interviews	The study identified the perceptions of climate change and health adaptation among relevant stakeholders, decision-makers, and policymakers	Water quality and quantity, heat stress, food supply and safety, vector-borne diseases, and air quality

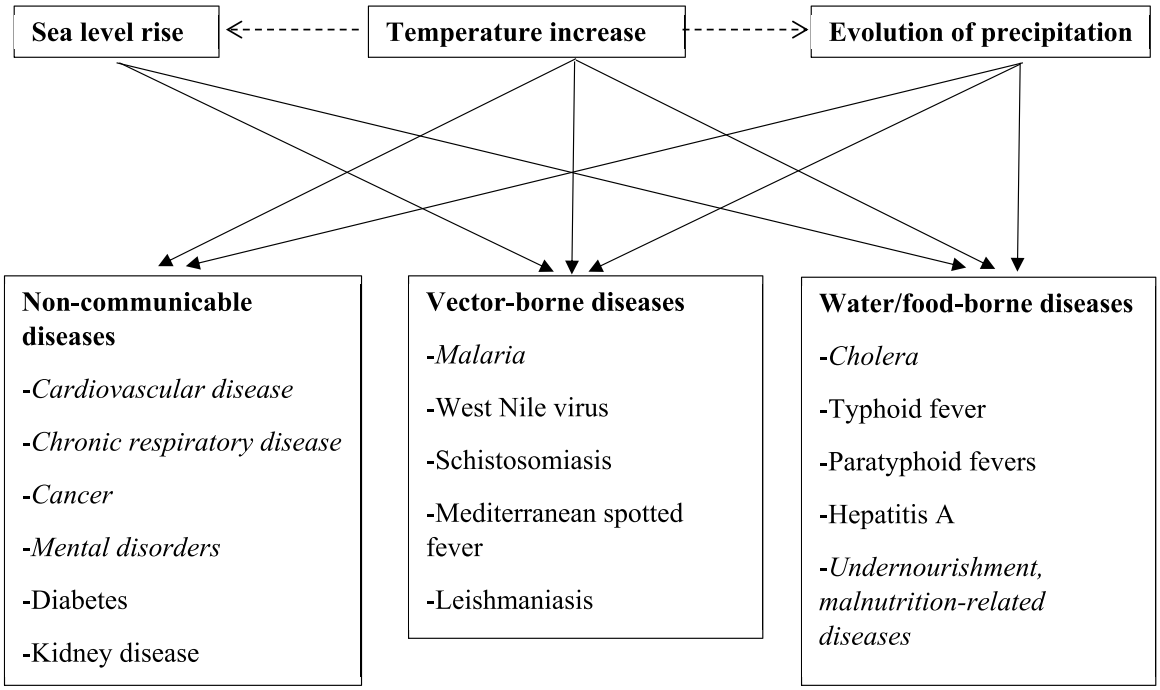

FIGURE 1 | Linking population diseases to climate change (Ouagadougou, Burkina Faso, 2024). Legend: text in italics represents cases clearly identified in the included studies.

effectiveness of policies in lessening the impact of environmental factors on NCDs for people living in urban areas of SSA. Indeed, 80 percent of NCDs occur in low- and middle-income countries, and they are linked to one-third of deaths in SSA [12]. It is unclear how these statistics would change if environmental risk factors for NCDs (e.g., pollution, chemicals) linked to climate change were prevented and controlled [12]. Heat waves can affect human health through the physiological effects of heat, including diseases of the circulatory system (e.g., hypertension, atherosclerosis, ischemic heart disease, myocardial infarction, heart failure, myocarditis) and diseases of the respiratory system (e.g., pneumonia, bronchitis) [22]. Furthermore, extreme heat is associated with increased mortality, accidents at work, suicides, and domestic violence and aggression (mental disorders) [15]. The review revealed that several NCDs are related to climate change in SSA: cardiovascular disease, chronic respiratory disease, cancer, and mental disorders.

Vector-Borne Diseases Related to Climate Change in SSA

Climate change is altering the epidemiology of vector-borne diseases and the spread of neglected tropical diseases, such as malaria, dengue, and chikungunya [23]. The review showed the following trends occurring in SSA as a consequence of climate change: an increase in the number of cases of intestinal infections, which have a considerable seasonal manifestation, with regular records in many countries in recent years; a resurgence of diseases (e.g., malaria, yellow fever); fluctuations in daily and weekly morbidity; and an increase in the frequency of hospitalizations during hotter summers (i.e., during the rainy season in most countries in SSA) [22]. As the incidences of malaria and dengue in SSA have been very high during recent years, it is essential to improve the coverage of programs designed to increase access to safe and effective drugs and diagnostics for society's poorest members [23].

Water- and Food-Borne Diseases Related to Climate Change in SSA

Human health is indirectly affected by changes in human behavior, which can increase the frequency of food-borne diseases, or other phenomena, such as floods or droughts [12]. More specifically, cholera outbreaks have been linked to variation in temperature and rainfall and in other variables, including sea and river levels [16]. In addition, climate change indirectly affects the health of a population by profoundly disrupting diet (e.g., undernourishment, malnutrition), food production systems (e.g., use of pesticides and chemical fertilizers), and the spatial distribution of the population (e.g., population migration).

Global warming is already reducing crop productivity and disrupting food systems. In recent years, yields of staple crops such as maize, wheat, and sorghum, as well as fruit crops such as mangoes, have declined across Africa, which has increased food insecurity [17]. Food insecurity and undernourishment, in turn, can jeopardize a population's health status. Indeed [24], highlights that malnutrition remains one of the most serious socio-economic and health problems in SSA and particularly affects the poorest members of the population, as well as women and children.

The Food and Agricultural Organization (FAO) and the World Health Organization (WHO) have jointly emphasized the need for an effective risk assessment of food additives, food contaminants, natural toxicants, and residues of pesticides in agricultural products [25]. These types of risks are likely to be caused and exacerbated by climate change events. Indeed, climate change affects the agricultural sector, which must already contend with variability in rainfall in SSA. However, Chaix and Slama [15] highlight that measures to combat and adapt to climate change can also influence health. These concern urban environments and the agricultural, transportation, energy, and industrial sectors (the main emitters), which shape major health determinants (e.g., physical activity, diet, air and noise pollution, chemical contaminants). While adaptative solutions are varied, examples such as changing crops to more heat-resistant strains or increasing the use of fertilizers and herbicides could cause new pathologies, particularly carcinogens and cardiovascular diseases.

In the face of the harmful effects of climate change, forced migration also carries a very high social cost. Migration and other population movements can lead to the introduction or reintroduction of diseases, especially when displaced populations live in temporary housing with inadequate sanitation and water purification and where there are poor water storage practices and limited access to healthcare [23].

Key Findings on the Health Insurance Implications of Climate Change

Climate change challenges the insurance industry because it involves uncertainty: risks are changing in terms of frequency, intensity, and diversity, and it is impossible to measure the extent of these changes [18]. Risks are also changing in diversity. Indeed, Gostimirovic et al. [26] highlight that, with climate change, a population can experience a decline in health status, since extreme ambient temperature affects the pharmacokinetic parameters of many cardiovascular drugs.

Therefore, climate change will challenge the insurance business by making cost containment difficult. This is because climate change alters disease risk and increases the difficulty of identifying and measuring it. Robineau [18] highlights that this change in risk configuration makes it impossible to reverse the insurance production cycle and to determine premiums in advance.

Dos Santos et al. [8] conducted the only study that questioned the impact of climate change on health insurance in SSA. The analysis focused on expert perceptions, and the results indicated that participants had no clear sense of how the organization and functioning of the NHI system of South Africa should address the health implications of climate change. There was, however, an indication that medication, mental health, and other morbidity and mortality issues would need to be factored into the NHI [8].

Abstract of Findings

In summary, the pathways through which climate change affects health and health insurance can be grouped into three categories: the direct effects of weather events, the indirect effects of natural systems, and the indirect effects mediated by humans [16]. We provide a graphical abstract depicting the results of the literature review of the effects of climate change on health and health insurance (**Figure 2**). Climate change is driven by human actions and global environmental change. The main manifestations of climate change are increased temperatures, rising sea levels, and changes in precipitation. On the one hand, these manifestations can directly affect health risk factors and population health, making health insurance systems increasingly vital. Indeed, analyses of health risk factors are essential for health insurance implementation. On the other hand, they can indirectly affect health through their impact on the natural world, including by accelerating the mutation and emergence of pathogens and by affecting food availability, food technologies, and productivity technologies. Finally, climate change can adversely affect the pharmaceutical industry by limiting drug efficiency [26].

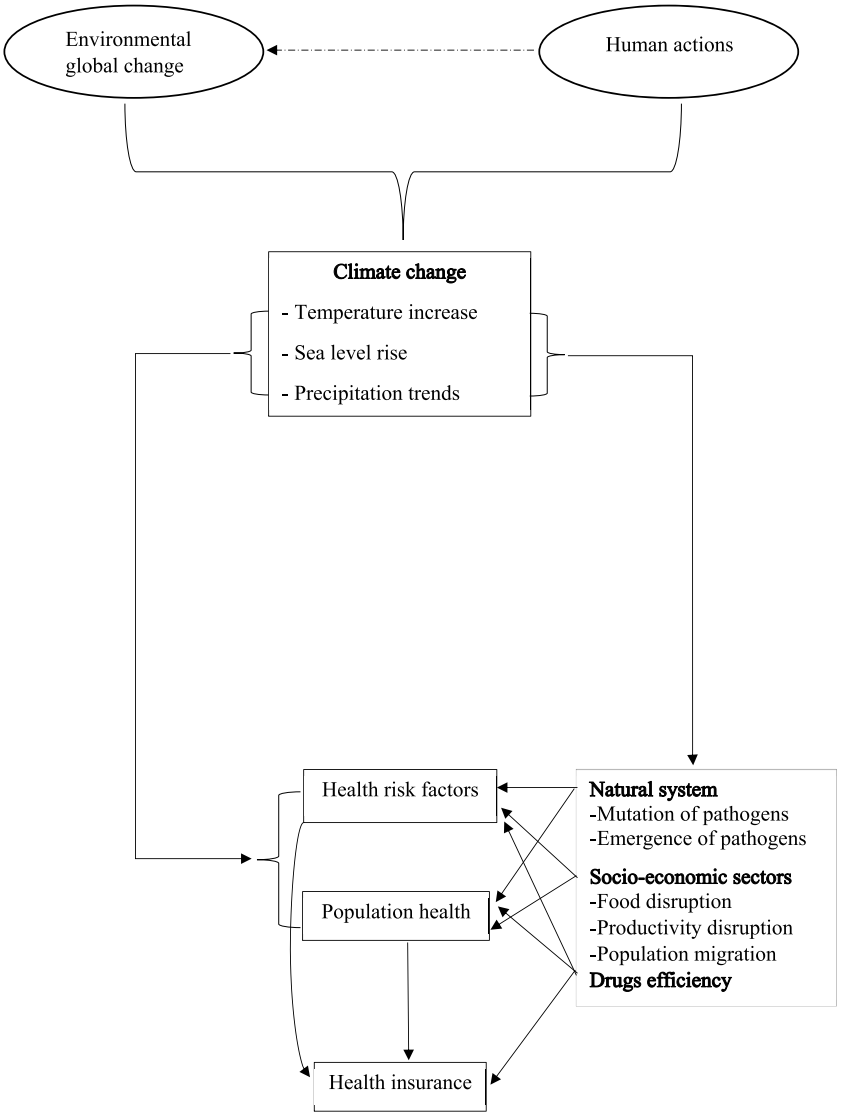

FIGURE 2 | Key findings graphical abstract (Ouagadougou, Burkina Faso. 2024).

DISCUSSION

Globally, the discussion of health and climate change adaptation strategies by sub-national or provincial governments is often limited [7]. This literature review highlights that climate change is associated with a wide range of human health problems, which pose a burden to health systems, especially in regions such as Africa.

Through its direct and indirect effects on population health, climate change may impose challenges on health insurance systems. Across the African continent, public health systems are already under severe pressure, partly due to fragile socio-economic conditions [3]. At the same time, disasters related to climate change and gradual changes in temperature and precipitation are expected to result in an average annual loss of 3.2 percent of gross domestic product (GDP) for Africa as a whole by 2050 [27]. Additionally, Maino et al. [28] found that the effect of a 1°C rise in temperature decreases *per capita* income growth in fragile states in SSA by 1.8 percentage points. In this context, adequate funding is needed to maintain the essential functions of the healthcare system, especially in times of crisis, such as this period of climate change. Indeed, for funding sources, whether national or international, to be appropriate and effective, they must not lead to major trade-offs between sectoral budget allocations within countries, nor to a fashion or imitation effect between countries in the mobilization of resources. In the case of countries' national adaptation plan to face climate change effect on health, Hounkpatin et al. [19] highlight that Benin prioritizes heat, drought, and flooding. But in this case, the authors find that the dominant role of global agencies in financing health system adaptation planning contributes to policy mimicry. In such a context, the various external supports could lead

to a narrower focus that does not fully meet Benin's needs in terms of climate shocks and adaptation priorities [19].

In addition to funding for essential healthcare and public health services (e.g., water, sanitation, environmental health, disaster preparedness, and health emergencies), there is a need for insurance and replacement costs for health equipment that has been destroyed or damaged by extreme weather events [29]. Improving the basic knowledge of healthcare institutions to help them better respond to a changing climate is also recommended [3].

In addition, climate change, including very high temperatures, can make the supply or use of specific drugs, vaccines, and diagnostic tests more expensive in heat-exposed regions. The storage of these products, often at low temperatures, can result in significant costs for health systems or individuals.

Thus, it appears that climate change may be an important factor in the failure of cost containment in a health insurance system, which is a prerequisite for achieving the objectives of insurance. As such, government intervention in insurance systems will be required to regulate and define more appropriate health insurance financing mechanisms that integrate the reality of climate change.

Because of the effects of climate change on health risk factors, a specific challenge for health insurance system management is to define climate change as a variable to be included in risk adjustment schemes. Indeed, the results of Dos Santos et al. [8] underscore this compelling need for health insurance systems. Health risk adjustment (or risk equalization) is a mechanism for classifying the risk profiles of insurers in order to provide subsidies or equalization levies adjusted to the risk of their insured members. It is a functional mechanism of health insurance systems that ensures equity and cost containment [30]. Thus, region- and population-specific vulnerability related to climate change must be defined as subsidy risk factors in the management of the consequences of climate change. Other seasonal variation in health expenditures must also be subsidized by risk equalization funds. Hence, the previous estimation and decomposition of annual or periodic health expenditures can be done in a way that allows for seasonal variation related to climate effects.

Climate change, through its disruption of agricultural systems, may reduce the sources of funding for these subsidies in economies where the agricultural sector substantially contributes to GDP. As such, some countries in SSA will have to find a sustainable method of resource mobilization for their health insurance systems. In such systems, government subsidies for vulnerable individuals, which are essential to the effectiveness of universal health insurance in developing countries [31], must also be strengthened in response to climate change crises. One solution is to opt for a tax on products that are harmful to the health of the population, such as tobacco, alcohol, sugar, and oils. Taxing products or activities that generate or accelerate climate change, including aviation, polluting industries, and the use of internal combustion vehicles, could provide an alternative source of funding. Finally, the real estate and land sector, which is still largely untaxed in many countries in SSA, could generate significant additional revenue, even with low tax rates. One important strategy to adapt to climate change–associated health risks is to provide training for local communities, thus ensuring adaptation strategies and climate change advocacy [20].

Conclusion

Climate change constitutes one of the greatest threats to human health and requires political awareness for effective and efficient adaptation planning [21]. Weather, climate, and climate change are affecting human health, as has been shown by a growing body of scientific evidence over the past two decades. However, there continues to be very limited research on the implications of climate change for low- and middle-income countries [14]. More specifically, to the best of our knowledge, only one previous paper attempted to link climate change and health insurance in SSA. Therefore, our review serves as a meaningful contribution to the exploration of the possible mechanisms of the effects of climate change on health insurance and highlights the key challenges faced by health insurance systems in SSA in the context of a changing climate. Three main challenges were underlined for countries in SSA. First, they must ensure the successful operation of the core functions of healthcare systems in the face of climate change. Second, they must define the climate change–related risk factors to be included in health insurance risk adjustment schemes. Third, they must acquire adequate funding for their health insurance systems. Most countries in sub-Saharan Africa are in the process of experimenting with or implementing health insurance systems. Thus, the embryonic nature of health insurance systems in the region is a limitation of our research, insofar as there is very little literature to draw major lessons on the adaptation of these health insurance systems to the effects of climate change.

AUTHOR CONTRIBUTIONS

JT suggested the research area, reviewed the paper and coordinated a webinar for the paper discussion. OT wrote the paper and presented it to a webinar. All the authors have read the paper.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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Integrating Maternal and Child Health Into Climate Change: A Holistic Approach

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Objectives: In everyday language, climate change is an increase in the Earth's average temperature. Climate change negatively affects life support systems, including air, food, water, shelter, and security, on which humans depend. This paper aims to holistically integrate maternal and child health into climate change.

Methods: A narrative/literature review approach were adopted using papers sources from google scholar, research gate and web of science. About 10 papers was initially gathered and it was later scrutinized to 6.

Results: It was discovered that, climate change negatively impacts food and water security, heat stress, extreme weather, and air pollution, with women and children most affected. The World Health Organization estimates 250,000 climate-related deaths annually by 2050, disproportionately affecting maternal and child health. Integrating climate and maternal health strategies could offer benefits, yet research on adapting to climate change's effects on pregnancy outcomes is limited.

Conclusion: Addressing maternal and child health requires integrating health-focused strategies into environmental policies to reduce vulnerabilities to climate-related risks. A comprehensive approach can enhance resilience by improving healthcare access, education, and sustainable resource management, benefiting public health and environmental outcomes.

Keywords: heat, malnutrition, forced migration, infectious diseases, mental health problems

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INTRODUCTION

Climate change, recognized as one of the most significant global threats of the 21st century, is associated with immediate harm to early childhood development, long-term health consequences, and profound effects on future generations. These impacts extend beyond the present, influencing not only current health outcomes but also shaping the wellbeing of future populations [1]. To protect

vulnerable populations, the relationship between climate change and mother and child health is essential. Human activity-induced climate change has accelerated the development of vector-borne illnesses, raising health hazards for young children and expectant mothers [1]. Furthermore, the paucity of resources brought on by climate change increases susceptibility to malnutrition and associated health issues. The World Health Organization and other international health organizations stress how critical it is to understand the unique health risks that pregnant women and children confront considering the shifting environment [2]. A holistic strategy must incorporate interventions, fortify health systems, foster community resilience, and advance sustainable development objectives. Therefore, understanding the complex pathways through which environmental shifts impact vulnerable populations is necessary for a comprehensive approach to addressing maternal and child health in the context of climate change mitigation. The global community's commitment to achieving the Sustainable Development Goals (SDGs) underscores the need for a synergistic approach addressing maternal and child health while mitigating climate change.

METHODS

In order to thoroughly examine the body of literature already written about the research issue, this review paper employed a narrative review methodology. The procedure started with a thorough search of pertinent scholarly articles from three important databases: Web of Science, ResearchGate, and Google Scholar. These platforms were picked in order to guarantee that scholarly sources of a high caliber and variety would be included.

Ten papers were first selected based on their titles, abstracts, and applicability to the research question. Studies that were published in peer-reviewed publications and that addressed important issues about how climate change affects the health of mothers and children were among the selection criteria for inclusion. Furthermore, only English-language works published in the previous 10 years were used, guaranteeing the literature's currentness and relevancy.

A thorough screening procedure was applied to every document after it was first collected. The quality, methodology, and conclusions of the papers were evaluated by full-text reviews. Studies that examined the connection between climate change and its consequences on pregnancy outcomes—more especially, mother and child health—were the subject of further refinement of the inclusion criteria.

Six papers were ultimately included after a rigorous examination. These studies were selected based on their methodological soundness, relevance to the larger framework of how climate change affects mother and child health outcomes, and compatibility with the research topic. These criteria were not met, and papers that were judged to be overly vague or out-of-date were not included in the final selection.

In order to minimize any bias and provide a clear and thorough grasp of the subject, this systematic methodology made sure that the review concentrated on the most pertinent and trustworthy studies.

RESULTS

Pregnancy Risks in Changing Climates

An estimated 2.0 million stillbirths, 2.5 million neonatal deaths, and 295,000 maternal fatalities occur annually worldwide [1]. Pregnancy and labor are major health risks in low-income nations, with maternal morbidity and maternal deaths being more prevalent in these countries [2]. Climate change is one of the largest threats to world health in the 21st century [3], with long-term effects on pregnant mothers, infants, and future generations. Pregnant women and newborns are increasingly recognized as vulnerable groups, and extreme weather events like heat waves, droughts, and storms are affecting their health [2, 4]. Climate change can impact pregnancy health directly through specific climatic disasters and indirectly through changes to natural and social environments. Pregnancy-related disasters are linked to higher risks of prenatal problems, pregnancy loss, reduced fetal growth, low birth weight, preterm birth, and specific delivery/newborn issues [4]. Despite the controlled physiological and psychological changes experienced by pregnant mothers and the developing fetus, there is limited research on how to adapt to and reduce the effects of climate change on pregnancy outcomes. The consequences of the climate on the health of expectant mothers can be recognized as (a) direct impacts via discrete environmental disasters [5], (b) indirect impacts through changes in the natural environment, and (c) indirect impacts through changes in the social environment (**Figure 1**).

Implications of Changing Climate on Pregnancy Outcomes

Physiological and anatomical changes that occur during pregnancy and the newborn period reduce the body's capacity to regulate body temperature. Pregnant women experience significant body changes, including increased body mass index, fat deposition, and increased metabolism due to fetal growth [5, 6]. Heat stress, resulting from the inability to maintain thermal balance, releases heat-shock proteins, which can negatively impact the health of expectant mothers and their babies. Heat exposure is linked to risks of stillbirth, low birth weight, premature membrane rupture, and preterm birth. Infants with low birth weight are more vulnerable to infections [7]. Dehydration caused by increased sweating during pregnancy can cause labor to start prematurely and persist for longer. Prenatal exposure to extreme weather events like heat waves, wildfires, and droughts has been linked to adverse pregnancy outcomes [6].

Childhood Diseases and Climate

Global climate change (CC) is widely regarded as the most significant threat to human health in the 21st century, impacting air quality, food security, water resources, and

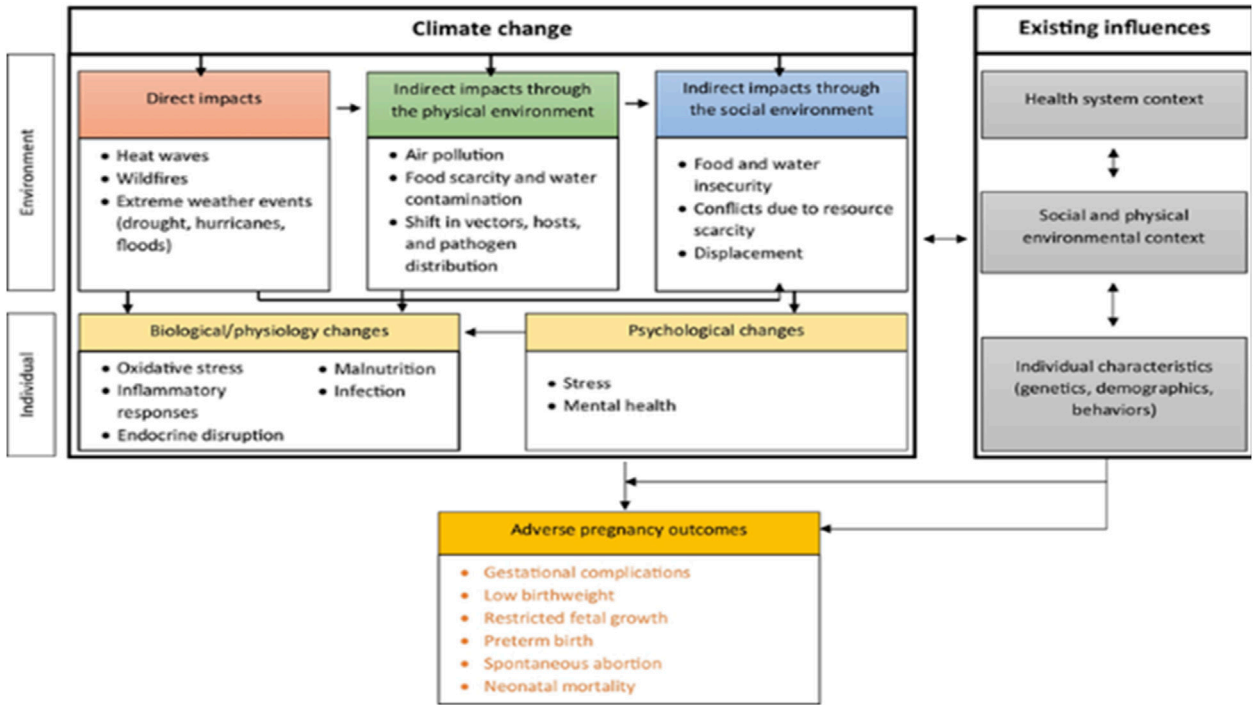

FIGURE 1 | Implications of climate change on pregnancy outcomes [5] (Accra, Ghana. 2024).

disease prevalence. Due to their developing organ systems, psychological immaturity, the nature of their everyday activities, and higher levels of exposure, children are especially the major victims of climate catastrophe [8–10]. Data suggests that climate change is contributing to the rise in certain disorders and allergies by intensifying environmental factors, such as air pollution, allergen exposure, and extreme weather events, which interact with genetic predispositions to exacerbate health outcomes. A child's development can be greatly impacted by the complex interactions between climate change and childhood diseases, which can lead to stress, mental health issues, food-borne, water-borne, or vector-borne diseases, respiratory disorders, malnutrition, illnesses brought on by extreme heat, and displacement [9]. According to the British Thoracic Society's report, *The Environment and Lung Health 2020*, individuals with chronic respiratory conditions are particularly vulnerable to the adverse effects of climate change, as environmental changes exacerbate respiratory health challenges. Due to their smaller peripheral airways, developing bodies, and higher breathing rates, children, especially those under the age of five—are more vulnerable than adults to CC-related respiratory morbidity [10].

Additionally, during the warmer months, youngsters typically play outside more. Consequently, because of their limited capacity to sustain ideal internal temperatures during heat stress, they are more vulnerable to the harmful effects of exposure to high temperatures [10]. A child born today will grow up in a world projected to be over four degrees warmer than pre-industrial levels, with climate change impacting their health throughout their lifetime, from birth through old age [11]. Unpredictable precipitation patterns driven by climate change have been linked to an increase in communicable and vector-borne diseases, as altered rainfall influences waterborne pathogens' spread and expands habitats for vectors like mosquitoes [12]. Heat waves have been connected to reduced cognitive function and an increase in mortality while maternal stress, nutritional insults from low harvests, and exposure to infectious diseases have all been associated with poor childhood growth and development because of climate change [7, 13]. Pediatricians need to incorporate evidence-based knowledge into their clinical practice and fully understand the effects of climate change (CC) on children's health to offer comprehensive care. This is crucial, especially considering their responsibility to educate families on the implications of CC and its impact on children's wellbeing [10].

Maternal Health

The World Health Organization (WHO) defines maternal health as the wellbeing of women during pregnancy, childbirth, and the postpartum period [14]. Approximately 536,000 women die annually due to complications, with 99% occurring in developing countries. The UN Millennium Development Goals (MDGs) aim to address maternal health, with MDG 5 aiming for a 75% reduction in maternal mortality and universal access to reproductive health [15]. MDG 4 aims to reduce child mortality by two-thirds by 2015, addressing prevalent causes like pneumonia, diarrhea, and malaria in children under five. Climate change poses a significant threat to achieving MDG 5, necessitating a more nuanced understanding of its impact on

maternal health [15, 16]. Migrant birth outcomes are also affected by forced resettlement, population movements, and inadequate medical services. The COVID-19 pandemic has highlighted the potential for disruptions in low- and middle-income countries to result in additional maternal and child deaths [17, 18].

Pediatric Health Interventions

Over the past decades, efforts have been made to achieve the Millennium Development Goal (MDG) on child survival, with 13 countries experiencing an increase in overall child deaths [19]. However, some have met the MDG target of reducing mortality rates among children under five by two-thirds. In 2020, around 5 million children under five died, mostly from treatable and preventable causes [20]. Newborns in the first 28 days of life accounted for approximately 2.4 million of these deaths. Child mortality in sub-Saharan Africa (SSA) remained the highest in the world at 74 deaths per 1,000 live births, 14 times higher than the risk for children in Europe and North America [20].

Preterm birth problems, birth asphyxia/trauma, pneumonia, diarrhea, and malaria are the major causes of death for children under the age of five. Access to health and sanitation treatments can help avoid or treat these conditions [21]. However, most child health programs do not reach the world's poorest families, contributing to the inability to meet proposed reductions in child mortality numbers [20, 22]. The SDG agenda emphasizes the need for inclusive and targeted strategies for the most vulnerable and marginalized children. Evidence suggests that effective interventions in pregnancy and delivery care, hygiene facilities, environmental settings, and access to health resources can improve child survival and health [23]. Vaccination campaigns and other survival interventions have shown that the children who need it most are not adequately covered. Initiatives such as the measles vaccination campaign have reduced measles mortality in sub-Saharan Africa by 92% between 2000 and 2008. Implementing WHO guidelines on the management of severe acute malnutrition has also shown a reduction in child mortality rates [20, 24].

Long-Term Developmental Effects

In everyday language, climate change refers to the ongoing increase in the Earth's average temperature, commonly known as global warming, and its repercussions on the planet's climate system [1]. This phenomenon is giving rise to a spectrum of escalating environmental impacts. Even if endeavors to curtail future warming prove successful, certain consequences will persist for centuries, including ocean heating, ocean acidification, and rising sea levels [2]. The impact of global warming on local climates varies across regions, countries, and specific locations [4]. The Arctic region is expected to experience a significant temperature rise, with the potential human health impact expected to be minor due to initial low temperatures [5]. However, the "urban heat island effect" and decline in air quality in tropical regions can create hot spots, posing additional risks. Climate change can affect human health through issues like insufficient access to food, safe drinking water, substandard sanitation, population displacement, disease patterns, extreme weather events, and lack of shelter [25, 26]. Maternal health is crucial, with approximately 536,000 women dying annually due to pregnancy, childbirth, or postpartum complications. Blood loss or hypertension accounts for half of all maternal deaths, while indirect causes like malaria, HIV/AIDS, and heart diseases contribute to 18% and 11%, respectively [5, 11]. Most maternal deaths are preventable, with 99% occurring in developing countries. These factors collectively heighten susceptibility to variations in external temperatures, sometimes leading to significant alterations in core body temperature [6]. **Table 1** delineates specific pregnancy complications with a focus on climate-related factors.

TABLE 1 | Instances of clinical and physiological consequences of pregnancy resulting from hormonal shifts (Accra, Ghana. 2024).

First Trimester	Second Trimester	Third Trimester
Spontaneous abortion	Spontaneous abortion	Premature contractions
Missed abortion	Premature contraction	Abruption placentae dehydration Heartburn
Exhaustion	Weight gain	Indigestion
Altered appetite	Dizziness	Yeast infections
Breast pain	Headaches	Fluid retention
Yeast infections	Yeast infections	Dizziness
Weight loss	Hemorrhoids	Hemorrhoids
Headache	Backache	Constipation
Nausea and vomiting	Fluid retention	Backache Difficult sleep pattern
Pica	Difficult sleep pattern Leg cramps Joint pain Hair loss	Discomfort while sleeping Increased urination

Source [14].

In Africa, rising temperatures are anticipated to enhance the transmission and spread of vector-borne diseases by increasing mosquito density in specific regions and amplifying the replication rate and frequency of mosquito bites [26]. Furthermore, the increased sweating leading to dehydration as part of thermoregulation in pregnant women can potentially trigger premature labor onset and protract the duration of labor [15]. A study conducted by Costello et al. [26] contends that malaria, dengue fever, and tick-borne encephalitis are poised to become more prevalent, putting individuals without current infections or lacking sufficient immunity at risk in the future. Additionally, there is a heightened potential for increased schistosomiasis infections [16]. Climate change intensifies mercury (Hg) exposure through its impact on environmental conditions and ecosystems. Rising temperatures increase the conversion of elemental mercury into toxic methylmercury in aquatic systems, which accumulates in fish and other organisms at the top of the food chain. Warming waters, such as in the Gulf of Maine, have already been linked to significant increases in methylmercury levels in species like tuna, even as overall mercury

emissions decrease. This process poses heightened health risks for populations consuming seafood, as methylmercury is a potent neurotoxin [27]. Additionally, altered precipitation patterns and thawing permafrost caused by climate change release stored mercury into water systems, further amplifying exposure risks in regions like the Arctic. Mitigation strategies require addressing both mercury emissions and greenhouse gas reductions to curb the compounding effects of climate change on mercury contamination [17].

Heat stress during heat events can lead to adverse effects on maternal and perinatal health, including the neonatal period. Air pollution increases the risk of infants being born with low birth weight and experiencing preterm birth, which is the leading cause of neonatal mortality globally. The lack of access to clean energy significantly contributes to climate change and negatively impacts maternal and newborn health by increasing exposure to harmful pollutants and limiting access to essential healthcare services [28]. For example, Lack of clean energy often forces reliance on traditional biomass fuels (e.g., wood, charcoal, dung) and fossil fuels (e.g., coal, kerosene) for cooking, heating, and lighting. This contributes to greenhouse gas emissions, exacerbating climate change through deforestation and carbon dioxide release [29]. In addition to clarifying this, burning biomass fuels and kerosene releases harmful indoor air pollutants, such as PM2.5 and carbon monoxide, linked to preterm births, low birth weight, and stillbirths. Pregnant women and infants are particularly vulnerable, with air pollution affecting fetal development and increasing respiratory illnesses. Limited clean energy also hampers healthcare by restricting essential equipment use and proper vaccine storage, further jeopardizing maternal and neonatal health [30]. Climate change indirectly impacts vulnerable populations through various mechanisms, potentially resulting in profound social, economic, and health implications [31]. Disruptions in services from the COVID-19 pandemic could lead to additional maternal and under-five child fatalities. Contaminant exposure during the prenatal period may impact cardiovascular homeostasis, potentially increasing the burden of diseases attributable to contaminant exposure [20].

Lead exposure has been linked to neurodevelopment and behavior in children, with recent studies revealing a correlation between cord blood lead concentrations and inattention, even at concentrations below 10 mg/L [20]. In Arctic Russia, associations have been noted between spontaneous abortions and mercury levels in the blood, but no adverse associations were identified between maternal exposure to nickel and the risk of delivering a newborn with genital organ malformations [32].

The global communities focused on health and climate change must collaborate and mobilize initiatives to heighten awareness among policymakers about the repercussions of climate change on the health of women and children, as well as on forthcoming generations [33]. It is essential to enhance the availability of high-quality data regarding the influence of climate change on maternal and newborn health. This improvement aims to comprehend the global burden and its attributes, particularly in the most vulnerable and least resilient societies that are currently and will be most significantly impacted by climate change [34].

Policy Implications to Minimize the Negative Impacts of Climate Change on Maternity and Child Health

Maintaining a healthy diet is crucial for preventing infections, lowering infant mortality, and managing obesity and chronic illnesses [28]. Climate change impacts food production, contributing 20%–30% of greenhouse gas emissions. It may also raise the hazards of weather-related disasters to the health of newborns, making child health a priority in the adaptation process [28]. To mitigate this effect, policies addressing food security with climate change and its impact on mothers and children are needed. Fair distribution of food production and monitoring of nutritional content are essential. Sustainable environmental policies should support clean, sustainable energy, water access, and natural resource management [32].

Gender inequality in low- and middle-income countries should be addressed by empowering women and girls to make decisions, facilitate access to resources and basic services, and support them during climate-related disasters [35]. Enhanced policies and actions to improve disaster preparedness, such as coordinated emergency planning and assistance for women, are also necessary. Breastfeeding infants can be challenging due to climate change events, but it supports policy while reducing greenhouse gas emissions [28, 32].

The disproportionate impact of climate change on women's health and food security is not given enough priority in the UN and national agendas. Women and children are more susceptible to its effects due to changes in their anatomy, physiology, and sociocultural background [31, 35]. To minimize the effect on maternal and child health, behavioral change policies, health education about heat-related hazards, natural ways to lessen urban heat islands, space cooling in medical facilities, and fair changes in food and housing systems are effective ways to lower the dangers associated with heat [31].

In Africa, the effects of climate change on mother and newborn health will likely continue to be severe. Research is needed to determine who is most at risk, close knowledge gaps, and coordinate initiatives to lessen detrimental effects on health. For adaptation programs to be more effective and widely adopted, children and young people must be meaningfully included in their design and execution [34, 36].

Future Directions

Future research on integrating maternal and child health into climate change mitigation should focus on understanding the direct and indirect impacts of climate change on maternal and child health, particularly in vulnerable populations and low-resource settings. Adaptive healthcare models need to be developed to address climate-induced risks such as malnutrition, infectious diseases, and heat stress in pregnant women and children. Studies should assess the effectiveness of integrating climate resilience strategies into existing maternal and

child health programs while exploring emerging technologies to monitor and mitigate these effects.

Research must evaluate the long-term consequences of prenatal exposure to climate-related pollutants on child development and health outcomes. Cost-effective interventions aimed at reducing maternal and neonatal mortality during climate-related disasters are critical. Additionally, the psychosocial impacts of climate change on maternal mental health and its influence on child-rearing practices require attention. The intersection of water scarcity, hygiene, and maternal-child health in climate-stressed regions should be explored, alongside the design of community-based education programs to raise awareness of climate risks on health.

Innovative solutions, such as climate-smart healthcare facilities, can be tested to simultaneously reduce carbon emissions and improve care quality. Research should also address disparities in health outcomes caused by socioeconomic inequalities and identify policies that integrate sustainable agriculture with nutrition-focused maternal and child health initiatives. The role of indigenous knowledge in mitigating climate impacts on maternal and child health deserves exploration. Finally, modeling future scenarios of climate change effects on maternal and child health can guide policy decisions, with interdisciplinary collaboration to establish evidence-based guidelines for integrating climate action into maternal and child health frameworks.

DISCUSSIONS

Research Limitations

Climate change negatively affects life support systems, including air, food, water, shelter, and security, on which humans depend [37]. Climate change negatively impacts regions with development constraints, disproportionately affecting women and children. It leads to acute food insecurity, reduced water security, heat stress, extreme weather events, and air pollution [37]. Annually, it causes around 2.0 million stillbirths, 2.5 million neonatal deaths, and 295,000 maternal deaths, primarily in low-income countries [38]. This segment identifies some areas that could advance our understanding of complex climate-related phenomena, guide effective decision-making, and develop strategies to mitigate and adapt to the impacts of climate change [26].

Research is needed to assess the effects of climate change and heat waves on maternal and perinatal health in low- and middle-income countries. This will help develop targeted interventions and strategies to improve health outcomes [26]. Replicating and intensifying efforts like the CHAMNHA (Climate, Heat, and Maternal and Neonatal Health in Africa) project can help tailor intervention strategies and review global policies. Investigating lags in adopting low-emission technologies in developing countries is essential for policy recommendations and capacity-building initiatives [39, 40]. Research should also focus on mitigation strategies like energy efficiency, improved forest management, and reduced food waste and loss. Understanding these measures within a holistic framework is crucial for developing comprehensive climate action plans [40].

Climate change is expected to have the most significant impact on children and future generations, with over 88% of the global disease burden occurring in children under five [33, 34]. Therefore, comprehensive climate change and health research is crucial, particularly in Africa. Research should explore the opportunities and challenges of involving women, children, and young people in climate change policy, as they are often underrepresented in political structures [33]. Research should identify cost-effective and sustainable measures to address climate change to equip children and their communities with the skills and resources to cope with climatic changes, particularly in vulnerable developing countries.

Interdisciplinary collaboration is essential, and key areas for investigation include communication, knowledge transfer, community engagement, capacity-building programs, and inclusivity [34]. Also, addressing the intersection of social and political unrest and climate change's negative effects on maternal and child health could be a potential research gap in Africa [33]. Studies could investigate healthcare access for pregnant women and children during unrest, as well as how disruptions to agricultural activities, displacement, and economic instability may contribute to malnutrition and related health problems [34].

Conclusion

The review presents a comprehensive framework that combines health policies, environmental sustainability efforts, and strategies for enhancing community resilience to address maternal and child health challenges. It highlights the potential benefits of combining health initiatives with climate change mitigation, guiding policymakers and healthcare practitioners in formulating integrated strategies for sustainable development. The study also advocates for a paradigm shift towards inclusive and interdisciplinary solutions, acknowledging the inextricable linkages between human health and environmental wellbeing in the face of a changing climate.

AUTHOR CONTRIBUTIONS

Conceptualization FA; methodology, FA, NK, and WS; validation, FA, DA, and WS; formal analysis, FA, SK, GD, and JA; investigation, DA, NK, and FA; resources, FA and SA; data curation, SA, WS, and FA; writing—original draft preparation, SA, GD, SK, JA, and ZD; writing—review and editing, FA; visualization, FA, DA, and SW; supervision. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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Unmasking the Neglected Cholera Outbreaks in Sub-Saharan Africa

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Keywords: Sub-Saharan Africa, cholera endemic areas, economic instability, oral cholera vaccines, climatic factors

INTRODUCTION

Cholera is a communicable infection that is predominantly transmitted by the bacterium *V. cholerae* after ingesting contaminated water or food. It causes excessive diarrhoea and vomiting that can result in severe dehydration. *V. cholerae* traces its natural habitat in waterlogged settings, therefore, to effectively manage the spread of cholera, it is critical to research the interactions of the disease's causative agent with that of human comportment and the ecosystem [1]. Despite the momentous breakthroughs that have been documented in the medical field, cholera remains a public health threat in some countries of Sub-Saharan Africa (SSA) as well as the East Mediterranean Region (EMR), and it claims thousands of lives, whenever there is an outbreak. The health crises are persistent in regions that lack adequate water supply and experience poor sanitation and hygiene services (WASH) alongside substandard healthcare infrastructure [2]. However, to productively highlight the neglected cholera incidences that reemerge year after year, in SSA, it is important to carry out detailed investigations of their systemic limitations that propagate their reoccurrence [3]. Thereafter, coming up with sustainable solutions to widely address this ongoing crisis (**Table 1**).

The social constraints such as gender inequalities contribute to the public health challenge that is posed by cholera due to water scarcity. Girls and women bear the burden of caregiving during outbreaks as they are usually in the forefront [4]. Healthcare expenditures tend to strain fragile economies and reduce productivity. The cost of cholera treatment in Africa varies significantly depending on factors such as WASH infrastructure, severity of outbreaks, and access to resources. In Somalia for instance, the overall average cost of cholera treatment for health facilities and households was estimated to be US$ 116.59 in 2023 [5]. This hefty cost considering the socioeconomic inequality, disproportionately affects the poor in society. Additionally, the young population below the age of five are highly susceptible, especially those that have little to no food to eat, the malnutrition renders disease vulnerability to the children, due to their compromised immune systems. Their bodies find it hard to defend themselves against foreign invaders [6]. Cholera epidemics repeatedly erupt during foreseeable periods in Africa, they frequently align with the rainy seasons and are intensified by environmental and infrastructural dynamics [7]. The infectious disease is remarkably prevalent in SSA, where countries such as Zambia, Nigeria and the Democratic Republic of Congo have succumbed to major episodes and recorded high case fatality rates [8]. According to the World Health Organization (WHO), the SSA reports the highest number of cholera cases, globally, the region records over 150,000 laboratory confirmed cases, and about 3,000 deaths annually [9].

In several countries of SSA, specifically in conflict-affected regions and rural areas, health centres are not fully equipped to execute timely diagnosis and reporting of cholera cases. As a result, most outbreaks remain masked to both national and international health authorities, until they escalate [10]. Political influences equally play a key role, as some governments may shy away from reporting cholera outbreaks for fear of ruining their international reputation or suppressing the tourism industry and discouraging investment. Additionally, the prolonged regional or internal conflicts contribute to the prevalence of cholera chapters in SSA. They disrupt the healthcare systems and

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TABLE 1 | The persistent challenge of cholera in Africa: a complex interplay of climatic factors, Africa, 2024

Category	Key causes/patterns	Context in SSA
Structural Poverty and Inequalities	- Marginalized populations in urban slums and rural areas are underserved - Poverty forces reliance on contaminated water sources	- Limited political prioritization leaves communities without access to clean water or sanitation - Informal economies restrict resources for public health investments
Environmental and Climatic Vulnerabilities	- Seasonal floods contaminate water supplies - Droughts exacerbate water scarcity - Unplanned urbanization overwhelms waste management	- Rapid urban growth in informal settlements increases exposure to cholera - Climate extremes amplify risks of waterborne diseases in vulnerable regions
Conflict and Fragility	- Displacement due to armed conflicts leads to poor camp conditions - Fragile health systems fail to provide adequate cholera prevention	- Refugee and IDP camps often lack water, sanitation, and healthcare. - Reliance on emergency aid undermines sustainable solutions
Cultural and Behavioural Barriers	- Traditional practices hinder adoption of hygienic behaviours - Distrust in authorities limits acceptance of health interventions	- Hygiene education efforts are culturally insensitive or absent - Behavioural norms (e.g., open defecation) perpetuate unsafe practices
Gaps in Governance and Policy	- Inconsistent funding focuses on reactive measures instead of proactive investments - Poor collaboration across sectors (water, sanitation, health)	- Cholera response programs remain underfunded and poorly coordinated - Long-term investments in public health infrastructure are deprioritized
Cross-Border Transmission Patterns	- Porous borders and trade routes enable cholera spread across countries	- Frequent migration and regional trade increase risk of cross-border outbreaks
Neglected Investment in Preventative Measures	- Vaccination campaigns are limited and reactive - Health education efforts fail to address systemic barriers	- Oral cholera vaccines are underutilized - Public awareness campaigns are rare and lack cultural or contextual relevance

cause limited access to quality medical services [11]. Furthermore, there are fragile systems of water supply and drainages, especially in rural settings [12]. Climate change including floods and droughts contaminate water sources [13]. Insufficient vaccination coverage, particularly in hard-to-reach districts is also a chief cause of cholera outbreaks in SSA [14]. The high population density in refugee camps together with the informal settlements in urban areas increase the transmission rate, turning small outbreaks into large-scale epidemics [15]. Similarly, in the EMR, cholera remains a pressing health concern, with Afghanistan, Pakistan, Haiti, and Yemen being among the most severely affected countries. The prevalence of cholera in these nations is driven by protracted conflicts, political instability, and widespread displacement, which disrupt healthcare and sanitation infrastructure [16].

In the period between 2010 and 2020, 34 African countries recounted cholera outbreaks [17]. The ten most affected countries being Ethiopia, the Democratic Republic of Congo (DRC), Somalia, Kenya, Mozambique, South Sudan, Nigeria, Tanzania, Zimbabwe and Uganda. Cholera endemic countries undergo a series of challenges when a crisis is neglected, such as high mortality rates [18], because cholera can kill within hours if left untreated [19] and economic instability that burden the commerce industry [20]. Similarly, high-risk communities face social exclusion and marginalization [21]. Also, cholera brings about long-term health consequences such as malnutrition [6], kidney damage and increased immunodeficiency. Notwithstanding, some of these countries have implemented strategic measures to spearhead the control and prevention of cholera transmission and in turn, break the cycle of neglect [22–26]. The innovative actions adopted by some countries include investing in improved WASH facilities [27], engaging in targeted vaccination programs, intensely in cholera hotspots [28] and empowering medical practitioners by training them how to diagnose and treat cholera patients. Public involvement has equally proven to be a pillar of cholera prevention, educating local communities in control and response efforts ensures disease awareness [29]. Alternatively, addressing underlying conflicts and providing emergency assistance can minimize the displacements of people and reduce the cross-border transmission [30].

To further mitigate cholera outbreaks in SSA and beyond, it is imperative for local stakeholders, governments, the international community, and non-governmental organizations to prioritize cholera control and prevention [31]. It would equally be of help to incorporate successful strategies that have been implemented in other regions. Ahmed *et al.* [32], reported that in March 2017, a team of specialists from ten Asian cholera at risk nations alongside various representatives from WHO came together in Vietnam to share progress in terms of prevention and control interventions on water, sanitation and hygiene (WASH), surveillance and oral cholera vaccine use [32]. This multi-sectoral collaboration can be implemented in SSA by integrating the Africa CDC's "One Health" approach, to address broader factors contributing to cholera outbreaks. Besides, it is crucial to explore the WASH coverage indicators and their effect on the spread of cholera. Because the impact of inadequate WASH coverage on cholera in Africa contributes largely to the higher cholera incidence due to the ease of pathogen transmission [12]. Thus, improved WASH services, including access to safe drinking water, standard sanitation supplies, personal hygiene practices, and wastewater management, especially in cholera-prone areas and refugee camps would significantly reduce outbreaks by breaking the transmission cycle, enhancing prevention, and promoting community resilience [33].

Another method to upscale the alleviation of outbreaks in cholera-prone areas, would be the introduction of mass immunization movements using the Oral Cholera Vaccines (OCVs) [34]. A few African countries have initiated OCV

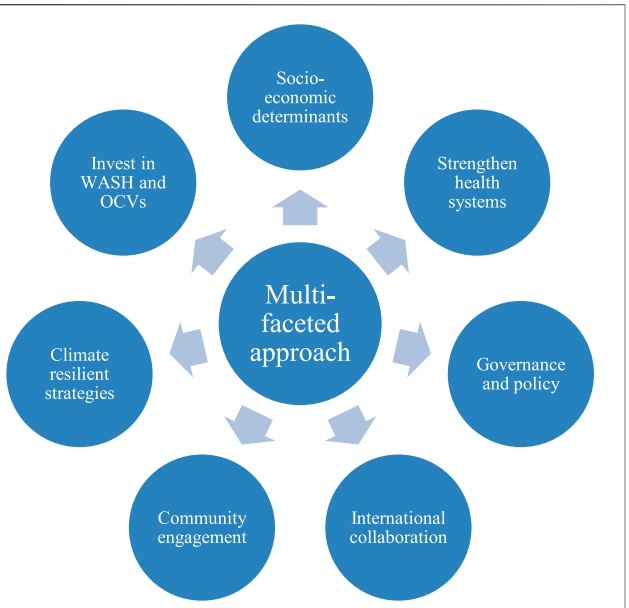

FIGURE 1 | Cholera in Zambia: Explanatory factors and mid-term impact of the sustainable development goals, Zambia, 2024.

campaigns in their respectful predisposed districts. Even though OCVs offer provisional protection, they are certainly an essential component in the fight against cholera. Likewise, local establishments and initiatives led by the community whose aim is to tackle triggers that bring about cholera outbreaks [35], could be supported by governments to unmask the overlooked threats on matters public health. In addition, the healthcare technologies need to be ameliorated to heighten cholera surveillance and medical response in the quest for combatting cholera outbreaks in SSA [36]. This involves developing standard early warning schemes that can detect outbreaks before they spiral out of control [37].

RECOMMENDATIONS

A multifaceted approach to address cholera as a public health problem in Africa should focus on tackling the root causes linked to socioeconomic inequalities. These disparities such as limited access to clean water, sanitation and healthcare are critical drivers of cholera outbreaks in vulnerable populations. Hence, addressing poverty and housing conditions are crucial to mitigating cholera risks, alongside involving policymakers and strengthening international collaboration. In the EMR, multisectoral collaboration is often led by international agencies due to weak local governance. Non-Governmental Organizations (NGOs) equally play a critical role in coordinating cholera responses across sectors in the EMR. Over-reliance on external actors limits the sustainability of such approaches. SSA's focus on strengthening domestic multisectoral frameworks offers valuable insights for EMR, while EMR's reliance on global partnerships highlights the importance of leveraging external support in resource-limited SSA countries (**Figure 1**). Ultimately, an effective approach must integrate health, education, and infrastructure efforts to address the systemic inequities that perpetuate cholera outbreaks in Africa.

Conclusion

Cholera remains a persistent yet preventable public health crisis in Sub-Saharan Africa, exacerbated by socioeconomic inequalities, poor WASH infrastructure, and the impacts of climate change. Despite its devastating effects, cholera often receives inadequate attention and resources, leaving vulnerable communities disproportionately affected. Addressing this crisis requires a holistic approach that prioritizes investments in clean water and sanitation, strengthens healthcare systems, and implements climate-resilient strategies. Empowering local communities through education and proactive policies targeting poverty and inequality can ensure sustainable change. International collaboration is also crucial for funding and technical support. By unmasking the structural challenges underlying cholera outbreaks and committing to comprehensive solutions, the region can break the cycle of neglect and secure better health outcomes for all.

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All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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Community Use and Perceptions of Climate Shelters in Schoolyards in Barcelona

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Objectives: This study explores the use and perceptions of thermal comfort and wellbeing among the local community in the schoolyards in Barcelona that had been transformed into accessible climate shelters.

Methods: We conducted a qualitative evaluation through a spontaneous ethnographic approach, combining 22 non-participant observations in the 11 transformed schoolyards with brief spontaneous interviews with 76 users and 18 caretakers who supervised the schoolyards during non-school days (June–July 2022). We conducted a thematic content analysis. We analyzed user characteristics, thermal comfort and wellbeing, activities and differences by age and gender, social behavior, additional benefits, and areas for improvement.

Results: Adapted schoolyards were mostly visited by families and groups of adolescents with a higher proportion of boys. Participants reported that shade provided coolness and comfort, vegetation offered pleasant and naturalized environments, and water features were enjoyed for their cooling capacity and play opportunities. Schoolyards were mainly used as places for outdoor recreation and socialization.

Conclusion: This study provides policymakers with evidence to support the transformation of schoolyards into climate shelters, creating comfortable outdoor recreational areas for the surrounding urban community.

Keywords: climate change adaptation, community, schools, thermal comfort, urban health

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INTRODUCTION

Climate change has exacerbated the urban heat island effect in the Mediterranean region, leading to hotter summers and more frequent heatwaves [1] This phenomenon negatively affects human health, increasing the risk of hospitalization [2] and heat-related mortality [3]. Urban areas face particular threats due to the lack of green spaces [4]. These challenges highlight the urgent need for effective nature-based mitigation and adaptation strategies to create healthier and more resilient cities.

As part of its Climate Plan, Barcelona City Council has created a network of climate shelter spaces within the city, adapting urban public spaces to provide residents with thermal comfort. These areas

are designed to be easily accessible, safe, and provide comfortable rest areas and free water [5]. As part of this strategy, 11 public primary schoolyards in Barcelona were transformed into climate shelters through the "Climate Shelters in Schools" project. This involved implementing vegetation (trees, green walls, and planters with Mediterranean species), water features (drinking fountains, fountains for playing and cooling, and evaporative misters), shade structures (pergolas and canopies), and seating areas (benches and tiered seating). Each schoolyard was adapted according to its characteristics, potential, and needs [6, 7]. These areas were also integrated into the "School Playgrounds Open to the Neighborhood" program, which aims to make the schoolyards in Barcelona available to the public outside school hours (weekends, holidays, and summer).

Transforming schoolyards into climate shelters is a promising strategy for enhancing urban climate resilience [8–10]. Implementing vegetation, natural surfaces, and shade structures in schoolyards can provide cooler environments, reducing outdoor thermal discomfort and heat stress [11–14]. Green spaces also have the ability to improve mental wellbeing, quality of life, and general health [15–17]. Additionally, incorporating water infrastructure offers potential for drinking and cooling [11].

Climate-adapted schoolyards are not just potential spaces for shelter but can serve as accessible community areas that promote physical activity and outdoor play in natural settings [18] and provide opportunities for social interaction, fostering social cohesion [18, 19]. In addition, schools are strategically located throughout the city, making them easily accessible to large numbers of people, ensuring that the benefits of the intervention are equally distributed throughout the city.

Schoolyard transformations have already proven beneficial for the school community by improving thermal comfort during school hours and promoting play diversification and social inclusion during recess [20]. The present study aims to understand the potential benefits of this intervention beyond the school community, exploring the use and perceptions of thermal comfort and wellbeing of the transformed schoolyards as accessible climate shelters among the local community in Barcelona.

METHODS

Study Design

We conducted a qualitative evaluation study using a spontaneous ethnographic approach, combining non-participant observations and brief spontaneous interviews. The transformations were carried out between July and August 2020. After the implementation, we collected data during non-school periods (summer June–July 2022) as part of the "School Playgrounds Open to the Neighborhood" program.

Study Setting

The study area comprised the 11 schoolyards in Barcelona that had been transformed as part of the "Climate Shelters in Schools" project and were opened to the community. These schools had been selected previously based on their higher climate change vulnerability while ensuring representation of all city districts [7].

Measures

We used a spontaneous ethnographic approach, consisting of non-participant observations combined with brief semi-structured interviews. Non-participant observation involves observing participants and their behavior without actively interacting with them. Photographs with some examples of the interventions implemented in the schoolyards were captured during the observation sessions (**Supplementary Figure S1**).

We performed a total of 22 observations in the 11 schoolyards that underwent the intervention (2 sessions/school). Observations lasted approximately 1.5 h and were conducted on 2 days of the week (1 weekday and 1 weekend day) and in the afternoon during the non-school period (June–July 2022). The schoolyard was divided into various target areas, each defined by the type of equipment available. Target areas were defined before the observations and the same target areas were observed in both sessions. Data were collected through a field diary and included information on the number of users and their characteristics, such as age, gender, and type of relationship between group members (family, friendship, alone). We defined 6 age groups: younger children (aged 0–5 years), older children (aged 6–11 years), adolescents (aged 12–18 years), young adults (aged 19–35 years), middle-aged adults (aged 36–55 years), and older adults (aged >55 years). We also analyzed users' activities and types of play, social behavior, and use of the schoolyard equipment, materials, and areas (paying special attention to the use of shaded areas, interaction with greenery, and use of water facilities). We also gathered data on temperature, relative humidity, and weather (sunny/cloudy/rainy) using a weather app. Shade coverage and the perception of thermal comfort according to the observers were also collected in the various target areas.

We conducted and audio-recorded 3- to 5-minute interviews with 76 users who were spontaneously selected during observations. We aimed to include diversity by selecting different profiles, particularly regarding age and gender. Interviews were conducted individually or in groups. We also interviewed 18 caretakers who supervised the schools during opening hours. Initially, we gathered information about respondents' age and gender. We adopted the same age group classification as that used in the observational data. We then assessed their previous experience with the schoolyard prior to the intervention (yes/no). Users were also asked whether they lived in the neighborhood (yes/no), belonged to the school community (yes/no), and were aware of the role of the schoolyard as a climate shelter (yes/no). The interviews conducted with schoolyard users included questions on how often they visited the schoolyard and their main reasons for doing so. Caretakers were interviewed about users' main characteristics, activities, and reasons for using the schoolyard, as well as their perception of thermal comfort and wellbeing at the schoolyard and differences in schoolyard use according to users' age and gender. Both users and caretakers were asked to provide their opinions on shaded areas, vegetation, and water features, report the features they most appreciated about the schoolyard,

TABLE 1 | Observational data on schoolyard use and thermal characteristics. Presence of shade, observer's thermal comfort, user characteristics, activities and social behavior by schoolyard area. Climate Shelter in Schools, Barcelona, 2018–2022.

Schoolyard area	Shade coverage and observer's thermal comfort	Age group	Activities by gender	Social behavior
Resting areas (including shade structures and/or seats)	Total or partial shade coverage (trees, green wall, shade structures, building) • Average thermal comfort score: 7.5	Children (younger and older)	• Girls and boys: sitting, eating, jumping • Mainly girls: skating	• Solitary or social play • Peer interaction
		Adolescents and young adults	• Girls and boys: talking, sitting, using mobile phones, listening to music	• Verbal interaction with other users • Peer interaction
		Middle-aged and older adults	• Women and men: sitting, resting, talking, reading, writing, using electronic devices, watching their children, viewing others' activities	• Verbal interaction with other users
Sports court	Partial or poor shade coverage (building, trees, shade structures) • Average thermal comfort score: 4.6	Children (younger and older)	• Girls and boys: ball sport games (younger children), running, frisbee • Mainly boys: ball sport games (older children), riding a scooter • Mainly girls: skating	• Social play • Parent-child interaction • Interaction with children of similar and different ages
		Adolescents and young adults	• Mainly boys: ball games, riding a scooter	• Social play • Peer interaction
		Middle-aged adults	• Mainly men: playing with their children	• Parent-child interaction
Playground areas (i.e., sandpit, slide, climbing wall)	Total or partial shade coverage (building, shade structures, trees) • Average thermal comfort score: 8.4	Children (mainly younger)	• Girls and boys: sandpit, slide, frisbee, climbing, interacting with nature, chasing games • Mainly girls: balancing, building games, bowling, pétanque	• Solitary or social play • Peer interaction
		Middle-aged adults	• Women and men: watching their children, sitting, resting, talking to other adults, playing with their children	• Verbal interaction with other users • Parent-child interaction
Water features	Not applicable	Children (younger and older)	• Girls and boys: Playing and cooling with water, drinking water	• Solitary or social play • Peer interaction
		Adolescents and young adults	• Mainly boys: drinking water, cooling down with water	• No interaction
		Middle-aged adults	• Women and men: little use of the fountains	• No interaction

and propose suggestions for improvement. Respondents were also asked to rate the suitability of the schoolyard as a climate shelter on a 1 to 10 scale.

Data Analysis

Interviews were transcribed and complemented with the interviewer's field notes. Observation notes and interview transcripts were analyzed following a thematic content analysis. Assisted by ATLAS.ti software, we coded the data thematically and subsequently grouped the emerging codes into different categories and sub-categories. We adopted a grounded theory approach, allowing codes and categories naturally arise from the data and refining our coding frame throughout the data analysis process. Three members of the research team with biomedical, medical, and pharmaceutical background were involved in the coding process. Codes and categories were agreed upon by all members of the research team. We analyzed each technique separately and converged the data during the interpretation of the results.

For the observations, we described the observed activities, social behavior, the presence of shade, and the observer's thermal comfort. We analyzed these factors for different user characteristics and for each type of schoolyard area, including resting areas (i.e., places designed for relaxation and peacefulness, which include shade structures, seats, or both, and may also have areas with vegetation), sports courts, playground areas (i.e., sandpit, climbing wall, or slides), and water features. We also calculated the median temperature and median relative humidity of the observation days.

For the interview transcripts, six categories emerged from the thematic analyses: 1) users' characteristics; 2) thermal comfort and wellbeing; 3) activities and differences by age and gender; 4) social behavior; 5) additional benefits; and 6) areas for improvement. We also calculated the caretakers' and users' mean scores on their perception of the suitability of the schoolyard as a climate shelter.

RESULTS

Non-Participant Observations

Temperatures during the observation sessions ranged from 27°C to 30°C (median = 29°C), relative humidity ranged from 17% to 52% (median = 45%) and the weather was mostly sunny. We observed a total of 263 community members (90 groups) using the climate shelters, with the number of users ranging from 0 to 24 depending on the school and day. In most of the schoolyards, we observed a higher number of men and boys (n = 168) than women and girls (n = 90). The gender of 5 individuals was not recorded. We also observed individuals from different age groups, mainly younger children (n = 33), older children (n = 67), adolescents (n = 57), and

TABLE 2 | Respondents' characteristics of the spontaneous interviews. Climate Shelters in Schools, Barcelona, 2018–2022.

	Caretakers (N = 18)	Users (N = 76)
	n (%)	n (%)
Gender		
Female	13 (72.2)	32 (42.1)
Male	5 (27.8)	44 (57.9)
Age (years)		
Younger children (aged 0–5)	0 (0.0)	7 (9.2)
Older children (aged 6–11)	0 (0.0)	20 (26.3)
Adolescents (aged 12–18)	4 (22.2)	12 (15.8)
Young adults (aged 19–35)	9 (50.0)	1 (1.3)
Middle-aged adults (aged 36–55)	4 (22.2)	31 (40.8)
Older adults (aged >55)	1 (5.6)	5 (6.6)
Previous experience with the schoolyard before the intervention (yes)	6 (33.3)	30 (39.5)
Lives in the neighborhood (yes)		51 (67.1)
Belongs to the school community (yes)		17 (22.4)
Is aware of the schoolyard's role as a climate shelter (yes)		21 (27.6)

middle-aged adults (n = 86). Occasionally, we observed young adults (n = 9) and older adults (n = 11).

Table 1 shows the results from the observational data regarding the use of the schoolyard and thermal characteristics by schoolyard area. Areas designed for resting (i.e., areas with shade structures, seats, which may or may not include vegetation) and children's areas (i.e., sandpit, climbing wall, slides, etc) had total or partial shade, while the sports court areas had partial or poor shade coverage. Shade was provided mainly by shade structures, trees, and the school building. Observers' perceptions of thermal comfort were more favorable in the areas with more shade, such as the resting and children's areas compared to the sports court.

Resting areas were popular among middle-aged adults, who mainly sat in the shade, chatting with other adults, and watching their children. Children, adolescents, and young adults used the shaded and seating areas to rest and sit briefly between active play periods. Children also used these areas as places to eat or engage in vigorous activities such as jumping or skating, either alone or with their peers. Adolescents and young adults used these spaces for quieter activities including chatting with friends, using mobile phones, or listening to music.

Sports courts were one of the most frequently used areas. Children, adolescents, and young adults played sports games with balls, especially football and basketball. Younger children, regardless of gender, were observed in the court, while older children, adolescents, and young adults who were playing in this area were mostly boys. Children also engaged in other activities in this area, such as running, playing frisbee, and skating (mainly girls). We observed social play between same-age groups as well as mixed-age groups.

Children's areas were mostly used by younger children and their parents. Children played alone or with their peers in the sandpit, on slides, at the climbing wall, or occasionally interacted with nature. Parents watched their children or talked to other adults, while sitting under the shade.

Fountains were mainly used by children, adolescents, and young adults. Children used them to play, cool off, and drink water. Adolescents and young adults, mostly boys, used them to drink water and cool off during short breaks from their main activity, usually football.

Brief Spontaneous Interviews

User Characteristics

Respondents' characteristics are shown in **Table 2**. Most caretakers (72.2%) were female and 50% were aged between 19 and 35 years. Most users (57.9%) were male and the most widely represented age groups were middle-aged adults (40.8%), older children (26.3%) and adolescents (15.8%). The majority of users (67.1%) lived in the neighborhood where the school was located and 27.6% were aware of the role of the schoolyard as a climate shelter. As shown in **Table 3**, caretakers reported that schoolyards were mainly visited by families (adults with children of both genders aged under 12) and/or groups of friends consisting of adolescents and young adults (more boys than girls).

Thermal Comfort and Wellbeing

In general, users perceived the schoolyard as thermally comfortable and enjoyed the presence of shade areas provided by natural and artificial structures. Some respondents familiar with the pre-intervention schoolyards noted significant improvements in shade coverage after the transformations. According to one of the caretakers, the abundance of shade encouraged families to use the schoolyard. At some schools, caretakers observed an increase in new users visiting the schoolyards following the transformations. Users emphasized the importance of water features, especially during hot weather. These elements were considered effective for cooling off and staying hydrated and, according to caretakers, were mainly used by children and adolescents. Respondents noted that vegetation created a fresher, more pleasant environment, while creating more beautiful and naturalized spaces compared to pre-intervention schoolyards and improving air quality. Notably, respondents experienced a sense of wellbeing, and some expressed their satisfaction with the open schoolyards, finding them more comfortable than other neighborhood areas. This was particularly the case for the neighborhoods lacking green space, water, or shade. Adolescents and young adults stated they prefer the transformed over non-transformed schoolyard because of the shade and water structures (**Table 3**).

TABLE 3 | Schoolyard use and users' and caretakers' perceptions collected through brief spontaneous interviews. Climate Shelters in Schools, Barcelona, 2018–2022.

Category	Code	Quotations
User's characteristics	• Adults with children (families) • Adolescents (groups of friends) • Higher number of boys	"The people who usually come here are families with children. Sometimes, teenagers also come and use the court to play football or basketball." (22-year-old female caretaker) "More boys than girls come to the schoolyard." (17-year-old male caretaker)
Thermal comfort and wellbeing	• Natural and artificial shade • Water for drinking and cooling off • Sense of thermal comfort and wellbeing • Improved air quality (vegetation) • Improved aesthetics (vegetation) • Comfort provided by seating areas • Significant contribution to the neighborhood (shade, water, vegetation, comfort)	"I feel good here, cool, and there are plants, and it's pleasant." (72-year-old female user) "We use [the water features] to drink and cool off when it's very hot." (6- and 9-year-old male users) "The perception of heat and wellbeing is quite good. It's comfortable." (17-year-old male caretaker) "It's good because there is a lot of shade and, well, I like being in the shade where it's not so hot and I do not sweat so much." (8-year-old male user) "Vegetation is good because it offers a beautiful way to create shade." (20-year-old female caretaker)
Activities and differences by age and gender	• Ball games and other sports played mainly by older children and adolescents • Large number of male participants in ball sports • Greater play diversification among younger children: playing with water, sandpit, slides, climbing • Sitting, chatting, and relaxing mainly by adults • Men play with their children more often	"Families with young children usually play in the children's area, in the sandpit or sometimes with water, and those who are older usually play basketball or football in the court." (22-year-old female caretaker) "I do not see any 20-year-old girls playing football or basketball here." (48-year-old female caretaker) "Fathers and mothers sit in shaded areas or play with their children." (27-year-old male caretaker)
Social behavior	• Meeting friends • Social play (children and adolescents) • Same-age and mixed-age playgroups • Verbal interaction with other users (parents) • Respect among users	"A friend of mine usually comes here and we play basketball together. And I also play with my father." (9-year-old female user) "15- to 20-year-old boys usually come to play football (. . .). They let young children join in. It's great. That way young children do not feel excluded." (48-year-old female caretaker)
Additional benefits	• Friendly, car-free, and supervised • Clean • Closeness to home • Peacefulness, homely, not crowded • Better equipped than other public recreational areas	"I come here so my daughter can play and have space, be calm, and can meet other kids, and it's not crowded . . . If I go to other parks in the city, there are usually more people. Here it's more quiet and safer." (48-year-old female user)
Areas for improvement	• Perception of heat • Insufficient shade, especially in the court • Lack of places to sit under the shade • Little, insufficiently grown, or poorly maintained vegetation • Dissatisfaction with fountain height, water jet, and number • Potential waste of water and safety concerns • Damaged equipment • Little diversity of playing areas • Insufficient provision of material and equipment • Underutilization and little dissemination	"They should look for a measure to really provide more shade in the sports court. It should be covered because it's a large area of sunlight." (53-year-old male user) "Some trees are missing water or. . .they look a little dry." (13-year-old male user) "I like the fountain, but it would be better if you did not have to lower your head so much to drink and I would improve the water jet." (10-year-old male users)

Figure 1 shows respondents' scores regarding their perception of the suitability of schoolyards as climate shelters. Caretakers' mean score was 8.8 out of 10 while users' score was 8.2.

Activities and Differences by Age and Gender

As shown in **Table 3**, caretakers noted that younger children tend to play a wider range of games than older children and adolescents, who usually engage in a single activity, mainly football or basketball. They also reported that users playing ball sports were usually boys. According to caretakers and some users, younger children usually engaged in activities such as playing in the sandpit, on the slides, or climbing. Another common activity, particularly among younger children, was playing with water. Adult users and caretakers stated that parents usually sat in shaded, seated areas, where they chatted with other users or relaxed.

Social Behavior

Respondents described the climate shelters as places for social gathering where they usually met friends and interacted with other families (**Table 3**). According to caretakers, while children, adolescents, and young adults played with their peers, parents usually interacted verbally with other users. Respondents also reported that adolescents occasionally let children of different ages join in their football games.

Additional Benefits

Users expressed their satisfaction with schoolyards being open to the public. Adults found them to be safe because, in contrast to other parks and playgrounds in the neighborhood, schoolyards were supervised by a responsible adult and were car-free. They also described the schoolyards as being peaceful, calm, clean, and uncrowded, making them a welcoming environment for their

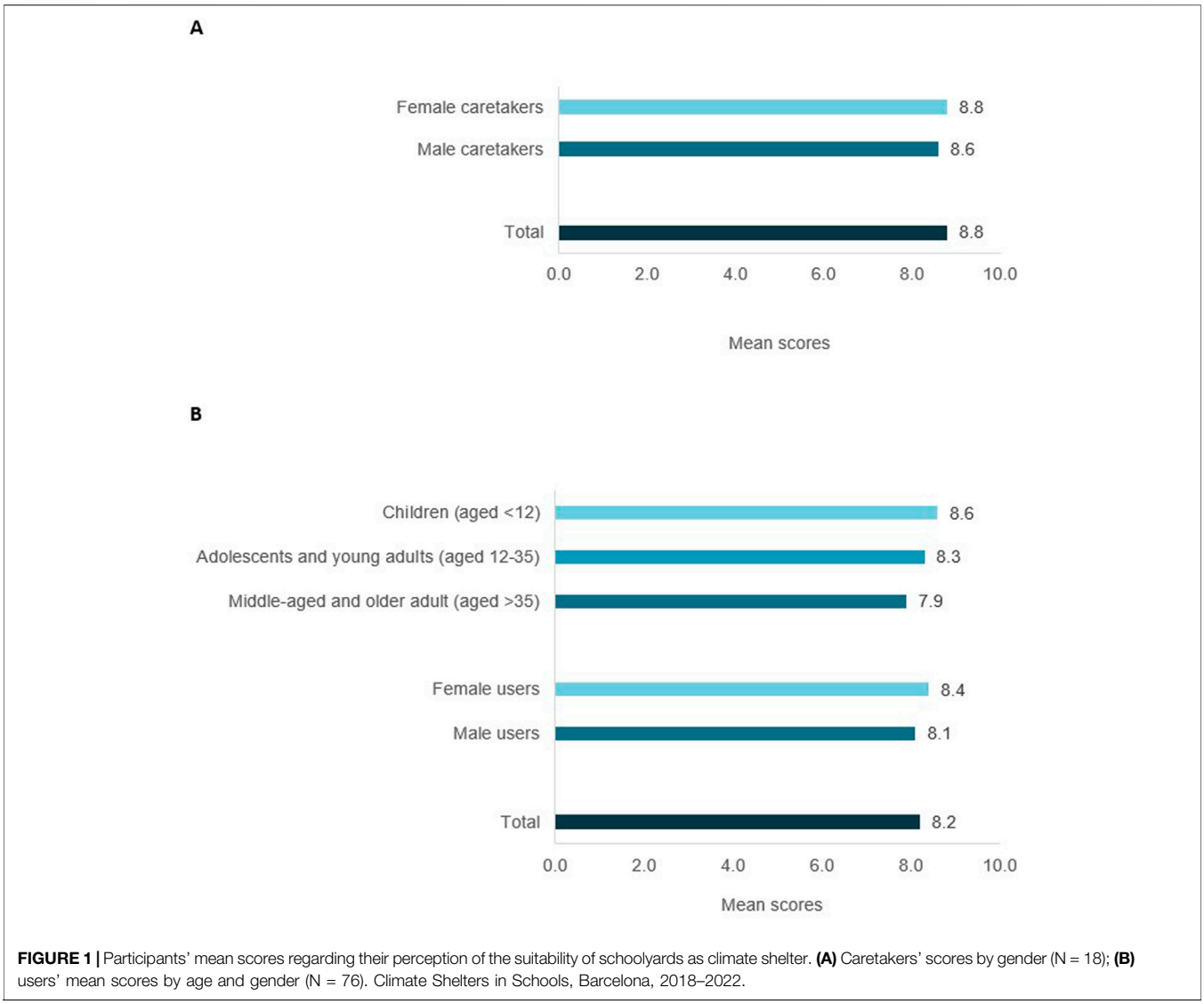

FIGURE 1 | Participants' mean scores regarding their perception of the suitability of schoolyards as climate shelter. **(A)** Caretakers' scores by gender (N = 18); **(B)** users' mean scores by age and gender (N = 76). Climate Shelters in Schools, Barcelona, 2018–2022.

children. Another positive feature was their proximity to their homes. Finally, users emphasized that schoolyards were better equipped than other public recreational areas in the neighborhood due to the presence of sports courts, a diversity of areas, and comfortable facilities (**Table 3**).

Areas for Improvement

Despite giving positive feedback, respondents also suggested specific areas for improvement (**Table 3**). Both users and caretakers reported that some areas of the schoolyard were still hot, particularly the sports courts where there was little or no shade. In addition, adult users found that shaded seating areas were scarce in some schools. Respondents believed that vegetation was insufficiently grown or poorly maintained and suggested increasing the amount of greenery. Although water features were among the most widely used and appreciated interventions, concerns were raised about the fountains being too high for younger children and the water jets being too strong. Users also suggested increasing the number of these elements. Some of them expressed additional concerns about potential water waste and the puddles that are sometimes formed.

Some adults requested more varied play spaces and additional materials. Lastly, some respondents stressed that information on the program should be more widely disseminated to increase utilization of these schoolyards (**Table 3**).

DISCUSSION

Transforming schoolyards into publicly accessible climate shelters through the provision of vegetation, water, and shade provides a unique opportunity for urban adaptation to climate change. This study provides evidence of the benefits of this initiative, demonstrating the potential of schoolyards to provide urban local communities with areas for cooling and relaxation while offering infrastructure that encourages outdoor recreation and social interaction in safe and welcoming spaces.

In this study, both the observational data and caretakers' reports indicated that the schoolyards were mainly used by families with children and groups of adolescents. This finding may be influenced by the schoolyards' designs, which incorporate features and amenities tailored to younger users. While older adults can also benefit from this type of initiative, a small number were observed visiting the schoolyards. Possible reasons for their low numbers are that this age group may not be fully informed about the availability of these spaces as climate shelters [21] or may prefer visiting outdoor green spaces without the presence of young people [22] or outside of afternoon hours [23].

In line with the findings of previous studies on the use of outdoor public spaces [24–26], our results showed that boys used the schoolyard more than girls outside school hours, especially among adolescents and young adults. In this study, we found that the presence of sports courts may attract adolescent boys to the schoolyard since they reported that these facilities were one of their favorite features. However, these facilities might appeal less to girls [26–28], which may explain why they tend to visit these spaces less frequently outside school hours. These results highlight the need to encourage the utilization of open schoolyards among adolescent girls. Prior literature suggests programming can enhance parks' inclusivity by increasing accessibility, flexibility, relatability, and sociability [29]. Strategies to increase schoolyards' usage among adolescent girls should focus on implementing targeted community programs that increase access to organized activities or planned events that offer a wide range of recreational activities tailored to their interests. An additional initiative could be actively involving adolescent girls in the design process to understand their needs and preferences.

In the present study, users and caretakers showed high levels of satisfaction with the schoolyards as climate shelters. They appreciated the shade, water, and vegetation, which reduced perceived thermal discomfort and made the areas more comfortable than other neighborhood spots and non-transformed schoolyards. Despite limited pre-intervention data, our finding suggests that a subset of respondents observed significant improvements in post-intervention schoolyards when compared to their previous state. The provision of greater shade coverage, water features, and vegetation appears to have created more inviting environments. Observational data showed that fountains and evaporative misters for cooling purposes were frequently used by young users, as were shaded and seating areas for relaxation by adults. These results add to a growing body of evidence demonstrating the potential of greenery, water features, and shade to reduce heat stress and improve urban thermal comfort [11, 12, 14, 17, 30]. Overall, our findings support the idea that using multiple cooling measures in urban schoolyards is a promising strategy for creating outdoor areas where the local community can comfortably enjoy spending time.

Supported by previous work [18, 19], we found that climate-adapted schoolyards also provided opportunities for outdoor recreation outside school hours, especially for children and adolescents. In line with prior research [31–33], our findings suggest that the presence of sports courts are important for young people's engagement and physical activity in urban green spaces. Also in line with other studies [25, 26, 28, 31], we found a gender gap in the use of such areas, with use being higher among boys. Our study also revealed that younger children tend to engage in a wide diversity of activities and use different spaces (e.g., resting areas, playground, court) during their visits. Notably, water fountains were one of the favorite features for younger children to play with, indicating the benefits of such features not only for cooling but also for children's enjoyment.

Recent work has suggested the potential of green schoolyards to become areas for social engagement [18, 19]. Our results show that seating and shaded areas encouraged verbal interaction among schoolyard users, particularly parents but also adolescents and young adults. These findings are in agreement with a previous study reporting that adults often socialized on benches in Mediterranean urban playgrounds [27]. Another study reported that seating and shaded areas, as well as sports courts, encouraged socialization among adolescents in parks [28]. In this study, we found sports courts and playground areas in the schoolyards encouraged social interaction by fostering social play among groups of young people of both similar and different ages. Social interaction during outdoor play and mixed-age play can positively impact young people's socio-emotional development and social cohesion, potentially extending to their parents [16, 34]. Thus, our findings highlight the value of designing schoolyards as community spaces with a diversity of areas that may encourage various types of socialization among different population groups, providing opportunities for community bonding.

Characteristics such as perceived safety and cleanliness have been linked to greater use of community parks [26, 35, 36]. Thus, a positive finding of our study is that parents perceived the schoolyards as safe (car-free and supervised), peaceful, and clean. Indeed, they cited these factors as reasons for choosing the transformed schoolyards over other community areas. Another factor attracting users to the schoolyards was their close proximity to home, supporting the need to increase the number of urban climate-adapted recreational spaces near residents' homes. This finding is consistent with previous research reporting a link between residential proximity and greater park use [24].

The results of this study indicate that potential improvements of the intervention include increasing shade coverage in sports courts which could enhance schoolyard users' thermal comfort, as evidenced by both respondents' and observers' perceptions of heat, particularly in these areas. In addition, greater efforts are needed to maintain vegetation in good condition. Some respondents also raised concerns about potential water waste, which is particularly significant in cities facing water shortages, such as Barcelona. Improving the efficiency of water interventions and promoting responsible water use among residents could help provide cooling opportunities while minimizing water waste. Respondents' suggestions for improvement include increasing the amount of vegetation, as well as the number of fountains and shaded seating areas. Tackling these issues may improve users' enjoyment and comfort in schoolyards.

Our results also indicated potential underutilization of the schoolyards, with the number of users observed ranging from 0 to 24. Limited use of schoolyards outside school hours has already been reported in the U.S. [37]. Our findings could be partly explained by low awareness of the program among city residents.

This explanation is supported by previous research suggesting that Barcelona residents have little awareness of the municipal climate network [21], as well as our finding that most interviewees reported they were unaware of the schoolyard's role as a climate shelter. Therefore, greater dissemination of the program could increase the use of schoolyards as climate shelters. To achieve this, the local government, educational institutions, and community organizations must collaborate. Strategies may include raising awareness through community events, targeted communication campaigns, and actively involving the local community in decision-making processes. Another reason that may contribute to the low number of visits to schoolyards could be that the transformed schoolyards do not currently seem to accommodate the needs of all population groups, as evidenced by the small number of older people in our study. In this regard, an important consideration is that while these spaces are open as a community climate shelter during off-school hours, schoolyards are primarily designed and adapted to accommodate children's needs.

This study is limited by the absence of a comparison group and pre-intervention data. However, some data is available from users who were familiar with the schoolyard before the interventions and perceived changes after the transformations. No comparable schools were opened to the community during data collection (summer 2022). In addition, data collection was restricted to 2 visits per school, which could limit the generalizability of the results. To minimize potential biases, we ensured consistent timing (afternoon visits), used standardized protocols, avoided certain weather conditions (e.g., rainy days), and conducted weekend and weekday observations to account for potential fluctuations in patterns of use. Furthermore, we enriched the observational data with interviews from informants such as caretakers, who provided a broader perspective on the usual schoolyard dynamics. Finally, our qualitative approach offered valuable insights into participants' experiences with the intervention and allowed us to understand the potential effects of specific elements (i.e., vegetation, water, shade, seats) and how the intervention could be improved.

This study adds to existing knowledge by evaluating an innovative project ("Climate Shelters in Schools") to demonstrate how combining water, vegetation, and shade to schoolyards and opening them to the public can create climate-resilient settings that enhance the wellbeing of the local community. The study offers valuable insights for policymakers and urban planners to optimize the design and implementation of these types of climate adaptation strategies, especially in cities facing challenges similar to those in Barcelona. This study also complements previous research assessing the impact of the same intervention at the school-level [20], offering a broader perspective on its benefits.

Another strength of the study is the use of different methods to gain deeper understanding of schoolyard use and perceptions of the intervention. We included the perceptions of people of different ages and genders and incorporated the viewpoint of community members as well as schoolyard caretakers.

Conclusion

The schoolyards transformed as part of the "Climate Shelters in Schools" project can positively impact the local community, creating safe and convenient spaces where residents can feel comfortable and protected from the heat. The diversity of features and areas in the schoolyards can encourage recreation, exercise, and social interaction, particularly among adolescents, children, and their parents. While the benefits seem clear, this study also underlines the need to maintain greenery, improve water sustainability, and provide greater shade coverage in future implementations. The successful implementation of these projects requires effective dissemination strategies to maximize their impact. Overall, we provide policymakers with evidence to guide the adaptation of schoolyards into climate shelters, which can benefit the local community by providing comfortable recreational environments.

ETHICS STATEMENT

The studies involving humans were approved by Parc de Salut Mar Clinical Research Ethics Committee (2019/8820/I). The studies were conducted in accordance with the local legislation and institutional requirements. The ethics committee/ institutional review board waived the requirement of written informed consent for participation from the participants or the participants' legal guardians/next of kin because oral consent was obtained and audio-recorded from users and caretakers of the schoolyards open to the neighbourhood at the beginning of the interviews.

AUTHOR CONTRIBUTIONS

Conceptualization, MJL, MM-D'O, and XC; methodology, MJL, MM-D'O, MS-M, and XC; validation, XC; formal analysis, MS-M; investigation, MS-M; writing–original draft preparation, MS-M; writing–review and editing, MJL, MM-D'O, and XC; visualization, MS-M; supervision, MJL and XC. All authors contributed to the article and approved the final submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

GENERATIVE AI STATEMENT

The author(s) declare that no Generative AI was used in the creation of this manuscript.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2025.1608083/full#supplementary-material

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Extreme Temperatures, Hospital Utilization and Public Health Insurance Spending

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Objectives: This study examines the impact of extreme temperatures on hospital utilization and public health insurance program spending in a country with no universal health coverage.

Methods: Using nationwide U.S. county-level panel data and a fixed effects model, we estimate the impact of annual variations in the number of hot and cold days on hospital utilization and medical reimbursements for low-income and elderly beneficiaries of public health insurance.

Results: Our results show that extreme heat and mild cold increase medical reimbursements to low-income beneficiaries, while extreme cold increases benefit transfer to the elderly. We find that extreme temperatures have particularly stronger positive effect on hospital admission and inpatient care utilization among old and poor patients. The fiscal impact of extreme temperatures is greater in areas with more generous income eligibility criteria for public health insurance.

Conclusion: The study advances our understanding of how extreme temperatures affect healthcare utilization of low-income and elderly populations and the roles public health insurance plays in supporting them from increasing weather risks. Our findings suggest that climate change can augment the financial burden on governments.

Keywords: extreme temperature, public health insurance, public health spending, health expenditure, hospitalization, healthcare utilization, climate change, United States

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INTRODUCTION

As climate change unfolds, extreme heat and cold events are increasing worldwide, posing growing risks to human health and causing substantial economic and welfare costs. The effects of extreme temperature on mortality [1–5] and morbidity [6–9] have been well documented by studies from both developed and developing countries. Earlier studies show that heat increases the use of hospital care and particularly emergency health services [6, 10–13], while cold may reduce hospital visits [14]. However, there remains limited understanding of how extreme weather conditions influence the use of different types of healthcare services, and the associated financial implications for both households and governments. Even less is known about how extreme temperatures affect government spending on public health insurance programs. In the U.S., Medicare and Medicaid enrollees are primarily low-income and elderly individuals, who are particularly vulnerable to extreme weather due to higher

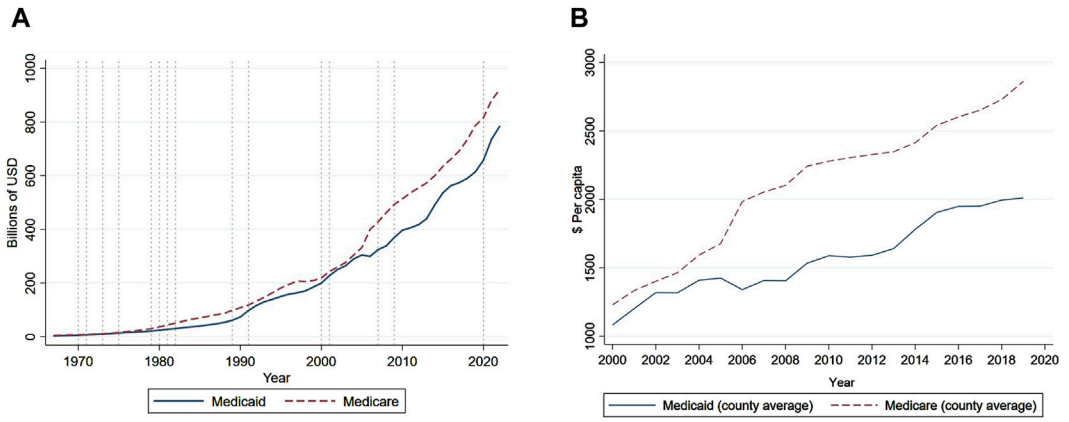

FIGURE 1 | Historical trend of Medicaid and Medicare transfer (United States, 2021). Note: Panel **(A)** shows the trend in the national sum of annual Medicaid and Medicare transfer payments. Panel **(B)** plots the county-level annual average amount of transfer payments during the sample period from 2000 until 2019.

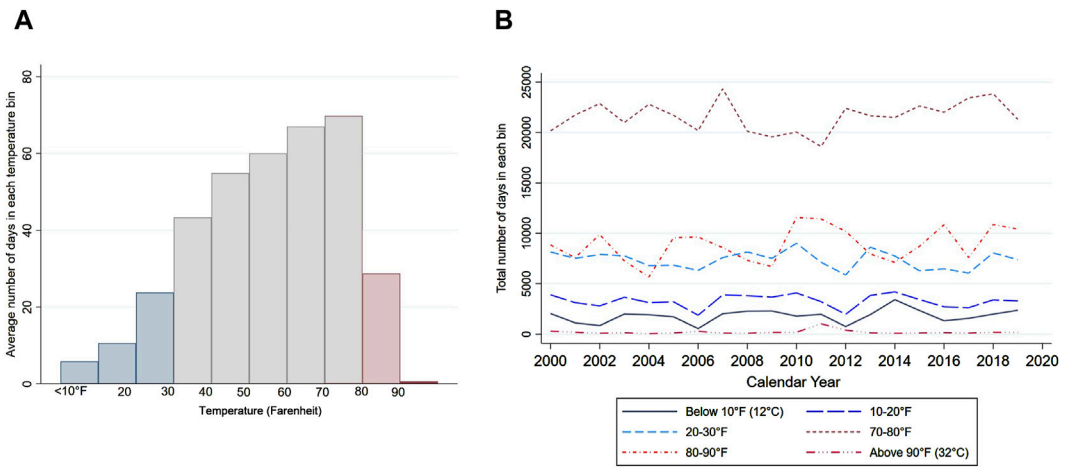

FIGURE 2 | Distribution of daily mean temperatures (United States, 2020). Note: Panel **(A)** figure shows the distribution of daily mean temperatures across ten temperature bins. The horixontal axis denotes the temperature bin separated by 10°F (or 12.2°C). Panel **(B)** shows the national average number of days in each temperature bin over the sample period.

medical risks and limited capacity to manage environmental challenges [15] Therefore, it is crucial to understand whether these individuals access more medical services in response to extreme temperatures, and whether public health insurance program spending increases further due to extreme weather.

Governments in the U.S. play an important role in providing and financing health services. At the federal level, Medicaid and Medicare spending, when combined, accounts for the largest share of the federal outlay (24% and 1.18 trillion USD in 2019). State and local governments spend a considerable part (322 billion US dollars in 2020) of their total general expenditure on public health services and hospitals. Conceptually, there are multiple channels through which extreme temperatures can affect medical service utilization and public health spending. First, heat and cold may affect the demand for healthcare services by worsening certain health conditions, particularly among the vulnerable populations such as the elderly. Such adverse health impacts can raise utilization of healthcare services and related spending. Second, extreme heat and cold may decrease healthcare service utilization by disrupting infrastructures and transportation systems [16]. Extreme temperatures may also impact adequate service provision at hospitals if hospital infrastructures are damaged, such as through power outages. The situation can be more complicated when the healthcare system does not meet the increasing demand, causing delays and decreases in healthcare utilization [16]. In this paper, we explore several mechanisms, by estimating the net effects of heat and cold on hospital service utilization.

Our analysis is based on nationwide U.S. county level annual panel data from 2000 to 2019 and hospital level annual data from 2008 until 2019, leveraging the plausibly exogenous annual variations in the number of extreme hot and cold days within each county. First, we find that extreme heat increases overall

hospital utilization (admissions, inpatient days, and emergency room visits), while cold reduces emergency room visits. Second, our study demonstrates that extreme heat and mild cold increase Medicaid benefit transfer payments, while extreme cold increases Medicare transfers. Third, we find that heat and cold induce a larger increase in Medicaid benefit transfers in areas with more generous public health insurance. We also find that the impact of extreme heat and mild cold on Medicaid transfers is more pronounced in counties with more elderly and low-income populations.

Our research contributes to different strands of literature on climate economics, public health policy, and public finance. First, this is one of the first studies to examine the fiscal implications of extreme temperatures for government spending on public health programs. No study has yet analyzed the impact of extreme weather conditions on public health insurance costs. Previous studies have documented how extreme weather shocks affect local economies, personal income, and other socioeconomic outcomes [17]. Meanwhile, other studies have investigated the effects of natural disasters such as extreme weather events on national and local governments finances including public spending and intergovernmental transfers [18–24], but only very few have examined the effects of disasters (hurricanes and flooding) on social safety net spending [23, 25]. This study fills the gap in the existing literature by focusing on the impact of extreme temperatures on public health insurance program spending through the mechanism of health service utilization, and also considering how these effects may vary depending on the generosity of the state-level Medicaid program.

A previous study reported larger increases in emergency hospital admissions associated with extreme cold than with extreme heat in England, showing a prominent effect among senior and socially deprived patients [8]. Nonetheless less is known about how extreme temperature may affect healthcare utilization among low-income and elderly populations covered by targeted public health insurance in a country without universal health coverage. Existing studies in the U.S. focus on the effect of extreme heat on hospital utilization in a specific city or state, which limits their external validity. For instance, several studies have shown the impact of extreme heat on hospital admissions in a single metropolitan city or a state [26–28]. Other studies focus on documenting the health impact of heat on specific population, such as the elderly [29–32] or pregnant females [33–35].

Therefore, the purpose of this paper is to present empirical evidence on the net effect of extreme temperatures on medical service utilization by patients covered by public health insurance and government expenditure on these programs in a developed country with no universal health coverage.

METHODS

Data

First, to create the temperature variables, we obtain the station-level daily temperature data from the Global Historical Climatology Network of the National Climate Data Center (NCEI). Our sample time frame is from 2000 until 2019. We measure the daily temperature using a simple average between the maximum and minimum temperatures reported by the NCEI and map the weather stations to counties using the station's latitude and longitude information. If a county contains multiple weather stations, we average their measures for each day following the previous literature [36]. This approach helps to minimize the impact of localized variations and outliers from individual stations, providing a consistent and reliable dataset for analysis. We merge our weather data with public medical transfer and hospital utilization data obtained from multiple sources. We aggregate the daily weather data to the county level for each year, measuring the number of days with temperatures falling in predefined bins and annual precipitation.

We use two separate samples depending on the outcome variable. In the hospital utilization sample, the unit of analysis is hospital-by-year, while in the medical transfer sample the unit is county-by-year. Our hospital utilization data is from the American Hospital Association Annual Survey, a yearly dataset that includes hospital level utilization records such as hospital admissions, inpatient day, emergency department and outpatient visits [37]. The final hospital-level sample is a strongly balanced annual panel of 5,558 hospitals in 2,457 counties from 2008 until 2019 (49,552 observations). We consider hospital utilization as a reasonable indicator of healthcare service utilization since hospital care represents the largest share of personal healthcare spending in the country.

For the medical transfer analysis, we use a separate annual county-level sample (57,809 observations for 3,045 counties) from 2000 until 2019 on government payments through public medical programs from the Regional Economic Information System published by the Bureau of Economic Analysis. Medical transfer measures are government transfer payments made directly or through intermediaries to healthcare providers for services utilized by individuals covered by Medicare and Medicare. Public health insurance is an integral part of the U.S. healthcare system and finances a sizable share of medical service fees incurred by low-income or older Americans. Medicare benefit transfers are paid by the federal government, since Medicare is a federal program. These fees have been increasing rapidly as shown in **Figure 1**. **Table 1** Panel A shows that benefit transfer (reimbursement of medical service fees from the government) to Medicaid beneficiaries accounts for 96% of total Medicaid expenditure in 2019. Medicare is primarily financed through the federal government's general revenues and payroll taxes. State Medicaid programs are co-financed by the federal and state governments, while some states also require their local governments to share the non-federal portion of Medicaid expenditure.

We also control for county-level socioeconomic and demographic characteristics that vary annually. These time-varying characteristics include the percentage share of Black, Hispanic or senior populations (from American Community Survey), unemployment rates (from the Bureau of Labor Statistics), and median personal income and weekly wage in the private sector (from the Bureau of Economic Analysis), all of which are aggregated to the county-annual-level. **Table 2**

TABLE 1 | Medicaid enrollment and expenditures, selected years (United States. 2018).

Panel A. Medicaid enrollment, benefit and administrative expenditures

Fiscal Year	Enrollment (Millions)	Benefit expenditures			Administrative expenditures		
		Federal (%)	State (%)	Total ($bn)	Federal (%)	State (%)	Total ($bn)
1970	14	53	47	4.9	50	50	0.2
1980	19.6	55	45	24	58	42	1.2
1990	22.9	56	44	68.7	57	43	3.5
2000	34.5	57	43	195.7	56	44	10.6
2010	54.5	68	32	383.6	55	45	17.9
2017	73.4	62	38	572.2	64	36	27.8
2019	75.1	62	38	611.7	62	38	27.7

Panel B. Medicaid benefit payments: share by beneficiary group and total amount

Fiscal Year	Aged 65Y	Disabled <65Y	Children <20Y	Adults 20–64Y	Expansion Adults 20–64Y	Total ($ per enrollee)
2010	38.3	44.6	6.7	10.4	NA	40,705
2011	38.0	44.2	6.9	10.9	NA	41,434
2012	38.1	44.5	6.9	10.5	NA	40,013
2013	36.8	45.5	7.1	10.7	NA	41,084
2014	35.7	45.0	7.6	11.7	0.1	41,145
2015	34.2	45.7	8.0	12.2	0.2	42,001
2016	34.0	45.8	8.2	11.9	0.1	43,220
2017	33.6	45.4	8.5	12.5	0.1	44,870
2018	33.1	45.8	8.8	12.3	0.1	44,526
2019	32.7	45.9	8.9	12.5	0.1	45,337

Note: Enrollment count is in millions of persons, while benefit and administrative expenditures are in billions of US dollars ($bn). Figures are from "2018 Actuarial report on financial outlook for Medicaid" by the Office of the Actuary Centers for Medicare and Medicaid Services, United States Department of Health and Human Services.
Note: Payment shares by beneficiary group are indicated as percentages. 65Y indicates at or above 65 years of age; <65Y means less than age 65; <20Y stands for less than age 20; 20–64Y refers to between ages 20 and 64. All figures are from "2018 Actuarial report on financial outlook for Medicaid" by the Office of the Actuary Centers for Medicare and Medicaid Services, United States Department of Health and Human Services.

shows the summary statistics of both hospital and transfer samples.

Empirical Models

We examine the impact of extreme temperature, measured by the number of extreme hot and cold days, on a variety of health-related outcomes including hospital utilization and transfer payments through Medicare and Medicaid. We first model the effect of temperature on various hospital utilization outcomes using the following two-way fixed effect model as shown in **Equation 1**:

$$U_{i,c,t} = \Theta D_{c,t,j} + \alpha M_{s,t} + \Pi X_{c,t-1} + \gamma i + \lambda t + \varepsilon_{i,c,t} \quad (1)$$

Where $U_{i,c,t}$ is hospital utilization outcome in hospital i in county c in year t. We specifically look at outcomes such as hospital admissions, emergency room visits; inpatient days and outpatient visits; share of Medicaid and Medicare inpatient days, all of which are in logged terms. $D_{c,t,j}$ is a vector of county-level temperature variables of interest, denoting the ten number of days in county c in year t where the daily average temperature fell in the jth of the ten temperature bins. Following Deschenes and Greenstone (2011), we create 10 temperature bins, separated by 10°F from below 10°F (−12.2°C) to above 90°F (32.2°C) and measure the number of days in a county-year with temperatures falling in each bin or prespecified degree ranges. The temperature bins of interest are the three lowest bins (below 30°F) and the two highest bins (above 80°F) as shown in **Figure 2**. We define hot and cold days as the following: We consider a day to be cold when the daily mean temperature falls below 30°F (−1.11°C), and a day to be hot when the mean temperature is above 80°F (26.7°C) in a given year. The omitted reference group is the sixth bin (50–60°F or 10–15.6°C). Θ is a vector of parameters of interest. For instance, the parameter for $D_{c,t,9}$ captures how much the dependent variable changes per 10 additional days of hot days where the daily mean temperature fell in the ninth bin ($j = 9$) between 80 and 90°F (or 26.7–32.2°C range), relative to the impact of moderate days in 50–60°F range.

Instead of regressing health-related outcomes on mean temperature, we use ten temperature bin variables as the key independent variables. This nonparametric approach allows us to exploit the annual variation in the number of extreme hot and cold days within a county and capture the potential non-linear relationship between temperature and dependent variables without requiring strong assumptions about the functional form [17]. Earlier literature suggested threshold effect of heat or U shaped relationship between temperature and health outcomes [4, 12, 35, 38, 39].

Variable $M_{s,t}$ is an indicator for whether state s where a county c is located, expanded their State Medicaid program under the Affordable Care Act in year t. All models include a vector of one-year lagged county-level characteristics that vary across time, $X_{c,t-1}$, which include annual total precipitation, percent share of aged, black, Hispanic population, urban indicator, log of total

TABLE 2 | Summary statistics of key variables (United States. 2019).

Variable	Obs	Mean	Std.Dev.	Min	Max
Panel A. County Transfer Sample					
Below 10°F	60,845	5.92	11.16	0	87.00
10–20°F	60,845	11	12	0	102
20–30°F	60,845	24	19	0	114
30–40°F	60,845	43.26	21.73	0	225.00
40–50°F	60,845	54.78	16.41	0	179.00
50–60°F	60,845	60.00	14.86	0	282.00
60–70°F	60,845	66.97	14.56	0	199.00
70–80°F	60,845	69.55	29.73	0	203.00
80–90°F	60,845	28.94	33.26	0	193.00
Above 90°F	60,845	0.66	4.27	0	120.00
Total transfer ($ per capita)	62,020	8,908	2,671	0	21,670
Medicare transfer ($ per capita)	60,998	2,107	750	127	6,777
Medicaid transfer ($ per capita)	60,998	1,571	823	0	9,011
Total transfer (log of $ per capita)	60,998	9.07	0.28	7.34	9.98
Medicare (log of $ per capita)	60,998	7.58	0.39	4.84	8.82
Medicaid (log of $ per capita)	60,988	7.23	0.55	1.74	9.11
Percent Aged	62,020	16.49	4.54	1.68	58.50
Percent Black	62,020	8.88	14.46	0	85.93
Percent Hispanic	62,020	8.04	13.11	0	97.54
Total population	62,020	97,747	315,215	55	10,100,000
Urban indicator	62,014	0.46	0.50	0	1.00
log of total employed	61,480	9.57	1.50	3.97	15.70
Average wage per capita, private sector	61,480	13.40	9.54	1.52	316.67
Panel B. Hospital Sample (logs)					
Hospital Admissions	49,552	7.75	1.54	0.69	11.92
Inpatient Days	49,552	9.69	1.47	0.68	13.54
Outpatient Visits	49,552	10.27	3.05	0	15.65
Emergency Room Visits	49,552	9.52	1.54	0	13.31
Medicaid Inpatient Days	49,552	7.62	2.10	0	13.22
Medicare Inpatient Days	49,552	8.78	1.50	0	12.76

Note: All fiscal variables are adjusted for inflation (constant 2010 U.S.dollars). Std.Dev. stands for standard deviation. "Min" stands for minimum and "Max" stands for maximum.

employment and log of private-sector wage *per capita*. We also include hospital-fixed effects and year-fixed effects. Standard errors are clustered by county since average temperature varies at the county level.

To examine the impact of extreme temperature on publichealth insurance program transfers, we use a county-by-year panel and a lagged dependent variable model which is specified as **Equation 2**:

$$Y_{c,t} = \Theta D_{c,t,j} + \Phi D_{c,t-1,j} + \beta Y_{c,t-1} + \alpha M_{s,t} + \Pi X_{c,t-1} + \delta c + \lambda t + \upsilon_{c,t} \quad (2)$$

Where $Y_{c,t}$ measures the average level of Medicaid or Medicare benefit transfers (in log of *per capita* dollars) for county c in year t. We also include the county-fixed effects to control for all time-invariant cross-county heterogeneity and year-fixed effects to absorb annual shocks that commonly affect all counties each year. We also include $Y_{c,t-1}$ on the righthand side of the equation to account for autocorrelation in fiscal outcomes, potential lagged effects of weather as well as unobserved time-varying confounders [35]. We also check for potential lagged effects of extreme temperature on Medical transfers, given that there may be a time lag between the day of health service and when payments from the government to vendors or intermediaries are made. In an alternative specification, we account for a potential one-year lag by including a vector of temperature variables from the previous year as regressors. We do not anticipate lagged effects when using annual data to analyze the hospital utilization effects. Previous epidemiology studies using daily or weekly data and found that delayed harvesting effects typically fade within 15–20 days [38, 40–44]. Since we use annual data, we expect health utilization behaviors to show in the contemporaneous year.

RESULTS

Hospital Utilization Results

First, we find that extreme heat increases overall hospital utilization. Our estimates in **Table 3** show that hot days with a daily average temperature between 80 and 90°F increase hospital admissions, inpatient days, and ER visits. Our estimates suggest that ten additional days of extreme heat, with a daily average temperature above 90°F are associated with a 1.56 percent increase in hospital admissions and 1.32 percent in inpatient days. These translate into approximately 36.5 additional admissions at hospitals (at the mean value of 2,321) and 164 more inpatient days (at the mean 16,155). Heat also increases inpatient care utilization at hospitals among patients covered by Medicaid and Medicare, as shown in the last two columns in **Table 3**. Ten

TABLE 3 | Impact of average daily temperature on hospital utilization (United States. 2019).

Daily temperature	Total				Medicaid	Medicare
	Admissions	Inpatient days	Outpatient visits	ER visits	Inpatient days	Inpatient days
	(1)	(2)	(3)	(4)	(5)	(6)
Below 10°F	0.0030	0.0063	−0.0142	−0.0110**	0.0056	0.0111
	(0.004)	(0.005)	(0.011)	(0.005)	(0.013)	(0.010)
10°F–20°F	0.0158***	0.0132***	−0.0111	−0.0024	0.0295**	0.0310***
	(0.005)	(0.005)	(0.012)	(0.004)	(0.014)	(0.012)
20°F–30°F	0.0032	0.0032	−0.0057	0.0053	−0.0094	0.0092
	(0.003)	(0.003)	(0.010)	(0.004)	(0.010)	(0.008)
80°F–90°F	0.0109***	0.0101***	−0.0133	0.0068**	0.0120	0.0169***
	(0.002)	(0.003)	(0.008)	(0.003)	(0.009)	(0.006)
Above 90°F	0.0156**	0.0127*	0.0073	0.0185	0.0439**	0.0343***
	(0.007)	(0.007)	(0.022)	(0.013)	(0.020)	(0.012)
Medicaid Expansion	−0.0046	−0.0264**	−0.0326*	0.0163	0.1087***	−0.0224
	(0.010)	(0.011)	(0.017)	(0.012)	(0.029)	(0.020)
Mean Dependent variable	7.75	9.69	10.27	9.52	7.62	8.78
Observations	49,552	49,552	49,552	49,552	49,552	49,552
R-squared	0.974	0.965	0.905	0.959	0.907	0.928

Note: All models include county covariates, hospital fixed effects, year fixed effects, and county covariates. ER visits refer to emergency room visit. All hospital outcomes are in logged values. Starred entries indicate significance levels at 0.1, 0.05**, and 0.01***.*

TABLE 4 | The impact of average daily temperature on Medicaid and Medicare transfer (United States. 2019).

Daily temperature	Baseline		With lagged temperature	
	Medicaid (1)	Medicare (2)	Medicaid (3)	Medicare (4)
Below 10°F	−0.0018*	0.0022***	−0.0019*	0.0024***
	(0.001)	(0.001)	(0.001)	(0.001)
10°F–20°F	−0.0002	−0.0005	0.0001	0.0001
	(0.001)	(0.001)	(0.001)	(0.001)
20°F–30°F	0.0051***	0.0001	0.0051***	0.0004
	(0.001)	(0.001)	(0.001)	(0.001)
80°F–90°F	0.0011*	−0.0003	0.0014**	0.0001
	(0.001)	(0.000)	(0.001)	(0.001)
Above 90°F	0.0085***	−0.0015	0.0089***	−0.0014
	(0.001)	(0.001)	(0.001)	(0.001)
Medicaid Expansion	0.0878***	0.0118***	0.0873***	0.0102***
	(0.003)	(0.001)	(0.003)	(0.001)
Mean Dependent Variable	7.23	7.58	7.23	7.58
Observations	57,799	57,809	57,678	57,688
R-squared	0.975	0.975	0.975	0.975

Note: All models include 1 year lagged dependent variable, county covariates, county fixed effects, year fixed effects and State Medicaid expansion indicator. Estimates in columns (1) and (2) are from baseline models only include contemporaneous temperature variables, while the results in columns (3) and (4) are estimated from ***Equation 2*** *which controls for one-year lagged temperature variables. Starred entries indicate significance levels at 0.1*, 0.05**, and 0.01***.*

additional days of extreme heat above 90°F increase inpatient days by 4.39 percent (91.48 at the mean 2,038) among Medicaid patients and 3.43 percent (226.91 at the mean 6,502) among Medicare patients. Ten additional hot days between 80 and 90°F are associated with a 1.69 percent (110.83 at the mean) increase in inpatient care utilization among Medicare patients.

We find that cold temperature leads to higher hospital admissions and inpatient care utilization. Ten more cold days (10–20°F) increases hospital admissions and inpatient days by 1.58 percent (36.97 at the mean) and 1.32 percent (214.66 at the mean), respectively. Notably, cold temperature has a particularly strong and positive impact on inpatient care utilization among Medicaid and Medicare patients. The latter finding is also consistent with the earlier empirical literature showing higher mortality rates among the elderly population (≥65Y) in the same temperature bin [4].

On the other hand, estimates in Panel A column (4) shows that extremely cold temperature below 10°F significantly reduces ER visits. Heat and cold seem to have opposite effects on ER visits. Our findings of decline in ER visits due to cold weather is similar to Davis et al. (2020), which report an immediate reduction in risks of emergency department visits at temperatures below 10°F in Virginia, explained by people being less willing to seek medical care or less likely to be outdoors.

TABLE 5 | The impact of average daily temperature on public medical benefit transfer: Heterogeneity by state Medicaid generosity (United States. 2019).

Panel A. Medicaid and Medicare benefit transfer

Daily temperature	Medicaid transfer (1)	Medicare transfer (2)
Below 10°F × Low	0.0007	−0.0017
	(0.001)	(0.001)
10°F–20°F × Low	−0.0063***	0.0016
	(0.002)	(0.001)
20°F–30°F × Low	0.0004	−0.0000
	(0.001)	(0.001)
80°F–90°F × Low	−0.0028***	−0.0003
	(0.001)	(0.001)
Above 90°F × Low	0.0058***	−0.0015
	(0.001)	(0.001)
Below 10°F × High	−0.0018	0.0072***
	(0.002)	(0.001)
10°F–20°F × High	0.0146***	−0.0044***
	(0.002)	(0.001)
20°F–30°F × High	0.0121***	0.0001
	(0.002)	(0.001)
80°F–90°F × High	0.0122***	−0.0004
	(0.001)	(0.001)
Above 90°F × High	0.0177**	−0.0052
	(0.008)	(0.007)
Medicaid Expansion	0.0865*** (0.003)	0.0109*** (0.001)
Observations	57,799	57,809
R-squared	0.976	0.975

Panel B. Temperature effect on Medicare enrollment and dually eligible individuals for Medicare and Medicaid: Heterogeneity by state Medicaid generosity

Daily temperature	Medicare enrollment	Dually eligible beneficiaries	
	Total (1)	All dual (2)	Full medicaid (3)
Below 10°F × Low	0.0008	−0.0120**	−0.0142***
	(0.002)	(0.005)	(0.005)
10°F–20°F × Low	−0.0018	−0.0018	0.0013
	(0.002)	(0.005)	(0.005)
20°F–30°F × Low	−0.0062***	−0.0040	−0.0082**
	(0.001)	(0.003)	(0.004)
80°F–90°F × Low	−0.0060***	−0.0115***	−0.0109***
	(0.001)	(0.002)	(0.002)
Above 90°F × Low	−0.0024	−0.0286***	−0.0392***
	(0.003)	(0.004)	(0.005)
Below 10°F × High	−0.0092***	0.0056***	0.0040*
	(0.003)	(0.002)	(0.002)
10°F–20°F × High	0.0019	−0.0014	−0.0075***
	(0.003)	(0.003)	(0.003)
20°F–30°F × High	−0.0049***	−0.0095***	−0.0116***
	(0.002)	(0.002)	(0.002)
80°F–90°F × High	−0.0002	0.0047**	0.0032
	(0.002)	(0.002)	(0.002)
Above 90°F × High	−0.0112***	0.0091*	0.0285***
	(0.003)	(0.005)	(0.007)
Medicaid	−0.0145**	0.0679***	0.0960***
Expansion	(0.006)	(0.007)	(0.007)
Mean Dep. Ver	8.10	6.74	4.39
Observations	39,777	39,777	39,777
R-squared	0.987	0.989	0.988

Note: All models include 1 year lagged dependent variable, county covariates, county fixed effects, year fixed effects and State Medicaid expansion indicator. Estimates in columns (1) and (2) are from baseline models only include contemporaneous temperature variables, while the results in columns (3) and (4) are estimated from ***Equation (2)*** *which controls for one-year lagged temperature variables. High indicator is a dummy variable equal to one if a county is in a state with Medicaid income eligibility threshold for children and parents that is higher than the national median. The key variables of interest are the interaction terms between high (or low) dummy indicator and each temperature bin variable. Starred entries indicate significance levels at 0.1*, 0.05**, and 0.01***.*

Note: All estimates are from county-annual level estimation and dependent variables are logged values of beneficiary count. High indicator is a dummy variable equal to one if a county is in a state with Medicaid income eligibility threshold for children and parents that is higher than the national median. All models include one-year lagged dependent variable, lagged county covariates, county fixed effects, year fixed effects. Starred entries indicate significance levels at 10 percent, 5 percent**, and 1 percent***.*

Medicaid and Medicare Transfer Results

Next, we examine the temperature effect on Medicaid and Medicare benefit transfers and report our estimates in **Table 4**. We find consistent evidence of heat increasing Medicaid transfer payments. The magnitude is largest above 90°F, where ten more days of extreme heat increases annual Medicaid transfer payments by 0.85 percent (equivalent to $11.78 *per capita*). Meanwhile, estimates in **Table 4** column (1) suggest that Medicaid payments increase with mildly cold (20–30°F) days but decrease with more extremely cold days. We find that ten additional days of mild cold weather increase annual Medicaid transfers by 0.51 percent ($7.06 *per capita*).

Temperature affects Medicare benefit transfer differently from how it impacts Medicaid transfer. Column (2) in **Table 4** shows that ten additional days with <10°F increase Medicare transfer by 0.22 percent ($4.30 *per capita*). However, heat surprisingly does not seem to affect Medicare benefit transfer payments. Estimates in columns (3) and (4) report estimates from **Equation 2** that include one-year lagged temperature variables on the right-hand side of the model. The contemporaneous temperature effect estimates do not change when accounting for potential lagged effects on medical benefit transfer. The coefficient estimates for the previous year's temperature variables are all insignificant and not reported. Overall, only extreme cold (<10°F) seems to incur additional fiscal costs on Medicare while Medicaid costs increase due to mild cold and heat. Across all columns, we show that Medicaid expansion is positively associated with Medicaid and Medicare benefit transfers.

Heterogeneity Analysis

In **Table 5** Panel A, we report our heterogeneity tests of how Medicaid and Medicare benefit transfer varies by the average generosity of State Medicaid, which is assessed based on the information on each state's average income eligibility thresholds (measured as the percentage of the federal poverty line) for children and parents during the sample period. The high generosity indicator equals one for a state with an average income eligibility threshold above the national median.

Estimates in column (1) indicate that extreme heat (>90°F) causes a larger increase in Medicaid benefit transfers in counties with more generous State Medicaid programs, which is consistent with our expectation Ten more hot days (80–90°F) increases Medicaid transfer by 1.2 percent in counties with more generous State Medicaid but decreases transfer by 0.28 percent in counties with less generous Medicaid. This may suggest that extreme temperatures may discourage healthcare utilization in areas

with less generous State Medicaid. We also find a similar impact of cold temperatures (10–20°F) having the opposite impact on Medicaid transfer, depending on the generosity of State Medicaid. These findings coupled with a significant positive correlation (0.084, p-value of 0.047) between personal income *per capita* and State Medicaid eligibility threshold, suggest that individuals in poor areas are not receiving as much support from public health insurance programs as those living in more affluent areas. This implies a possible gap between the need for assistance and the actual provision of government welfare support.

The results in Column 2 in **Table 5** Panel A show that extreme cold below 10°F also increases Medicare benefit transfer in states with more generous Medicaid, most likely explained by low-income elderly individuals who are dually enrolled in both Medicaid and Medicare. **Table 5** Panel B shows whether the effects of temperature on Medicare enrollment and low-income Medicare beneficiaries are different between counties with different State Medicaid generosity. The first column shows extreme temperatures reduce total Medicare enrollment. Results in the last two columns present a positive correlation between dually eligible beneficiaries and extreme temperatures (<10°F and >80°F) among counties with more generous Medicaid, whereas participation in Medicaid among Medicare beneficiaries declines with extreme temperatures in states with less generous Medicaid. These findings imply that the generosity of the Medicaid program can have important spillover effects on Medicare costs as well.

DISCUSSION

In this study, we examine whether and how extreme temperature affects hospital utilization and public health insurance program spending in the United States. We focus on how hot and cold days impact healthcare utilization among low-income and elderly populations covered by Medicaid and Medicare, as this group is also particularly vulnerable to extreme weather. We find that hot and cold days increase admissions and inpatient care service utilization at hospitals, and these effects are stronger in inpatient care utilization among both Medicaid and Medicare patients. Medicaid and Medicare inpatient days increase with more hot days, while we find weaker evidence of cold weather impacting Medicaid patients' hospital utilization. These results are consistent with findings from Illinois [45] and Virginia [14] in the United States as well as the United Kingdom [8]. Part of these findings correspond to changes in Medicaid and Medicare benefit transfers associated with extreme temperatures. We find that both mild cold (20–30°F or −6.7 to −1.11°C) and heat (>80°F or 26.7°C) significantly raise Medicaid transfer payment, while only extreme cold (<10°F or −12.2°C) increases Medicare transfer. Meanwhile, we observe a considerable heterogeneity in temperature's effect on both medical transfers, based on median income, the share of the elderly population, and State Medicaid generosity.

The results of our paper entail important policy implications. First, this study suggests that the additional costs of extreme temperature-associated healthcare utilization may be considerable, particularly among the vulnerable population. Our results in the **Supplementary Appendix** show stronger positive impact of extreme temperatures on hospital utilization and medical transfers in counties with a higher share of lower-income and elderly populations. Given that Medicaid covers over 40% of all births in the U.S. and 55% of Medicaid benefit payments finance health services among the elderly and disabled adults, extreme temperatures can considerably raise Medicaid costs. In countries where the government plays both the roles of financer and insurer, these fiscal costs may vary depending on systematic features of the public health insurance system such as the eligibility criteria, types of services covered and the level of benefits.

On the other hand, it is also important to understand the fiscal implications of more generous public health policy. We find that Medicaid expansion overall has a significantly strong and positive relation with Medicaid and Medicare benefit transfers. We also find larger increases in Medicaid transfers associated with mild cold and heat among areas with more generous eligibility criteria for Medicaid. The additional fiscal costs of extreme temperature could be even higher than our estimates in countries with universal public health insurance such as Canada or South Korea, or other countries with more comprehensive public health systems where governments highly subsidize healthcare costs.

Third, our findings resonate with prior research from Mexico which shows that the national expansion of universal healthcare policy prevented cold-induced deaths [38]. This suggests that public health insurance can play a crucial role in mitigating the adverse impact of extreme weather events. Future research will be needed to advance our understanding about the roles of different public health insurance systems in coping with climate change related extreme weather events.

At the same time, it is also crucial to understand the fiscal implications of expanding public health insurance coverage. We note that the additional fiscal costs of extreme temperature could be even higher than our estimates in countries with universal public health insurance such as Canada or South Korea, or other countries with more comprehensive public health systems where governments highly subsidize healthcare costs. Future research will be needed to advance our understanding about the roles of different public health insurance systems in coping with climate change related extreme weather events.

Lastly, we have to acknowledge the limitations of this study. First of all, we cannot observe detailed service utilization other than inpatient hospital care among Medicaid patients to assess whether there were changes in primary care utilization and the nature of ER visits. Similarly, we do not observe the public health insurance transfers data at the individual level which limits our ability to discuss the equity implications. One study from the United States for instance, suggests that the mean costs of additional hospitalization due to heat is higher among racial/ethnic minorities than whites [46]. Another limitation of this study is that we cannot provide explicit policy implications about how public health insurance programs may alleviate the adverse impact of extreme weather. Our findings suggest that if more people use health services due to extreme temperatures, expanding public health insurance coverage could encourage vulnerable populations to utilize necessary services by lowering their out-of-pocket payments. These can be subjects for future research.

AUTHOR CONTRIBUTIONS

QM and YK developed the original research question and analytical approaches. YK conducted the data analysis and wrote the manuscript. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/ijph.2025.1607160/full#supplementary-material

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Impact of Climate Variability on Foodborne Diarrheal Disease: Systematic Review and Meta-Analysis

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Objective: To determine the impacts of climate variability on foodborne diarrhoeal disease worldwide.

Methods: This work was performed based on PRISMA guideline. Articles were retrieved from the PubMed, MEDLINE, Web of Science, Scopus, DOAJ, and Google Scholar. The search was made using Boolean logic operators, medical subject headings, and main keywords related to foodborne diarrheal disease. STATA version 17 was used to perform an analysis. The quality of the articles was evaluated using Joanna Briggs Institute appraisal tools.

Results: The present study included 54 articles with an estimates of 103 findings. An increases in temperature, relative humidity, precipitation, rainfall, and flooding were associated with 4% [RR: 1.04; 95% CI: 1.03, 1.05], 3% [RR: 1.03; 95% CI: 1.01, 1.06], 2% [RR: 1.02; 95% CI: 1.01, 1.03], 1% [RR: 1.01; 95% CI: 1.00, 1.02], and 42% [RR: 1.42; 95% CI: 1.26, 1.57] increases in foodborne diarrhoeal disease, respectively.

Conclusion: There was a significant association between foodborne diarrhoeal disease and climate variability, and indicate the need for building a climate-resilient food safety system to reduce foodborne diarrheal disease.

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Keywords: foodborne diarrheal disease, diarrheal disease, food safety, climate variability, climatic factors

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INTRODUCTION

Foodborne diseases constitute one of the major causes of mortality and morbidity worldwide, even though they are common in developing countries [1]. Among foodborne disease, foodborne diarrheal disease is common and imposes significant health and economic burdens across the world, particularly in the African and Southeast Asian regions [2]. According to the World Health Organization (WHO) estimates of foodborne disease, there were approximately 600 million cases of foodborne illness globally in 2010, resulting in approximately 33 million disability-adjusted life years

Abbreviations: DOAJ, Directory of Open Access Journals; MeSH, Medical Subject Heading; JBI, Joanna Briggs Institute; PRISMA, Preferred Reporting Items for Systematic Review and Meta-Analysis; WASH, Water, Sanitation, and Hygiene; WHO, World Health Organization.

TABLE 1 | General characteristics of the studies reporting the impacts of different climatic factors or climate variability on foodborne diarrheal disease, worldwide, 2024 (54 articles: 103 estimates).

References	Sample size	Survey year	Target group	Foodborne diarrheal disease	Outcome: RR:95%CI	Location	Quality
[46]	58,773	2005 to 2010	Children	Diarrhea	T°:0.98: 0.97, 0.99	Vietnam	High
[51]	3,115	1996 to 2001	All age	Rotavirus	Rh:1.026:1.00·0, 1.053	Bangladesh	High
[52]	569	2008 to 2018	All age	Salmonellosis	Rh: 1.03:1.02–1.05	Iran	High
[53]	423,142	2000 to 2008	Children	Gastroenteritis	Rh:1.039: 2·8, 5·0	Japan	Medium
[42]	2,186	2018 to 2020	All age	Diarrhea	Rh:1.0213: 1.0179, 1.0247	Indonesia	High
[42]	1,246	2018 to 2020	All age	Diarrhea	Rh:1.0166: Rh:1.0151, 1.0181	Indonesia	High
[54]	167,691	2006 to 2017	All age	Diarrhea	Rh:1.23: 1.21–1.25	China	High
[48]	219,774	2003–2013	Children	Diarrhea	T°:1.081: 1.02–1.14, Rf: 1.009: 1.004, 1.015	Nepal	High
[47]	275,182	1997 to 2013	All age	Gastroenteritis	T°:1.21: 1.09, 1.34	Spain	High
[45]	1,483,316	2003 to 2013	All age	Diarrhea	T°: 1.006: 1.005, 0.6, Rf: 1.05: 1.049, 1.051	Bhutan	High
[16]	29,762	1999 to 2010	All age	*Campylobacter* jejuni	T°: 1.161: 1.072, 1.249	Israel	High
[16]	29,762	1999 to 2010	All age	*Campylobacter* coli	T°: 1.188:1.048, 1.328	Israel	High
[17]	5,040	1991 to 2001	All age	Salmonellosis	T°: 1.102:1.087, 1.116	Australia	Medium
[17]	7,212	1991 to 2001	All age	Salmonellosis	T°: 1.056:1.043, 1.07	Australia	Medium
[17]	3,973	1991 to 2001	All age	Salmonellosis	T°: 1.049: 1.03, 1.064	Australia	Medium
[17]	7,155	1991 to 2001	All age	Salmonellosis	T°: 1.051:1.038, 1.065	Australia	Medium
[17]	7,272	1991 to 2001	All age	Salmonellosis	T°: 1.041:1.031, 1.052	Australia	Medium
[2]	1,798,198	2005 to 2018	All age	Diarrhea	T°: 1.013:0.998, 1.027, Rh: 1.030:1.004, 1.057	Singapore	High
[18]	57,331	1993 to 1998	Children	Diarrhea	T°: 1·08: 1·07, 1·09, Rh: 0·97: 0·97, 0·98	Peru	Medium
[19]	12,717	2006 to 2012	All age	Bacillary dysentery	T°: 1·04: 1·00, 1·07	China	High
[20]	11,324	2005 to 2015	All age	Salmonellosis	T°: 1.043:1.003, 1.084, Rh: 0.987:0.981, 0.994, Rf: 1.008: 1.002, 1.015	Singapore	High
[21]	13,069	2003 to 2006	All age	Cholera cases	T°: 1.052: 1.04, 1.06, Rf: 1.025: 1.01–1.04	Zambia	High
[49]	6282	1992 to 2000	All age	Salmonellosis	T°: 1.012: 1.009, 1.015	Canada	High
[49]	1743	1992 to 2000	All age	*Campylobacter* infection	T°: 1.022: 1.019, 1.024	Canada	High
[49]	9,664	1992 to 2000	All age	*E. Coli* case	T°: 1.06: 1.05, 1.069	Canada	High
[49]	986	1992 to 2000	All age	*Campylobacter* cases	T°: 1.045: 1.033, 1.058	Canada	High
[22]	2,983,850	1981 to 2010	All age	Diarrhea	T°: 1.049: 1.036.1.062	Bangladesh	High
[23]	22,515	2010 to 2017	Children	Diarrhea	T°: 1.1666: 1.164–1.168, Rf: 1.00167: 1.00131,1.00193	Ethiopia	High
[24]	4,585	1992 to 2008	All age	Salmonellosis	T°: 1.0232:1.0038, 1.0427, Pr: 1.0024: 1.0002, 1.0046	Russia	High
[25]	2,180	2000 to 2010	All age	Salmonellosis	T°: 1.055:1.022, 1.088, Pr: 1.005:1.001, 1.01	Kazakhstan	High
[25]	6323	2000 to 2010	All age	Salmonellosis	T°: 1.015:1.027, 1.058, Pr: 1.001:1.003, 1.004	Kazakhstan	High
[25]	928	2000 to 2010	All age	Salmonellosis	T°: 1.00: 1.031, 1.029, Pr: 1.001:1.006, 1.008	Kazakhstan	High

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TABLE 1 | (*Continued*) General characteristics of the studies reporting the impacts of different climatic factors or climate variability on foodborne diarrheal disease, worldwide, 2024 (54 articles: 103 estimates).

References	Sample size	Survey year	Target group	Foodborne diarrheal disease	Outcome: RR:95%CI	Location	Quality
[25]	1,006	2000 to 2010	All age	Salmonellosis	T^{o}: 1.035:1.021, 1.09, Pr: 1.001:1.006, 1.035	Kazakhstan	High
[26]	536	2001 to 2002	All age	Gastroenteritis	T^{o}: 1.0248: 1.0101, 1.039	Australia	Medium
[27]	7,315,738	1997 to 2014	All age	Diarrhea	T^{o}: 1.0364: 1.0335, 1.0393, Pr: 1.0104: 1.0042, 1.0166	Mozambique	High
[28]	9,529	2002–2012	All age	Salmonellosis	T^{o}: 1.041: 1.013, 1.069, Pr: 1.056:1.035, 1.078	USA	High
[29]	596,343	1999 to 2013	All age	Shigellosis	T^{o}: 1.06: 1.04, 1.09, Rh: 1.01: 1, 1.01, Pr: 1.04: 1.01, 1.07	Vietnam	High
[30]	142,065	2007 to 2012	All age	Bacillary dysentery	T^{o}: 1.0106:1.0063, 1.0149, Rf: 1.0022: 1.0012, 1.0032	China	High
[31]	6511	2006 to 2012	Children	Bacillary dysentery	T^{o}: 1.0158: 1.0046, 1.0271	China	High
[32]	395,321	2014 to 2016	All age	Bacillary dysentery	T^{o}: 1.017: 1.012, 1.021	China	High
[38]	35,601	1990 to 2012	All age	*Campylobacter* cases	T^{o}: 0.995: 0.993, 0.997	Australia	High
[33]	7,845	1990 to 2012	All age	Salmonellosis	T^{o}: 1·013: 1·008, 1·019	Australia	High
[34]	136,694	2004 to 2011	All age	Diarrhea	T^{o}: 1.07: 1.04–1.08, Rh: 1.13: 1.12, 1.15, Rf: 1.05: 1.05–1.08	Vietnam	High
[35]	25,385	2013 to 2017	Children	Diarrhea	T^{o}: 1.046: 1.007, 1.088	Bangladesh	High
[36]	461	2017–2019	Children	Diarrhea	T^{o}: 1.0397: 1.0292, 1.0502, Rf: 1.0012: 1.0017, 1.0008	India	High
[37]	29,639	2010 to 2012	Children	Bacillary dysentery	T^{o}: 1.113:1.1047, 1.1212	China	High
[39]	11,194	2003 to 2009	Children	Diarrhea	T^{o}: 1.03: 1.02, 1.05	Australia	High
[40]	44,926	2010 to 2015	All age	Bacillary dysentery	T^{o}: 1.032: 1.024, 1.041, Rh: 1.007:1.001, 1.013, Pr: 1.01; 0.9997, 1.0003	China	High
[41]	710,202	2013 to 2017	All age	Bacillary dysentery	T^{o}: 1.01: 1.00, 1.02, Rh: 0.998:0.99, 1.00, Pr: 1.0101: 1.003, 1.019	China	High
[41]	710,202	2013 to 2017	All age	Bacillary dysentery	T^{o}: 1.04:1.03, 1.05, Rh: 1.00: 0.99, 1.01, Pr: 1.001: 1.00, 1.01	China	High
[42]	4,117	2018 to 2020	All age	Diarrhea	T^{o}: 1.0539: 1.0461, 1.0617, Pr: 1.0113: 1.0102, 1.0124	Indonesia	High
[43]	97,918	2017–2020	Children	Diarrhea	T^{o}: 1.103: 1.009, 1.206, Rh: 0.973: 0.953, 0.994, Pr: 1.0305: 2.09, 4.01, Rf: 0.999:0.999, 1.000	Indonesia	Medium
[50]	8,309	2002 to 2011	Children	Rotavirus	T^{o}: 1.0332: T^{o}: 1.026.1.0424, Rf: 1.004: 1.002, 1.0079	China	High
[50]	3,928	2002 to 2011	Children	Norovirus	T^{o}: 1.0234: T^{o}: 1.0152, 1.0358, Rf: 1.0193:1.0121, 1.0309	China	High
[44]	217,734	2013 to 2015	Children	Diarrhea	T^{o}: 1.019:1.0034, 1.0347, Rf: 1.0004:1.0001, 1.0007	Ethiopia	High
[55]	6243	2016 to 2020	All age	Hepatitis A	Pr: 0.97: 0.94, 1.00	Korea	Medium
[56]	105	2015 to 2016	All age	Shigellosis	Pr: 1.18: 1.06, 1.33	USA	High
[57]	14,800	2004 to 2013	All age	Salmonellosis	Pr: 1.146: 1.092, 1.203	Australia	High
[58]	33,927	2013 to 2014	All age	Diarrhea	Rf: 1.35: 1.14–1.60	Ecuador	Medium
[64]	18,976	2004 to 2010	All age	Bacillary Dysentery	Fl: 1.17: 1.03–1.33	China	High
[62]	24,536	2004 to 2009	All age	Dysentery	Fl: 1.66: 1.52, 1.82	China	High
[61]	45,131	2006 to 2010	All age	Diarrhea	Fl: 1.24: 1.11–1.40	China	High
[60]	9,255	2004 to 2010	All age	Bacillary dysentery	Fl: 1.78 : 1.61, 1.97	China	High
[59]	4,812	2005 to 2011	All age	Bacillary dysentery	Fl: 1.29: 1.14, 1.46	China	High

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TABLE 1 | (*Continued*) General characteristics of the studies reporting the impacts of different climatic factors or climate variability on foodborne diarrheal disease, worldwide, 2024 (54 articles: 103 estimates).

References	Sample size	Survey year	Target group	Foodborne diarrheal disease	Outcome: RR:95%CI	Location	Quality
[63]	274,621	2013 to 2017	All age	Diarrhea	FI: 1.11: 1.01, 1.23	China	High
[67]	45,691	2005 to 2016	All age	Bacillary dysentery	FI: 1.393:1.216, 1.596	China	High
[65]	7,591	2004 to 2010	All age	Dysentery	FI: 1.74:1.56, 1.94	China	High
[66]	2,852	2001 to 2007	All age	Diarrhea	FI: 1.55: 1.12, 2.15	Bangladesh	High
[68]	359,580	2013 to 2017	All age	Diarrhea	FI: 1.29: 1.15, 1.46	China	High

Keys: FI, Flooding; Rf, Rain Fail; Pr, precipitation; Rf, Relative humidity; RR, relative risk; CI, confidence interval; T°, Temperature.

(DALYs), of which 550 million were due to diarrheal diseases caused mainly by *norovirus*, *Campylobacter* spp., *Vibrio cholerae*, *Shigella* spp., enteropathogenic *Escherichia coli* (*E. coli),* and enterohemorrhagic *E. coli* [3].

According to the European Food Safety Authority (EFSA) report, the overall incidence of diarrheal per 100,000 people was highest for *Campylobacter* (19.5), followed by *Salmonella* (17.1), *Shigella* (4.8), *Cyclospora* (1.5), *Yersinia* (1.4), *Vibrio* (0.9), and *Listeria* (0.3) [4]. In Africa alone, approximately 91 million people become sick, and 137,000 die annually [1].

These problems occurred not only in lower-income countries but also in higher-income countries, including Europe, which reported 41–49 DALYs per 100,000 people attributable to foodborne disease [5]. Climate variability is considered a serious global challenge influencing the growth and survival of different pathogens that cause food- and water-borne diarrheal diseases and their transmission pathways [6].

Climate variability such as long-term changes in temperature, humidity, rainfall patterns, and extreme weather affect food safety throughout the food chain, including during farming, and they can also affect the nutritional quality of food by influencing the occurrence and intensity of foodborne diseases, particularly foodborne diarrheal diseases [4]. Many foodborne pathogens are zoonotic in nature, and are the major cause of foodborne diarrheal disease; therefore, there is a need for the integration of public health and veterinary communities for early disease detection and control of pathogens in food [7].

There is a need for precise information on the burden of foodborne diseases, particularly foodborne diarrheal diseases which can adequately inform policymakers and help allocate appropriate resources for food safety control and intervention efforts [3]. Because climate change is resulting in increased extreme weather and the emergence or re-emergence of pathogenic microorganisms, the integration of these factors into risk-based approaches for surveillance and response is an important element of improved preparedness [8].

Until this review was conducted, there is no study has provided comprehensive evidence regarding the impacts of various climate variability on foodborne diarrheal disease worldwide. Some of the previous studies reported regional-based evidence on foodborne diseases [9, 10] while another studies were not reported quantitative outcomes, particularly of associations between Climate variability and foodborne diarrheal disease [9–12], whereas other studies have been conducted on single pathogenic bacteria [13]. This indicate there is a need to provide a comprehensive pooled evidence which is necessary for effective intervention, particularly foodborne diarrheal disease associated with climate variability. Therefore, this review aimed to present the impacts of different climate variability on foodborne diarrheal disease.

METHODS

Protocol and Registration

The current systematic review and meta-analysis was performed under the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) protocols and guidelines. This review protocol is registered on PROSPERO, with a registration code of CRD42024532430.

Eligibility Criteria

Inclusion Criteria

- **Population**: Studies conducted on all age groups.
- **Outcome**: studies that reported quantitative outcomes (relative risk, risk ratio, and hazard ratio with a 95% confidence interval), particularly those that presented the associations between foodborne diarrhoeal diseases and temperature, relative humidity, rainfall, precipitation, and flooding. This review included studies conducted on any type of foodborne diarrheal disease, regardless of the type of foodborne diarrheal disease.
- **Intervention or exposure reviewed**: Foodborne diarrheal disease and climate variability
- **Types of Articles**: full-text, peer-reviewed, and published articles, particularly those written in English.
- **Publication and survey year**: there was no limitation in terms of publication or survey year.
- **Regions**: studies conducted in any region or country around the world.
- **Exclusion criteria:** Review articles, reports, commentaries, editorial papers, short communications, case studies,

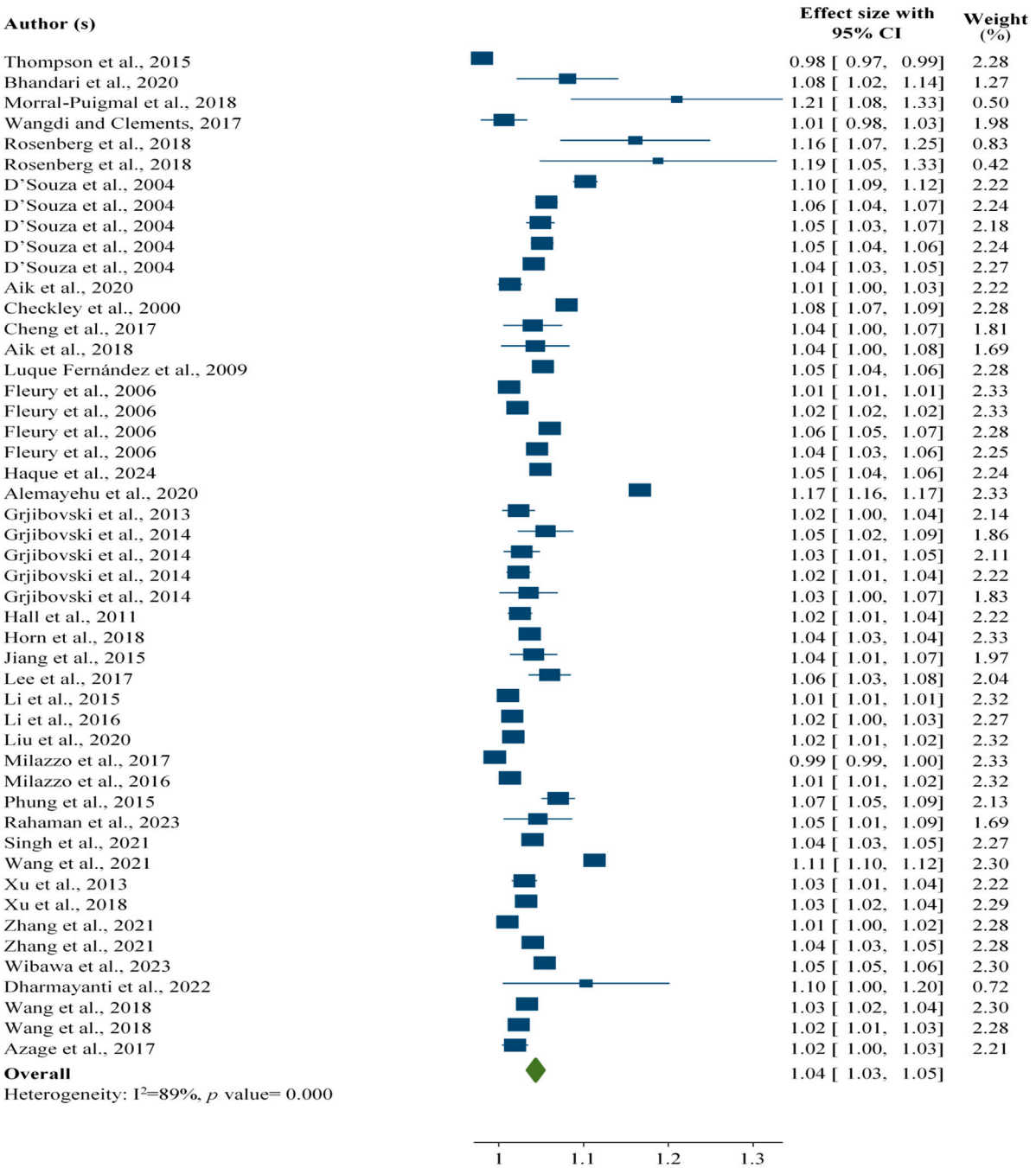

FIGURE 1 | Association between temperature and foodborne diarrheal disease among the study participants, worldwide, 2024.

preprints, theses and dissertations, and articles with a high risk of bias were excluded from the current review

Information Sources and Search Strategies

The authors (DAM and TG) retrieved articles from the following databases and websites: PubMed, MEDLINE, Web of Science, Scopus, Cochrane Library, CINAHL, DOAJ, and Google Scholar from 8 April 2024, to 25 April 2024. The authors (DAM and TG) used a combination of Boolean logic operators (AND, OR, and NOT), medical subject headings (MeSH), and main keywords such as climate change, foodborne disease, *salmonellosis, shigellosis*, dysentery diarrhea, *listeriosis*, *Campylobacter* infection, temperature, relative humidity, rainfall, precipitation, flooding, and extreme events, particularly to retrieve articles from

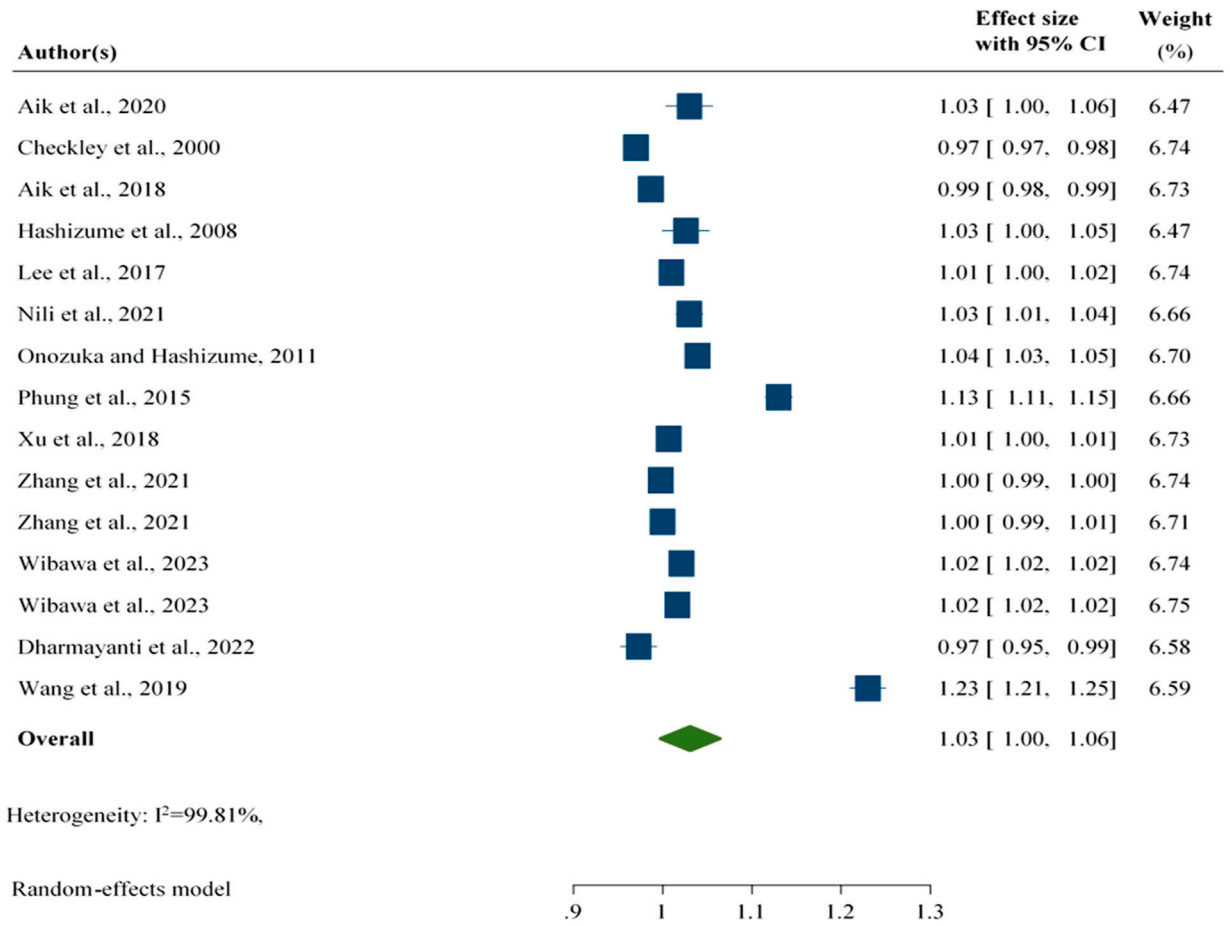

FIGURE 2 | Association between relative humidity and foodborne diarrheal disease regardless of the study group, worldwide, 2024.

the included data sources. Furthermore, the reference lists of the included articles were further screened for additional articles. The search strategies employed in this study are available as **Supplementary Material** (**Supplementary Material S1**).

Study Selection Process

A PRISMA flow chart was used for the selection process of studies included in the current review. The number of articles included in and excluded from the study is presented in the PRISMA flow chart, with the reasons for exclusion. The authors used Endnote (Thomson Reuters, United States) to remove duplicate articles. The authors independently screened and evaluated the articles to determine their eligibility. Disagreements made in the selection process, were resolved by discussion. Finally, those articles that met the inclusion criteria and were eligible for inclusion were included in the current review.

Quality Assessment

In the present study, the quality of the studies was evaluated using the Joanna Briggs Institute Critical Assessment Tool (JBI) [14]. This tool contains nine evaluation criteria (**Supplementary Material S2**). Each evaluation criterion parameter was given a value of one if it met the criteria and zero if it did not. On the basis of the total score obtained from these nine evaluation criteria, each article was categorized as low, moderate, or high quality; those articles scored 60% or less, 60%–85%, and 85% and above, respectively. Finally, those articles of moderate or high quality were included in this study. Disagreements between the authors during the quality assessment were solved by discussion and repeating the same procedures.

Data Extraction

The authors extracted the data using Microsoft Excel (developed by the authors). The following data were extracted from the included articles: authors, sample size, survey year, publication year, region or countries where the study was conducted, target group or study population, types of Climate variability or climatic factors (temperature, relative humidity, rainfall, flooding and precipitation), and their associations with foodborne diarrheal disease, including salmonellosis, *Escherichia coli* infection, dysentery diarrhea (shigellosis), *Campylobacter* infection, *hepatitis* A, *norovirus*, and *rotavirus* infections.

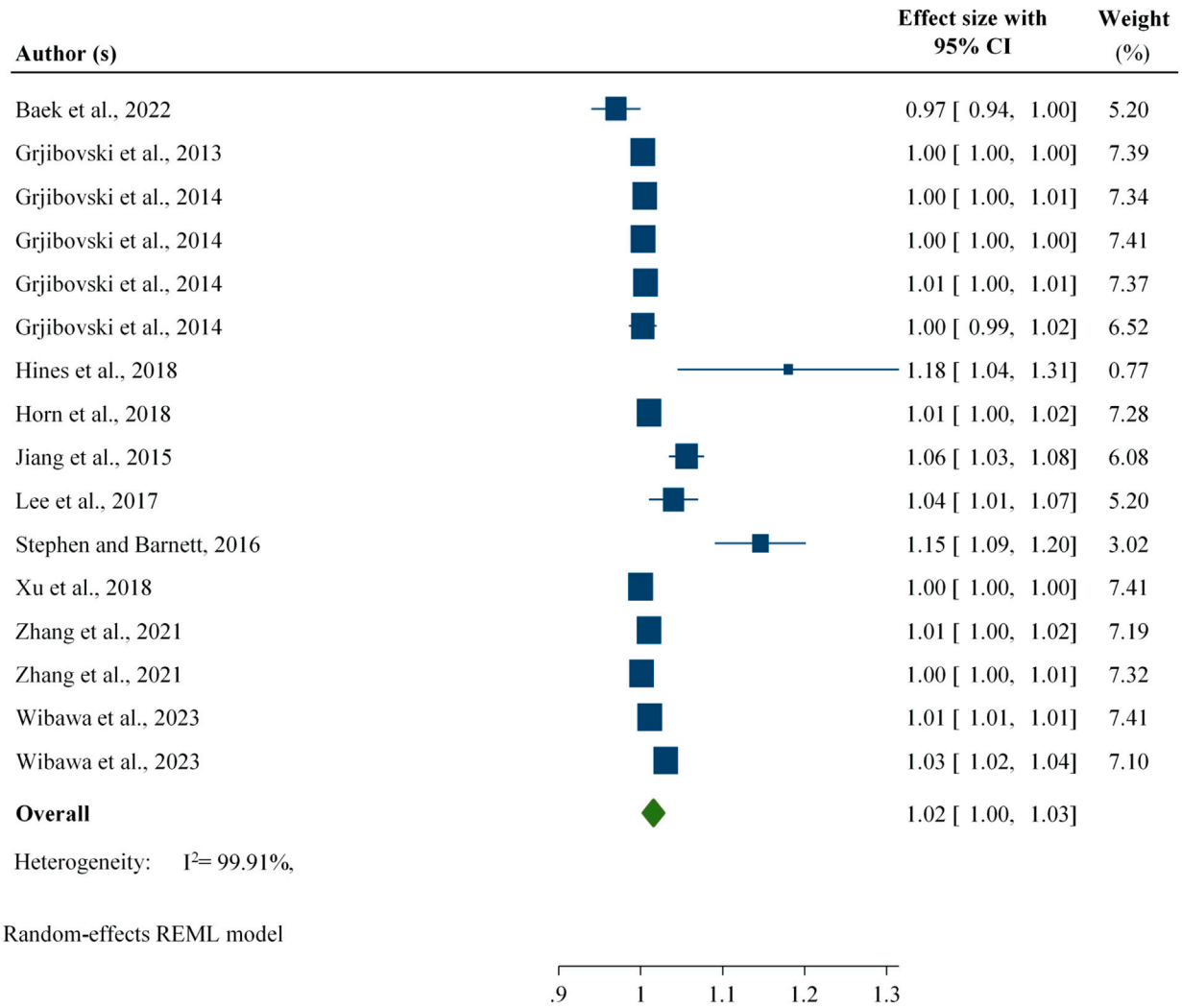

FIGURE 3 | Association between foodborne diarrhoeal disease and precipitation regardless of age group, worldwide, 2024.

Statistical Procedures and Data Analysis

The pooled estimate of the associations between foodborne diarrhoeal disease and climate variability, particularly temperature, relative humidity, rainfall, flooding, and precipitation, was performed via STATA version 17 statistical software. The pooled estimate of the associations between foodborne diarrhoeal disease and temperature, relative humidity, rainfall, flooding, and precipitation. Finally, the data were visualized and presented via a random-effects forest plot.

The heterogeneity of the articles was evaluated using the I-square test (I^2 statistic). The level of heterogeneity is presented as no significant heterogeneity (0%–25%), low heterogeneity (25%–50%), moderate heterogeneity (50%–75%), or high heterogeneity (>75%) [15]. The publication bias was assessed using the funnel plots. Subgroup analysis was performed based on the study population or target group to determine the pooled estimate among different to assess the potential explanation for heterogeneity.

Sensitivity Analysis

Sensitivity analysis was performed by excluding one or the highest outcome expected to influence the overall estimate of an association between foodborne diarrheal disease, and temperature, relative humidity, rainfall, flooding, and precipitation.

RESULTS

Study Selection Process

The authors (DAM and TG) retrieved 2,981 articles from the electronic databases and websites (PubMed, Web of Science, Medline, Science Direct, and Google Scholar as well as screening of references from the eligible articles). A total of 1791 duplicate articles were excluded. Then, 1,190 articles were evaluated on the basis of their title followed by their abstract, of which 642 were excluded because they were unrelated titles and research areas.

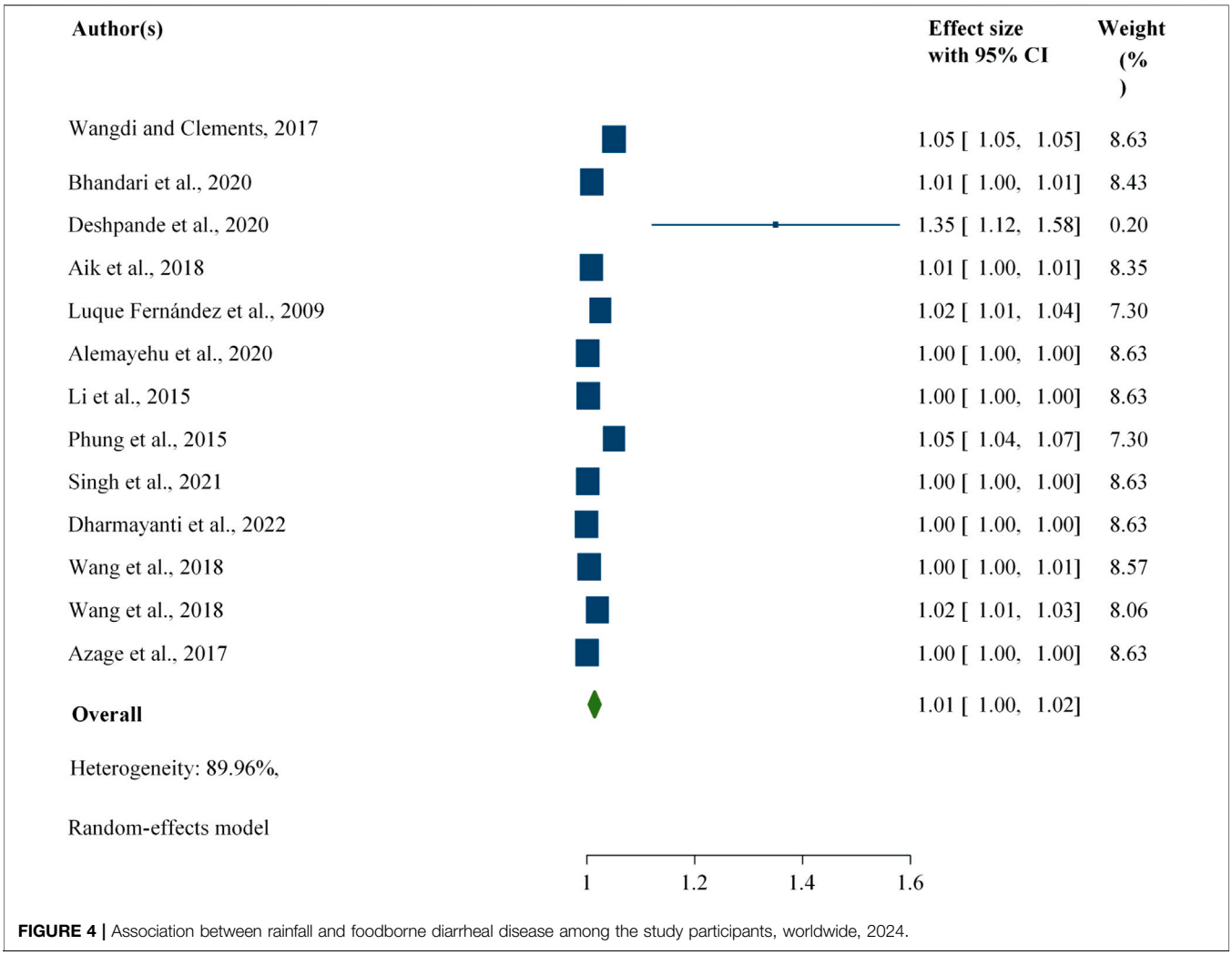

FIGURE 4 | Association between rainfall and foodborne diarrheal disease among the study participants, worldwide, 2024.

Furthermore, 548 articles were further evaluated on the basis of their full text, of which 109 were not available in the full text. Finally, 611 articles were evaluated on the basis of their objectives, methods, and outcomes of interest. Finally, 54 articles, with 103 estimates, that reported an association between different factors and foodborne diarrheal disease were included in the current study (**Supplementary Material S3**).

General Characteristics of the Included Articles

In the present study, 36 [2, 16–50] studies, with 49 estimates, reported an association between temperature and foodborne diarrheal disease, of which 6 articles reported more than one outcome. The estimates ranged from RR: 0.98, 95% CI: 0.97, 0.99 in Vietnam [46] to RR: 1.21:95% CI: 1.09, 1.34 in Spain [47]. Among the included articles, 36 focused on all age groups [2, 16, 17, 19–22, 24–30, 32–34, 38, 40–42, 45, 47, 49], whereas 13 focused on children [18, 23, 31, 35–37, 39, 43, 44, 46, 48, 50].

A total of 13 studies [2, 18, 20, 29, 34, 40–43, 51–54], with a total of 15 estimates, reported an association between relative humidity and foodborne diarrheal disease. Among these studies, 10 [2, 20, 29, 34, 40–42, 51, 52, 54] were conducted on all age groups, whereas three studies were conducted on children [18, 43, 53]. Furthermore, 11 studies, with 16 estimates reported an association between precipitation and foodborne diarrheal disease among all age groups [24, 25, 27–29, 40–42, 55–57]. The sample size ranged from 105 study participants in the USA [56] to 7315738 in Mozambique [27].

Furthermore, a total of 12 articles reported an association between rainfall and foodborne diarrheal disease [20, 21, 23, 30, 34, 36, 43–45, 48, 50, 58], with the number of study participants ranging from 461 in India [36] to 1,483,316 in Bhutan [45]. Among these studies, six were conducted on all age groups [20, 21, 30, 34, 45, 58], whereas seven were conducted on children [23, 36, 43, 44, 48, 50]. In the present study, 10 articles reported an association between flooding events and foodborne diarrheal disease [59–68], with the number of study participants ranging from 2,852 in Bangladesh [66] to 359,580 in China [68] (**Table 1**).

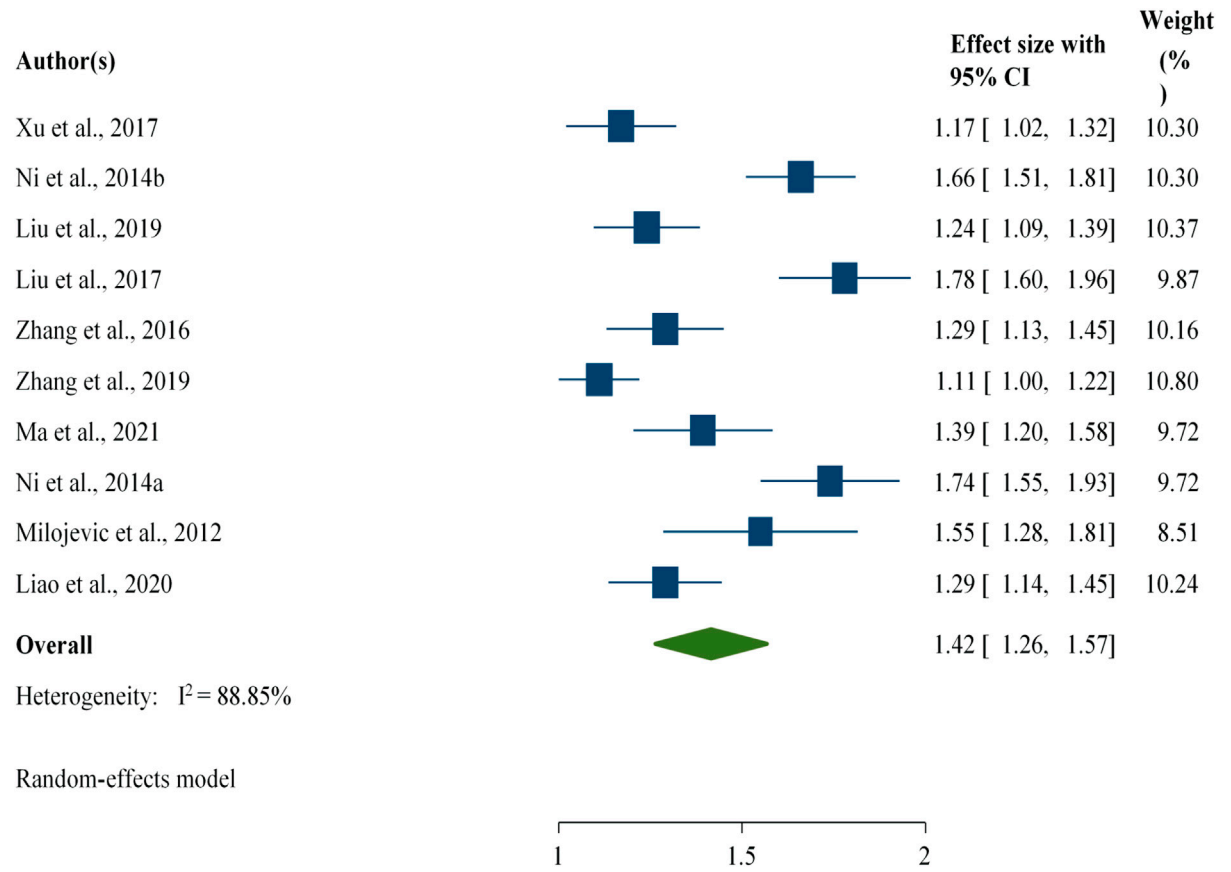

FIGURE 5 | Association between flooding and foodborne diarrheal disease among the study participants, worldwide, 2024.

Associations Between Temperature and Foodborne Diarrhoeal Disease

The current study revealed that every 1°C increase in temperature is associated with a 4% (RR: 1.04; 95% CI: 1.03, 1.05) increase in the number of foodborne diarrheal disease worldwide, regardless of the age and type of foodborne diarrheal disease reported in the studies included in the study (**Figure 1**).

On the basis of the subgroup analyses by the age group of the study participants, the evidence from the current findings revealed that every 1°C increase in temperature was associated with a 4% [RR: 1.04; 95% CI: 1.03, 1.04) increase in the number of foodborne diarrheal disease cases among all age groups, whereas it accounted for a 6% [RR: 1.06; 95% CI: 1.01, 1.1] increase in foodborne diarrheal disease among children across the world. The total increase in the number of foodborne diarrhoeal cases after the subgroup analysis was 5% [RR: 1.05; 95% CI: 1.03, 1.07] for every 1°C increase in temperature (**Supplementary Material S4**).

Furthermore, to determine the effects of extreme values expected to affect the pooled outcome, four extreme findings were removed. After four findings were removed, a 1°C rise in temperature was associated with a 4% [RR: 1.04; 95% CI: 1.03, 1.05) rise in foodborne diarrhoeal disease (**Supplementary Material S5**).

Associations Between Relative Humidity and Foodborne Diarrhoeal Disease

This study revealed that an increase in relative humidity was associated with a 3% [RR: 1.03; 95% CI: 1.01, 1.06] increase in the number of foodborne diarrheal disease cases worldwide, regardless of the age and type of foodborne diarrheal disease reported in the studies included in the study (**Figure 2**).

The subgroup analysis findings revealed that an increase in relative humidity was associated with a 4% [RR: 1.04; 95% CI: 1.01, 1.08] increase in the number of foodborne diarrhoeal disease cases among all ages. Furthermore, an increase in relative humidity was associated with a lower number of foodborne diarrhoeal cases among children [RR: 0.99; 95% CI: 0.95, 1.04]. However, the overall evidence after subgroup analysis revealed that an increase in relative humidity was associated with a 3% [RR: 1.03; 95% CI: 1.01, 1.06] increase in the number of foodborne diarrhoeal disease cases, which is similar to the findings of a previous subgroup analysis (**Supplementary Material S6**).

After the two largest outcomes were excluded from the analysis, an increase in relative humidity was associated with a 2% [RR: 1.02; 95% CI: 1.00, 1.02] increase in the number of foodborne diarrheal disease cases (**Supplementary Material S7**).

Associations Between Precipitation and Foodborne Diarrhoeal Disease

An increase in precipitation is associated with a 2% [RR: 1.02; 95% CI: 1.01, 1.03] increase in the number of foodborne diarrheal disease cases across the world, regardless of the age groups and types of diarrheal disease reported by the studies included in the study (**Figure 3**).

Furthermore, to determine the effects of extreme values expected to affect the pooled outcome, four findings were removed. After four findings were removed, an increase in precipitation was associated with a 1% [RR: 1.01; 95% CI: 1.00, 1.02] increase in diarrheal disease (**Supplementary Material S8**).

Associations Between Rainfall and Foodborne Diarrhoeal Disease

The evidence from 13 estimates revealed that an increase in rainfall was associated with a 1% [RR: 1.01; 95% CI: 1.00, 1.02] increase in foodborne diarrheal disease, regardless of the study participants (**Figure 4**).

This study revealed that an increase in rainfall was associated with a 3% [RR: 1.03; 95% CI: 1.01, 1.05) increase in the number of foodborne diarrheal disease cases among all age groups, whereas it accounted for 1% [RR: 1.01; 95% CI: 1.00, 1.01) among the children (**Supplementary Material S9**).

After one largest outcome was excluded from the analysis, the study revealed a similar association before excluding the largest outcome, which was expected to affect the pooled evidence [RR: 1.01; 95% CI: 1.00, 1.02) (**Supplementary Material S10**).

Associations Between Flooding and Foodborne Diarrhoeal Disease

The current study revealed that an increase in flooding events was associated with a 42% [RR: 1.42; 95% CI: 1.26, 1.57] increase in diarrhoeal disease cases, regardless of the study group (**Figure 5**).

DISCUSSION

The current study revealed that an increase in temperature is associated with a 4% [RR: 1.04; 95% CI: 1.03, 1.05) increase in the number of diarrhoeal disease cases across the world, regardless of the age and group of the study participants. The finding of the current study is supported by another meta-analysis, which reported a 7% (RR: 1.07; 95% CI: 1.03, 1.10) increase in diarrheal diseases among all cases in developing countries [69], this study revealed that the incidence of foodborne diarrheal disease was greater among children [6% (RR: 1.06; 95% CI: 1.01, 1.1)] than among all age groups [4% (RR: 1.04; 95% CI: 1.03, 1.043)].

An increase in relative humidity was associated with a 3% [RR: 1.03; 95% CI: 1.01, 1.06] increase in the number of foodborne diarrheal disease cases worldwide. However, an increase in relative humidity was associated with a lower number of foodborne diarrhoeal cases among children [RR: 0.99; 95% CI: 0.95, 1.04]. Furthermore, after two estimates with the highest outcome were excluded from the analysis, particularly to assess the influence of extreme outcomes on the pooled estimate, an increase in relative humidity was associated with a 2% [RR: 1.02; 95% CI: 1.00, 1.02] increase in the number of foodborne diarrheal disease cases, which indicates no potential impacts of extreme outcomes on the pooled estimate.

An increase in precipitation was associated with a 2% [RR: 1.02; 95% CI: 1.01, 1.03] increase in the number of foodborne diarrheal disease cases worldwide, regardless of the target population. In addition, to determine the effect of an extreme outcome on the pooled estimate, the data were analysed by excluding the estimate with the highest value, and an increase in precipitation was associated with a 1% [RR: 1.01; 95% CI: 1.00, 1.02] increase in foodborne diarrheal disease, which was relatively lower than the pooled finding before an extreme outcome was excluded. However, there was a significant association.

According to this study, an increase in rainfall was associated with a 1% [RR: 1.01; 95% CI: 1.00, 1.02] increase in foodborne diarrhoeal disease, regardless of the target population. This finding is supported by another study that reported an association between a rise in extreme rain events and increased incidence of diarrhoeal disease (IRR: 1.26; 95% CI: 1.05, 1.51) [70]. The present study revealed a lower incidence of foodborne diarrhoeal disease, which may be attributed to the variation in the scope of the study, outcome, and geographical location. Because the current study was conducted across the world, it focused particularly on foodborne diarrheal disease. Unlike the association between temperature and foodborne diarrhoeal disease, a higher incidence of foodborne diarrhoeal disease was reported among all age groups [RR: 1.03; 95% CI: 1.01, 1.05) than among children (RR: 1.01; 95% CI: 1.00, 1.01).

In addition, the current study revealed that an increase in flooding events was associated with a 42% [RR: 1.42; 95% CI: 1.26, 1.57] increase in foodborne diarrheal disease cases, regardless of the study group. This finding was supported by a review conducted in China [RR: 1.48; 95% CI: 1.14–1.91] but was slightly greater than the current findings [71]. Furthermore, another review reported a significant association between flooding and the incidence of diarrhea [RR: 1.40, 95% CI: 1.29–1.52] [72]. The variation may be attributed to the difference in their scope in terms of the study region and the number of articles included. Relative humidity, rainfall, and precipitation, flooding events presented major potential impacts on foodborne diarrhoeal disease.

In general, the present study revealed a significant association between foodborne diarrhoeal disease and the following climatic factors or climate variability: temperature, relative humidity, rainfall, precipitation, and flooding. This indicates the need for effective interventions or strategies, particularly for establishing a climate change-resilient food safety system to reduce the health and economic burdens associated with different types of foodborne diarrheal diseases.

Strengths

This study used multiple databases and websites to retrieve articles regardless of the region where the study was

conducted and the publication period. The extracted data were re-entered to avoid errors. The quality of the included articles was assessed via standard quality appraisal tools. Furthermore, this study was conducted according to the PRISMA guidelines for systematic review and meta-analysis.

Limitations of the Study

There were some limitations, including the unequal distribution of the studies across the world due to the lack of eligible studies and the lack of studies on the impacts of climate variability on foodborne diarrhoeal disease. In addition due to the lack of systematic reviews and meta-analyses conducted in these research areas, the authors compared some review articles with the current findings.

CONCLUSIONS

According to the current study, there were significant associations between foodborne diarrhoeal disease and various climate variability, such as temperature, relative humidity, rainfall, precipitation, and flooding. The prevalence of foodborne diarrhoeal disease associated with climatic factors was greater, particularly for flooding, followed by temperature and relative humidity. In general, the current findings highlight the need for community-based tailored intervention strategies for establishing a climate change-resilient food safety risk management system to reduce the burden of foodborne diarrheal diseases.

DATA AVAILABILITY STATEMENT

Almost all the data are included in this study, including those in the **Supplementary Material**. However, some data may be available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS

In this study, TG and DM conceived the idea of this systematic review and meta-analysis and played a major role in the review, extraction, cleaning, and analysis of the data, as well as in the writing, drafting, and editing of the manuscript. Both authors (TG and DM) read and approved the final version of this systematic review and meta-analysis manuscript and agreed on all aspects of this work. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/phrs.2025.1607859/full#supplementary-material

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Climate Change and Food Security: A Framework for Agenda Setting and Policy Analysis in Iran

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Objectives: This study identifies the key factors contributing to Food Security (FS) in the context of Climate change (CC), aiming to foster agenda setting for FS in Iran.

Methods: This is a qualitative study. We interviewed 32 relevant stakeholders from various backgrounds. We used a mixed inductive–deductive approach in data analysis, drawing up on an adopted framework comprising of health policy triangle and selected agenda setting framework.

Results: Our analysis revealed eight constructs, eight themes, and 26 subthemes. The constructs included: common voice, leadership, scientific evidence, economic, multi-sectoral collaboration, advocacy, early warning systems, and supreme decision-making center. The main themes identified were shortcomings in: consensus, high-level political commitment, cooperation, System approach, research, planning, economic resources, and public participation. The international data gathering was limited in this study.

Conclusion: To mitigate the risk of FS in CC condition and push the emerging subject into the government agenda in Iran, we recommend reforms in the eight identified constructs and advocate a combined policy approach including three dimensions: policy integration, coherency, and coordination, through a new model of governance.

Keywords: agenda setting, climate change, policy analysis, food security, food policy

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INTRODUCTION

Climate change and food security are two wicked problems that influenced the environment, ecology, economic, health, and social dimensions of nations' life [1]. These climate change (CC) events have influenced four components (food availability, food accessibility, food utilization, food sustainability, and stability) of food security (FS) [2]. It means that agricultural food production, food affordability and food prices, food safety, accessibility to water, oil prices, energy prices, health cost, population growth rate, and income of people that live in these areas have affected and threatened [3]. However, 25%–30% of Green House Gas (GHG) production is relegated to agricultural production [4]. Most areas in the globe are endangered more than others by whether extreme events. CRED (Center for Research on The Epidemiology of Disaster) reported in 2022, droughts impacted 88.9 million people

in six African countries (the Democratic Republic of the Congo, Ethiopia, Nigeria, Sudan, Niger, and Burkina Faso) and induced famine in Uganda causing 2,465 deaths. The cost of damaged by drought events occurred in three countries (China, USA, Brazil) worth 33.6 billion US$ in 2022. Hurricane "Ian" caused damage costing 100 billion US$ in the Americas. The economic damage of floods only in 2022 in countries (Pakistan, India, China, Nigeria, and Eastern Australia worth 34.6 billion US$ [5]. Moreover, global warming and the increased frequency and severity of climate extreme events are responsible for malnutrition and affected 422 million population in low-income countries [6]. Evidences revealed that, 30 countries in Africa and Asia which produce 80% of the crop by self-sufficiency are vulnerable to CC, hence, their people are more susceptible to hunger, poverty and are at risk of malnutrition. In Pakistan in the food-insecure provinces of Baluchistan and Sindh between June and August 2022, more than 11 million heads of livestock were killed by floods, and more than 9.4 million acres of cropland were destroyed [7]. The Middle East with 22 countries, is the region where the population experienced drought, flood, sand, and dust storms [8]. Iran is located in this region and is one of the ten most disastrous countries [9]. The precipitation is one-third compared to the mean world precipitation and the temperature increases 0.5 C (centigrade) every decade during the last three decades [10]. In addition, 70% of groundwater sources would with throw, and water bankruptcy is distinguished [9]. Two third of the climate in this country is arid and semi-arid [11], further, for three decades a large number of the population experienced drought and flood [12]. In 2019, 27 out of 31 provinces had affected by floods due to 2.5 billion dollars lost. A million hectares of agricultural land and production were damaged in these areas [13]. Iran is known as the seventh GHG producer among 187 countries in the 2020 report because a substantial part of countries' GDP is reforming oil and fossil fuel exportation [14]. The considerable point is, population growth policies and agricultural food production self-sufficiency which is followed by the government. Accordingly, policy analysis of Iran's FS under CC was necessary to understand key leverages, problems, and policies. Several studies demonstrated that the policy model was helpful to policy analysis of health, FS, and CC, e.g., the "Shiffman framework," with four components (Actor Power, Ideas, Political Context, and Issue characteristics) [15–17]. In Iran, there is a scarcity of studies investigating this topic, leaving a knowledge gap. Thus, we applied the "Shiffman framework" to policy analysis of FS under CC to introduce a governance model of food policy in Iran [18]. Such needed studies might inform decision-makers in the country about the impact of CC on FS and would be helpful to push this issue in agenda setting.

METHODS

This is a qualitative study. We used three methods of data collection for policy analysis: document analysis and semi structured expert interviews [19]. In the first stage of the qualitative policy analysis study, we applied framework analysis and then used a deductive approach according to four FS components and CC (three disaster risk factors: exposure, hazards, and vulnerability) [20, 21]. Afterward, through document analysis and interviews, we applied an inductive approach to identify the main structures of policies [22]. In the third stage, we applied two frameworks, the "Shiffman framework and triangle policy," to inform the interview design, data analysis and interpretation of the research findings [18, 23]. After extracting the codes and constructing the themes, we used the themes to develop the constructs and to design a new governance model of FS under CC for Iran. Policy dialog was performed for the validity assessment of the new model [24]. Twelve key informants took part in policy dialog and presented their ideas about vertical and horizontal positions and the relationships among the constructs in the governance model. The conceptual framework of the study methodology is presented in **Figure 1**.

Data Collection and Sampling

We selected 32 experts from 30 official and unofficial organizations, institutes, and private sectors related to FS and CC in national policy-making in Iran via purposive sampling and snowball sampling from April 2019 to May 2020 [25, 26]. However, we continued sampling until saturation occurred. That is to say, there was no new theme or insight to identified and explored from data collection during interview by researchers. The inclusion criterion for sampling was at least 5 years of experience in related issues (FS and CC) in academic or executive positions. To achieve greater sampling validity and provide different policy options, we selected samples with acceptable disparities from all related organizations with maximum variation. **Table 1** summarizes the list of interviewees.

We obtained 41 national and international documents, reports, and parliamentary proceedings related to FS and CC through a literature review and carried out document analysis according to a directed and conventional content analysis framework to extract codes, themes, and subthemes [20, 27].

Interviews

We conducted semi structured in-depth and face-to-face interviews aimed at exploring the principal governance issues of FS and CC policies in Iran. [25]. We scheduled interviews based on policy analysis frameworks (Shiffman framework; FS dimensions, health policy triangle framework) [18, 23] and designed an interview guide with 13 questions. In this stage, the trained researcher asked for information on actors' power and influential stakeholders; policy problems and characteristics; policy ideas and priorities; policy and political context; framing of FS and CC (policy process); opportunities to improve governance weaknesses; and threats to policy making from interviewees. Then, these two policy frameworks were used for data analysis and assisted interpretation of the research findings. Furthermore, based on the four stages (agenda setting, formulation, implementation, and evaluation) of the policy process, the codes were extracted [28]. We analyzed the informants' interview data to identify key themes and subthemes related to food and nutrition policy. Every interview lasted

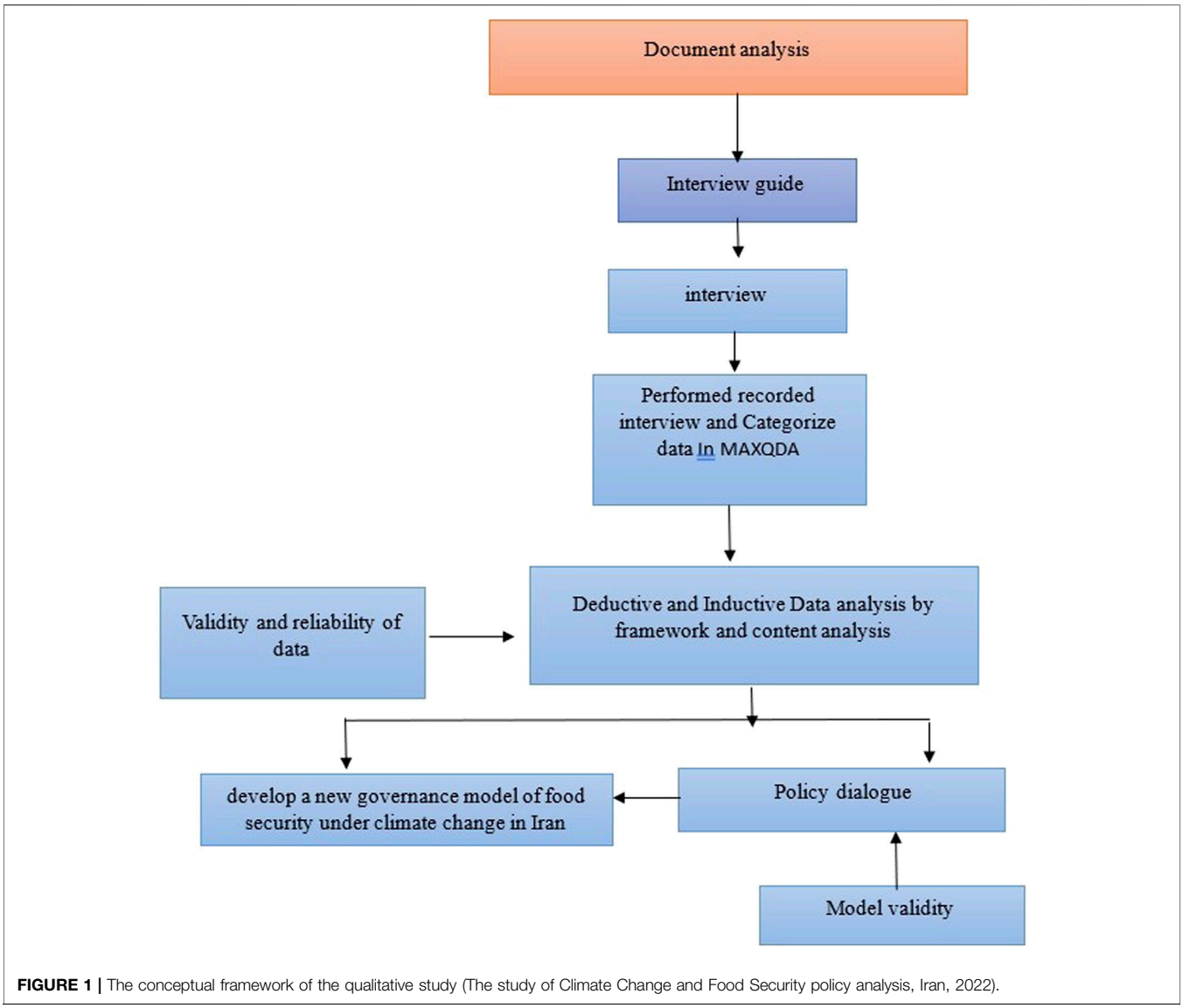

FIGURE 1 | The conceptual framework of the qualitative study (The study of Climate Change and Food Security policy analysis, Iran, 2022).

45–90 min. The interviews were recorded digitally and transcribed verbatim. Before the interview, the researcher sent an information sheet about the purpose of the study and a consent form to reassure the interviewees about anonymity, freedom to withdraw, and approval of participation by completing the informed consent form.

Data Analysis

We utilized framework analysis to analyze the data interviews in five phases: Familiarization, Identifying a thematic framework, Indexing, Charting, Mapping, and Interpretation [20]. We used MAXQDA software version 2020 for data management. We applied a mixed deductive-inductive approach, for thematic analysis. The deductive approach was utilized to identify codes according to FS dimensions and CC disaster risk factors. Then, based on an inductive approach, conventional content analysis was used to find new and latent codes and to develop themes and subthemes. The first and corresponding authors carried out the categorization process, and the other authors revised and approved the entire process. The validity and reliability of the findings were assessed by the methods of Guba and Lincoln [29]. We invited two researchers to assess the external validity of the coding system. The conceptual framework of policy analysis according to the health policy triangle and Shiffman policy framework is presented in **Figure 2**.

RESULTS

The identified themes, subthemes, and constructs (8 themes, 26 subthemes, and 8 constructs) related to FS under CC government policy in Iran are summarized and reported in **Table 2**.

TABLE 1 | The list and characteristics of interviewees (The study of Climate Change and Food Security policy analysis, Iran, 2022).

Experience (year)	Sex	Education	Workplace of interviewee (abbreviation)	Code Person (P)
30	F	PhD	MoHME	P1
31	M	PhD	IKRF	P2
25	F	MSc	DoE	P3
28	M	MSc	MoA	P4
8	M	PhD	MoA	P5
55	M	PhD	MoHME	P6
15	F	PhD	IRIMO	P7
25	M	PhD	MoA	P8
34	M	PhD	MoHME	P9
18	F	MSc	MIMT	P10
16	M	PhD	(Food & drug organization) MoHME	P11
35	M	PhD	(Industrial food and nutrition institute of research) MoHME	P12
15	M	MSc	MoHME	P13
15	M	MSc	MoA	P14
45	M	PhD	MoHME	P15
5	M	PhD	MRUD	P16
18	F	PhD	MCLSW	P17
25	M	PhD	APDIM	P18
28	M	PhD	(The forestation organization) MoA	P19
30	F	PhD	(Faculty of nutrition) MoHME	P20
28	M	PhD	(The research institute of agricultural economic) MoA	P21
35	M	PhD	PBO	P22
25	M	PhD	(The environmental department) MoA	P23
26	F	PhD	MoE	P24
32	M	MSc	MFA	P25
29	F	MSc	MoHME	P26
25	M	PhD	MoA	P27
32	F	MSc	MoP	P28
29	M	PhD	MoA	P29
25	M	PhD	MoHME	P30
30	M	PhD	MoA	P31
20	M	PhD	MoI	P32

Note: M, Male; F, Female; IRIMO, Islamic Republic of Iran Meteorological Organization; NDMO, National Disaster Management Organization; MoA, Ministry of Agriculture; MoHME, all data extracted from food balance sheet, Ministry of Health and Medical Education; MIMT, Ministry of Industry, Mine, and Trade; NCoS, National Center of Statistics; MoE, Ministry of Energy; MoP, Ministry of Petroleum; DoE, Department of Environment; MFA, Ministry of Foreign Affairs; MoI, Ministry of Information; PBO, Planning and Budget Organization; APDIM, Asian and Pacific Centre for the Development of Disaster Information Management; MRUD, Ministry of Roads and URBAN Developments; MCLSW, Ministry of Cooperatives Labor and Social Welfare; IKRF, Imam Khomeini Relief Foundation.

The results of the data analysis according to the 8 explored themes and subthemes are presented with evidence obtained from the key informants' comments in the following paragraphs. The results are presented in **Figure 3**.

In this framework, all of the constructs, themes, and subthemes extracted based on threats and barriers to agenda setting for FS under CC in the context of Iran are presented. Several pieces of evidence explored from informants' interviews are reported through cotes in the next paragraph. These cotes are categorized according to the components of the Shiffman health policy framework [18].

Political Context

We addressed 821 codes in this component and then categorized them into 9 subthemes and 4 themes. Finally, we developed 4 constructs. A weak system approach was a consequence of poor legislation, weak decision-making, conflict of interests, and conflicting interests. Several informants noted that the weakness or lack of legislation or overlooking stakeholders and decision-makers in the legislation process, the scarcity of evidence for legislation, and the contradiction of laws in FS under CC in Iran were the greatest barriers to appropriate legislation. An informant stated that a shortage of legislation is a crucial

> *"There is a problem in addressing a big picture of CC in the country, as well as national legislation in mitigation aims to decrease fossil fuel use as energy. The parliament ought to enact a law for using renewable energy and CC mitigation and adaptation strategies, while there is limited governmental policy making to deal with these complicated problems and risks."* (p 13)

> *Some informants complain about no executable FS and CC laws. One of them expressed that "from 2002 there are a couple of enactments in the supreme council of Health and FS that never executed. This is because there was no will for professional activity based on the scientific backbone for providing these laws. Hence, there are no administrations."* (P 1)

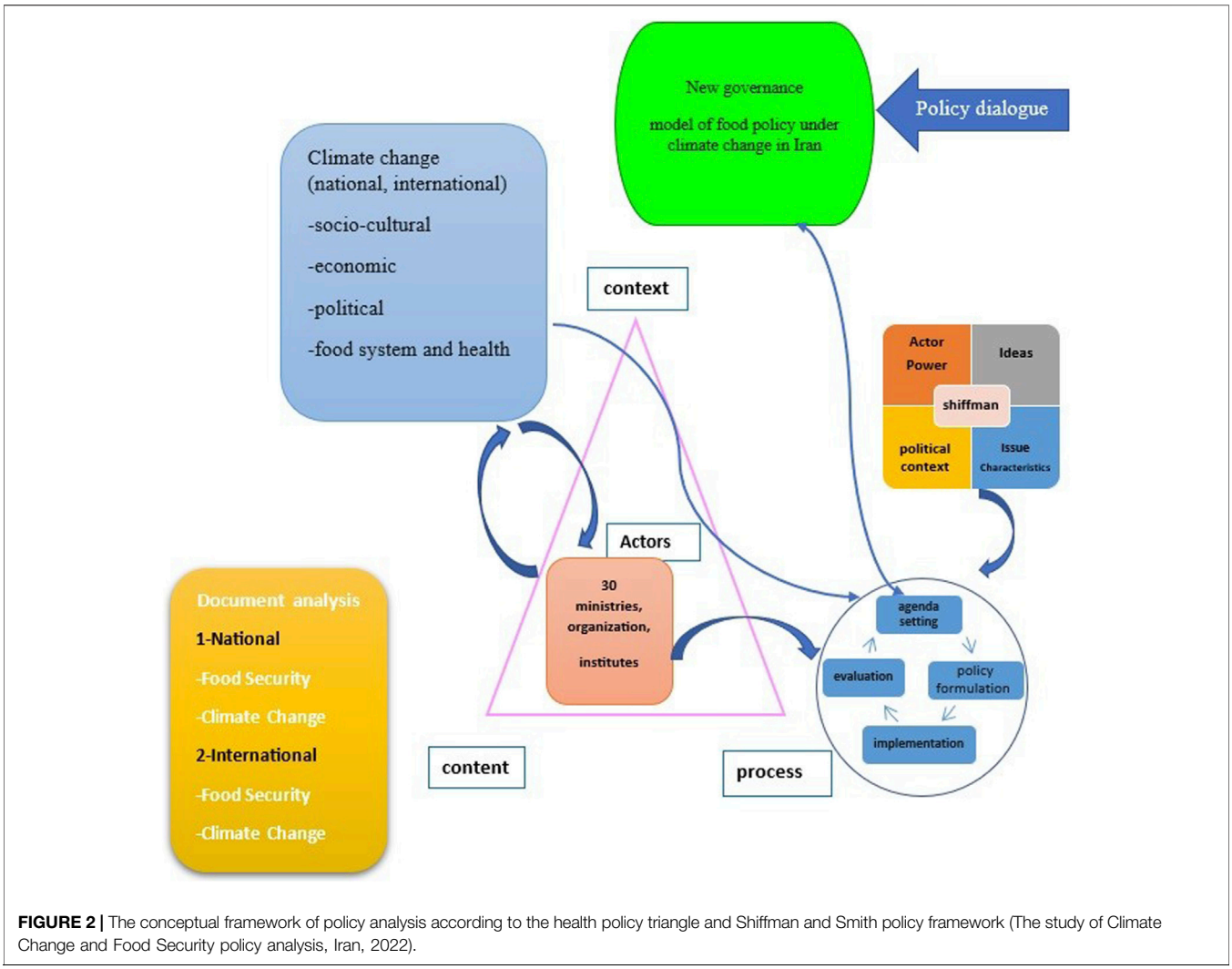

FIGURE 2 | The conceptual framework of policy analysis according to the health policy triangle and Shiffman and Smith policy framework (The study of Climate Change and Food Security policy analysis, Iran, 2022).

Issue Characteristics

This component of the Shiffman framework describes the problem's picture [18]. In this study, after the interview analysis, we extracted 1148 codes, categorized them into subthemes, and distinguished three themes (programming, research, and finance or economic support). Ultimately, we created three constructs, which are presented in **Table 2** and **Figure 3**. In the next paragraphs, to understand a different point of view, we present some cotes related to different problems of FS under CC in Iran.

> *Some interviewees believed that there was a lack of indicators, limited risk assessment and needs assessment, foresight scarcity, uncommon long-term planning, and weak monitoring and evaluation due to defective planning. One of the experts highlighted the estimation of aims: "We do not have quantitative estimation of aims in our action plans. Therefore, we could not address our needs, legislation or decision making based on rigorous aims. For example, if we decide to diminish 0.5% of malnutrition in children in our country, it is necessary to accurately investigate this disease and design quantitative targets."* (P 5)
>
> *A number of experts illustrated the connection between exposure and risk assessment in national FS planning under CC: "We have to know how many people in our country are exposed to risks of food insecurity. Because for national food insecurity mapping and estimation the extent of exposure to this threat, formulation of risk reduction based on categorization of the variables into external, internal, local and regional is indispensable."* (P 18)

Ideas

In this component of the Shiffman framework [18], we identified 220 codes and categorized them into three subthemes (common goals, priority setting, and stakeholders' ideas). Then, a consensus theme was created, which led us to develop a construct named the common voice. The experts stated that a common viewpoint is necessary to reach a consensus on FS under CC. This persuades

TABLE 2 | The identified themes, sub-themes, and constructs identified according to Shiffman framework related to food security under climate change government policy making (Iran, 2022). (The study of Climate Change and Food Security policy analysis, Iran, 2022).

Sub-themes	Themes	Constructs	Shiffman framework components
1. Legislation 2. Decision making 3. Conflicting interest 4. Conflict of interest	System approach	Supreme Decision-making center	Political context
1. Indicators 2. Risk assessment & needs assessment 3. Foresight 4. Long run planning 5. Monitoring & evaluation	Planning	early warning system	Issue characteristics
1. Ignore evidence 2. Multidisciplinary research 3. Limited evidence	Research	Scientific Evidence	Issue characteristics
Executive Guarantee	High-level political commitment	Leadership	Political context, Actor power
Cost Benefit	Economic support, financing	Economic evaluation	Political context Issue characteristics
1. Common goals 2. Priority selection 3. Stakeholders' beliefs	Consensus	Common voice	Ideas
1. International collaboration 2. National solidarity	Cooperation	Multi-sectoral collaboration	Political context Actor Power
1. Community education 2. Lobbing 3. Capacity building	Public Participation	Advocacy	Actor power

policymakers to put this subject on the agenda. In the next paragraphs, some cotes are presented to better highlight this issue.

> *An informant illustrated the lack of common ideas: "There is no opportunity to solve the CC and FS problems in our country until we believe in working lonely and in our islands without any consensus on common priorities".* (P 1)

Other informants explained the role of the Supreme Council of Health and Food Security (SCHFS) in performing common ideas:

> *"The role of this organization is conducting multi-sectoral collaboration among all stakeholders that contributed to health issues. The chief of the SCHFS is the president, and the health minister is the secretary, but unfortunately, there was not enough success in performing common ideas to push FS and CC issues on the agenda. This is because some decision makers suppose that heath is a luxury subject. Hence, these subjects are in second or third rank."* (P 13)

Some experts noted the importance of stakeholders' beliefs on common ideas for FS under CC agenda setting in Iran:

An informant explained the substantial role of decision making in CC management:

> *"In Iran, most policymakers have made efforts toward disaster management to control the harmful impacts of CC, although they have to pay attention to risk management to prevent the major negative impacts of this issue on people and the environment and decrease vulnerability".* (P 31)

Actor Power

The fourth component of the Shiffman framework is actor power [18]. We identified 314 codes and categorized them into six subthemes (international collaboration, community education, national solidarity, capacity building, executive guarantees and lobbing). Three themes were subsequently identified (national determinants, Public Participation and cooperation). Below, we present the viewpoints of the informants about these subjects.

Community education: Some interviewees believed that community partnership is a valuable capacity for FS and CC community education as well as for advocacy. People are powerful stakeholders.

The informant noted the substantial role of public participation, adaptation and mitigation policy education:

> *"People mute aware about the considerable role of their activities in declining the harmful impacts of CC on food resources. Moreover, the acculturalization of food production and consumption is essential for decreasing GHG emissions and diminishing resources, e.g., soil erosion and water misuse. Are people aware of these problems? Are the government involved in collaboration in education, forestation and pastural landscape expansion?".* (P 27)

Public participation: A number of experts stated that community education, lobbying and advocacy are important.

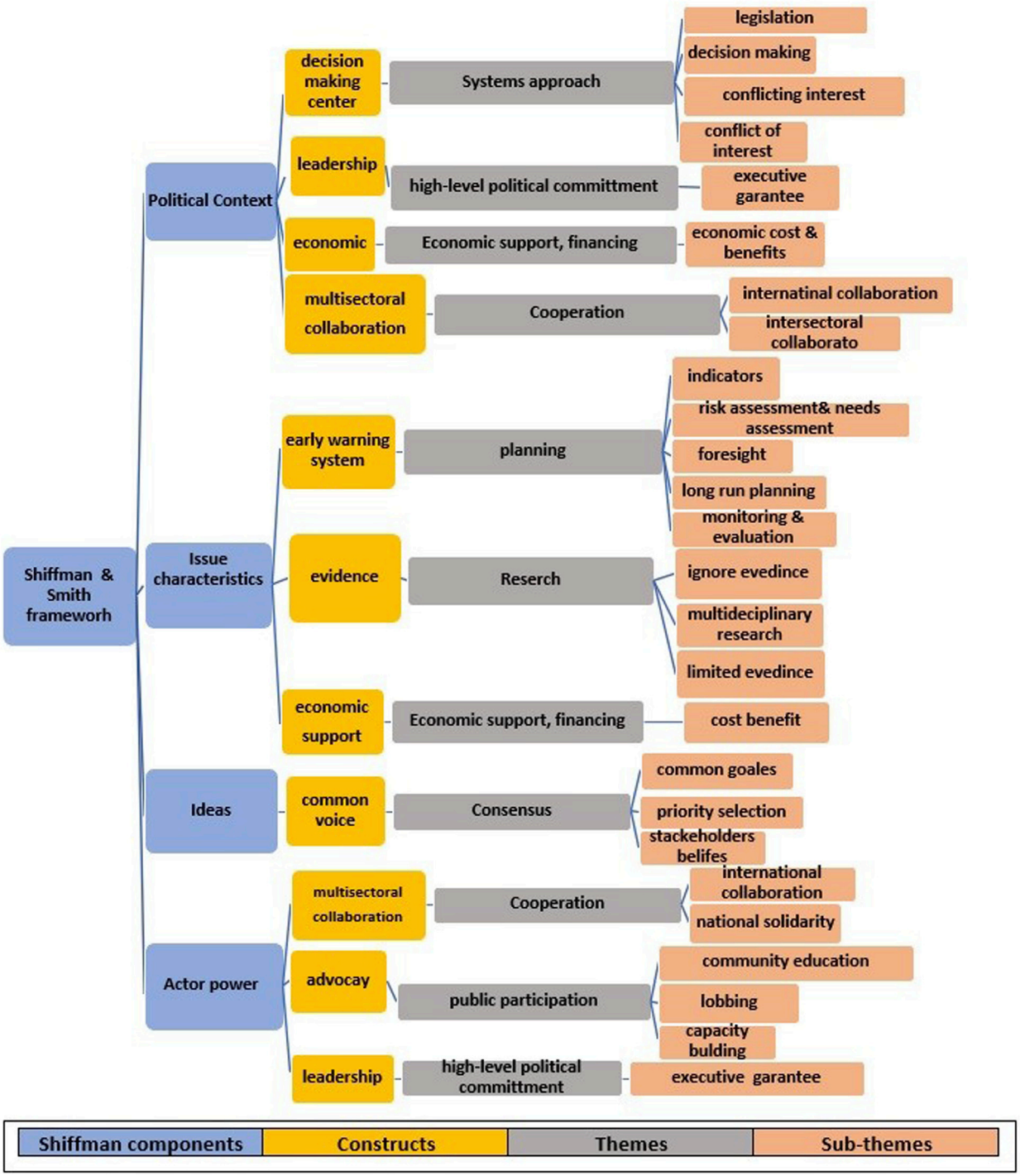

FIGURE 3 | Tree framework of sub-themes, themes and constructs of food security under climate change policy analysis in Iran based on "Shiffman and Smith" policy framework (The study of Climate Change and Food Security policy analysis, Iran, 2022). Note: sub-themes were investigated based on the codes that identified with food security dimensions availability, accessibility, utilization, stability or sustainability) and climate change disaster risk factors (exposure, hazards, and vulnerability), then themes and constructs were explored and categorized according to "Shiffman and Smith" policy framework with four components (Actor Power, Ideas, Political Context, and Issue characteristics) and policy triangle with three dimensions (context, content, process).

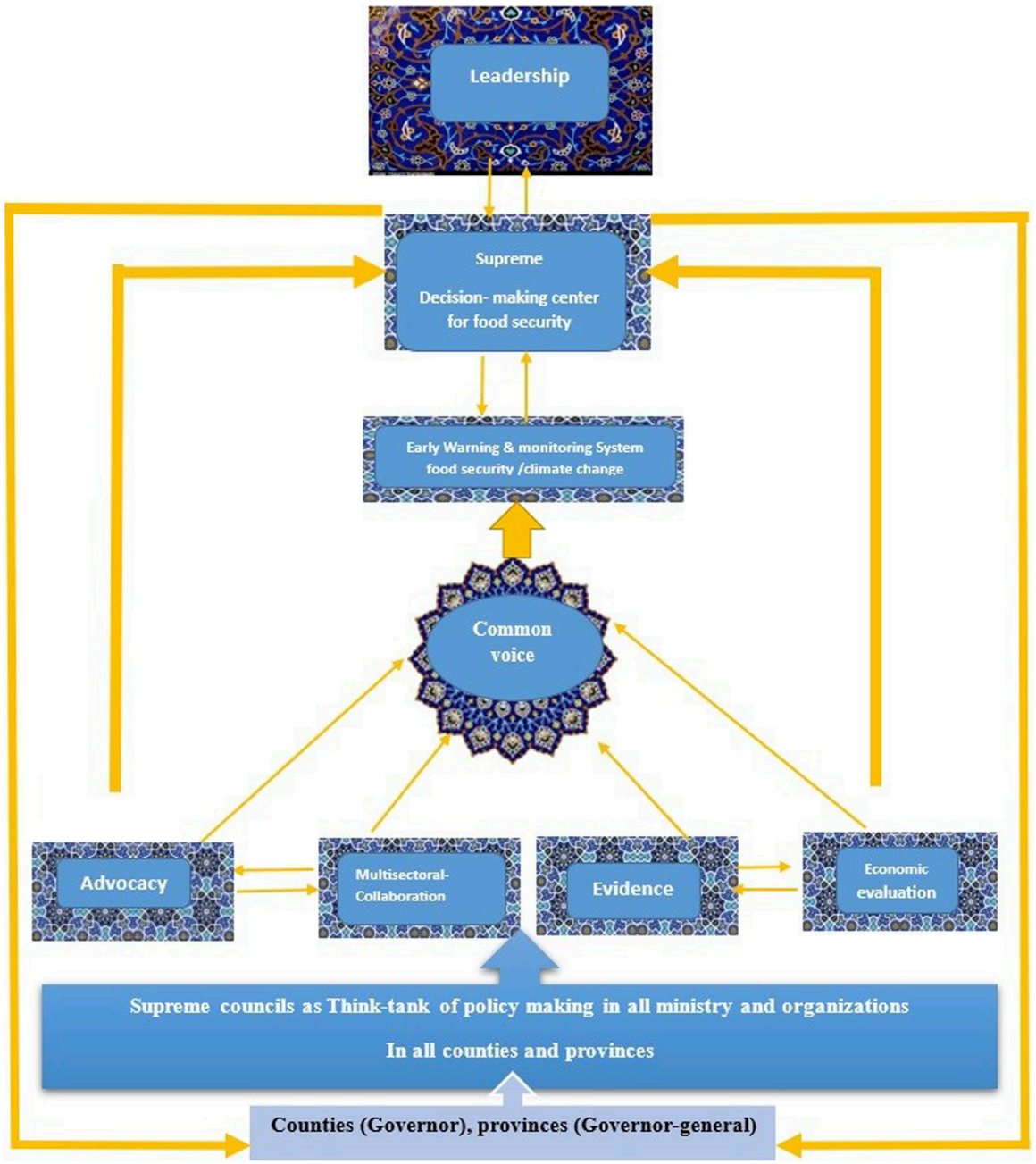

FIGURE 4 | Model for governance food security and climate change policy -making (The study of Climate Change and Food Security policy analysis, Iran, 2022).

Therefore, the government could apply this opportunity to increase FS under CC in Iran.

> *An expert illustrated the capacity of people to develop FS under CC. "If we informed our people about the harmful effects of deforestation and changed pastures to agricultural land for more food production, we would never be able to confront this extent of drought and pasture damage. This is because we did not use community participation's capacity and environmental acculturalization to improve people's information and behaviors."*

National Governance Model of Food Security Under Climate Change

Based on 8 constructs explored from the themes, we developed a model of FS under CC for the governance policy-making in Iran. Find it in **Figure 4**.

DISCUSSION

In this study, policy analysis based on the four components of Shiffman's policy framework highlighted a critical issue for (FS) and (CC) agenda setting [18]. It has revealed that certain barriers play a detrimental role in impeding effective decision-making for the implementation of national (FS) and (CC) programs: lack of (food decision-making center, leadership, economic support, multi-sectoral collaboration, early warning system, evidence, common voice, advocacy).

One fundamental problem is the governance fragmentation of FS, which leads to some issues in decision making by various institutes and organizations. This is partially due to conflicts of interest and divergent interests. Moreover, these barriers have a significant impact on the development of fair and equitable legislation. This complex situation arises due to the utilization of powers as non-decision-making by some stakeholders that employ powers to obstruct the creation of impartial legislation. However, the evidence showed that many countries face the same situation [30–32].

Another issue is parallel and conflicting legislation, Our finding indicates, this factor poses significant barriers to consensus on FS under CC national policy agenda setting in Iran, e.g., three key stakeholders namely, the Food and Drug Administration (FDA), the International Institute of Standards, and the Ministry of Agriculture are tasked with setting standards for assessing the levels of chemical contaminants and evaluating pesticide or herbicide residues in agricultural food products with different standards, that confused farmers [33–35]. This behavior come from economic interests of organizations [36]. Therefore, policymakers must prioritize policies that align with the shared objectives of all stakeholders aim to push the policy on agendas [36].

Addressing CC is a global imperative, necessitating international collaboration. Consequently, the Paris agreement was established to convene all nations around a common goal of reducing global warming [37]. This study indicated that, lack of inter-sectoral collaboration and international cooperation, stemming from weak multi-sectoral collaboration within the political context of Iran are significant barriers [38, 39].

Furthermore, several "issue characteristics" emerged from the subthemes, highlighting the importance of specific factors: limited indicators, risk assessment, needs assessment, long-term planning, monitoring and evaluating the impacts of CC on FS in Iran, and cost–benefit considerations for FS programs. Consequently, the establishment of an early warning system to monitor FS indicators and to provide accurate projections which show the severity of the situation is essential to informed FS policy-making under CC within the governance framework.

A feature of weak inter-sectoral collaboration is come from lack of effective data sharing by various institutions, organizations that diminished their ability to plan for the future based on accurate evidence, transparency, and accountability. Consequently, the adaptation programs related to CC and FS were unsuccessful, primarily because all stakeholders failed to fulfill their roles and responsibilities in shaping, planning, and implementing the policies. The other disadvantage of weak inter-sectoral collaboration is susceptibility of FS in high-risk communities to CC risks. The evidence from studies in other countries supported our results [40–42]. For instance, during the extreme flood events in 2017–2018 and 2020–2021 in some provinces in Iran, all four dimensions of FS were jeopardized, and many residents in these regions faced different features of food insecurity [43–45].

To shed light on the successful experience, Sweden's decision makers employed a policy convergence approach at the highest levels of government and created a new environmental policy framework to effectively implement a policy with 15 well-defined objectives and the active involvement of 24 government institutions and entities [46]. Their approach to addressing inter-sectoral collaboration challenges and mitigating conflicts of interest through policy integration aligns closely with our research that introduces a new governance model focused on policy integration to achieve FS under CC in Iran. This model takes into account the diverse powers, ideas, and political contexts of the various involved actors. In addition, one crucial factor contributing to the prioritization of a subject is achieving consensus [47, 48]. In the current study, stakeholders engaged in the examination of FS within the context of CC encountered challenges in establishing a consensus. Accordingly, they struggle to underscore the significance of this particular subject matter, substantiated with adequate evidence, for high-level policymakers. As such, in accordance with the Shiffman model and the structural component of "Ideas", common voice building is advocated as a foundational solution in this context [18].

The other identified obstacles for FS under the CC agenda setting in Iran is the lack of interaction, societal participation, and high-level political commitment, which is closely tied to the influence of various actors at different levels of government and within the government and private sectors related to FS and CC [49]. Also indicated an imbalance in the distribution of power among different actors. Therefore, within the framework of the agenda setting framework, the component of "actor power" suggests strategies for inter-sectoral collaboration, advocacy, and leadership to engage civil society in exerting pressure on these groups to steer policies toward prioritizing the issue.

To ensure FS in Iran and address the critical aspect of agenda setting within the nation's overarching policy framework, bridging the gap between policy objectives and their practical implementation is essential. Thus, presenting an evidence-based approach, one that considers the identified structures to map out interactions among diverse stakeholders during the policy-making process, is imperative [48]. Consequently, drawing upon best practices from various nations, this study introduces a comprehensive model for governance and policymaking in the realm of FS, particularly under the influence of CC conditions in Iran. This model is visualized in **Figure 4**.

The basis for policy convergence involves factors such as social behaviors, institutional coalitions, and the effectiveness of institutional policies. Moreover, the relationship between

subsystems. It can lead to the creation of a network of cooperation to address issues within the government structure, thus offering opportunities for horizontal collaborative solutions [48].

In fact, the result of such a process can give rise to a new subsystem within the government structure. The results of this study have shown the effectiveness of this framework in placing two policy issues, food policies and CC adaptation, on the agenda. Since CC affects policies in all sectors, it is necessary to develop plans that incorporate policy convergence in adaptation policies, such as the Paris Climate Agreement and Sustainable Development Goals [48, 50].

In the present study, considering the identified challenges, the political context of the country, the power of stakeholders, and the absence of a common voice, it appears essential to have an institution capable of making decisions beyond the established boundaries between ministries and agencies. This institution should possess a broad perspective on governance levels and hold legitimate authority in legislation and decision-making in the realms of FS and CC.

In such an environment, the possibility of formulating policies and making decisions with minimal opposition, conflicts, and maximum agreement and saliency is facilitated. Furthermore, the necessary conditions for supporting various stakeholders at different levels are established.

In successful experience, the Netherlands employed the policy integration framework method to explore both policy convergence and divergence within different governance structures on FS and CC. [48]. The results of this study were consistent with our findings.

Another effective policy integration framework was established in 2013, when Mexico launched a comprehensive program to combat poverty and hunger at the national level. One program, the "National Crusade against Hunger," focused on hunger reduction and involved 19 institutions to coordinate efforts. The program aimed to enhance coherence among social programs and improve policy integration. An inter-ministerial communication committee was formed for program selection, budget allocation, and monitoring. The former Mexican President established ministry committees at the national, state, and municipal levels. He was the leader of this committee. It was a successful program to diminish poverty and hunger after 3 decades in Mexico. Their approach of integrating policies and proposing a government model to overcome barriers (weak cooperation, leadership, high-level political commitment, common voice, public participation) in implementing FS policies aligns with the findings and recommended model of FS governance in our study [51].

In recent decades, many countries have globally embraced governmental fragmentation as a strategy to address evolving challenges in public services and the distribution of essential goods. However, this strategy has its drawbacks: it often neglects horizontal collaboration among institutions, leading to a decrease in the central authority of senior managers. Consequently, their impact and effectiveness in local governance declined due to power decentralization. This shift also decreased cooperation between sectors and generated tensions when complex issues related to public services were resolved. According to Peters, the specialization and lack of convergence only give rise to new problems, particularly in complex matters, as a result of dividing government activities [47, 52].

A study in England revealed that the government addressed air pollution from public transportation and rising carbon emissions by adopting a policy integration approach. Facilitated a horizontal coordination among entities and initiate vertical alignment. [53]. The UK government's strategy of policy integration and prevention of competition among different organizations for funding aligns with our study.

The experience in the Netherlands, aimed at improving FS and overcoming fragmented policy-making while maintaining and enhancing the agriculture, economy, and environmental infrastructure sectors, was designed in collaboration with all sectors and civil society by the Ministry of Economic Affairs and presented to the parliament. This initiative proposed a shift from the Common Agriculture Policy (CAP) to the Common Food Policy, and its draft was supported by think tanks and civil society organizations in Europe [48]. A similar approach is also influential in Iran, emphasizing self-sufficiency in food policies, with the Ministry of Agriculture [54].

Another policy designed in the Netherlands to adapt to CC involved the proposal to merge three ministries: The Ministry of Transport, the Ministry of Water, and the Ministry of Housing to create a new ministry called the Ministry of Infrastructure and Environment according to an integrated policy approach [48].

However, in Iran, CC has led to decreased precipitation and prolonged droughts, coupled with the utilization of seventy percent of underground water resources [55]. Additionally, reactionary and short-term policies such as the construction of dams and the redirection of water flow in some provinces have created water stress [56]. As a result, not only agriculture and sustainable food production are threatened on small farms, but the future of drinking water and industrial water supplies is also a cause for concern [57, 58].

Moreover, approximately two decades ago, Iran established the SCHFS, which aimed to address critical issues related to health and FS. However, despite its establishment, this framework fell short of achieving the desired level of inter-sectoral collaboration among the different actors involved.

Thus, we recommend the establishment of a supreme decision-making body for ensuring FS in the face of CC, with the president serving as its leader. This pivotal body comprises various key stakeholders, including all ministers, the Chief of the Planning and Budget Organization, the Department of Environment, the Speaker of the Parliament, the Chief Justice of the country, and representatives from relevant nongovernmental organizations (NGOs). This central authority would be vested with significant powers to execute comprehensive FS initiatives at both the federal and local government levels, in the vertical (from the federal center to provinces and counties) and horizontal (inter-sectoral collaboration by the activity of the supreme committee of health and FS and other related supreme committees such as

Think-Tank) levels of government and using a combination of bottom-up and top-down policy-making. Presented in **Figure 4**.

Malta's experience underscored the challenges faced by agriculture due to water scarcity, prompting a renewed focus on FS. A solution was to establish a joint committee among ministries, known as the "cross-ministerial water committee." Its primary objective was to facilitate vertical coordination across all levels of governance and promote horizontal collaboration among institutions, ministries, and all stakeholders engaged in water-related matters [30]. The findings of this study provide compelling evidence that supports our research.

Another example of successful policy convergence was the implementation of a nexus approach in Brazil, which integrated the energy, food, water, and CC sectors. This experience demonstrated the effectiveness of networking and policy convergence in addressing complex challenges. In 2016, Brazil developed a National Climate Change Adaptation Program, emphasizing the need for coherence with other national programs [40].

According to Hall's model, issues in the agenda must possess three characteristics: legitimacy, feasibility, and support [59]. Based on the current management model of FS in the context of CC in Iran, as discussed in the previous sections, The performance of SCHFS and other similar councils, numbering more than a hundred and five in the governance system of the Islamic Republic of Iran runs parallel to related ministries [60]. These councils represent clear examples of power division and fragmentation of management, as evidence has shown that their performance has failed to promote collaboration between sectors and policy convergence [61]. In our research, we utilized the Shiffman policy framework analysis as a foundational approach, carefully categorizing our results within this framework. However, we did not stop at mere categorization; instead, we effort to develop a new governance model according to joined-up policy. Moreover, it is designed in a way that, through policy-making based on the coalition of the two approaches, top-down and bottom-up, according to the advocacy coalition framework, engages civil society participation and creates conditions with advocacy, influencing policymakers.

Conclusion

Achieving a balanced distribution of power and influence among various actors, within a new governance framework for FS under the challenges of CC based on joined-up policy is critical. It encourages all stakeholders to actively engage in a coordinated policy approach. In this restructured framework, each stakeholder considers the interests of all parties involved, conducts comprehensive research, economic cost–benefit analyses, shares data for monitoring key indicators, and sets priorities aligned with collective objectives. Effective interaction and collaboration ensure the participation of the community and inter-sectoral cooperation with a common voice. These efforts culminated in a central hub for comprehensive FS management, ensuring a unified and effective response "political will" to the challenges posed by CC.

Limitations

This study focused primarily on the national perspective of FS stakeholders, primarily engaging with national-level policymakers. However, it is important to note that it did not encompass the international viewpoint of influential organizations such as the Food and Agriculture Organization (FAO) or the United Nations Children's Fund (UNICEF), which are significant players in the global FS landscape. Future research efforts could consider expanding their scope to involve international organizations such as the FAO or UNICEF.

ETHICS STATEMENT

The studies involving humans were approved by Ethic Committee of Tehran University of Medical Sciences in 2019. The studies were conducted in accordance with the local legislation and institutional requirements. Written informed consent for participation was not required from the participants or the participants' legal guardians/next of kin in accordance with the national legislation and institutional requirements.

AUTHOR CONTRIBUTIONS

Conceptualization, investigation, RA and AT; Writing original draft preparation, visualization, formal analysis, software, RA; Project administration, data curation, methodology, validation, supervision, AT; Investigation, writing-reviewing and editing, AK, HP, and AD. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

GENERATIVE AI STATEMENT

The author(s) declare that Generative AI was used in the creation of this manuscript. We use Grammarly application for grammatical editing of this manuscript.

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Effect of Climate Change on West Nile Virus Transmission in Italy: A Systematic Review

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Objectives: West Nile Virus (WNV) infection prevalence is increasing in recent years in Europe, particularly in Italy. Such increase has been related to climate and environmental factors. Our review aims to assess the relation between climate change-related factors and the spread of WNV in Italy.

Methods: We conducted a literature search across four online databases until 22 January 2025, using as search terms WNV, its vectors, and climate change.

Results: Out of 282 unique articles, we included 29 eligible papers published between 2011–2025, most of them assessing distribution of the main WNV vector (*Culex pipiens*) and epidemiology of the infection in relation to climate/environmental factors. We found a positive strong association of WNV transmission with temperature and agricultural land use. Associations with other environmental variables also emerged, but they were either weak or inconsistent.

Conclusion: Despite some inconsistencies in the results, likely due to heterogeneity in study methodologies and interactions of environmental variables, review findings indicate that some climate change-related factors favor WNV spread through its vectors in Italy, in line with exploratory observations obtained on the entire Europe.

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INTRODUCTION

West Nile fever is a disease originating in subtropical areas, which in recent decades has been increasing in Europe, especially in Southern Europe [1], but there are also concerns about its spread to other parts of the continent [2]. West Nile disease is an arbovirosis, i.e., an infection caused by viruses transmitted by vectors, represented in Europe mainly by two mosquitoes of the genus *Culex* (*Cx.*), *Cx. pipiens* and *Cx. modestus* [3]. The reservoirs of this pathogen are birds, especially magpies, grey crows, turtle doves and passerines, who live in both natural and urban environments, and are all characterised by large migrations. For this latter reason, the virus spreads through the vectors and

infects other hosts, especially but not limited to equines and humans, affecting also reptiles, amphibians and other mammal species [4–8]. In humans, the infection runs asymptomatically in most cases, but 20%–30% of subjects present the symptomatic form, i.e., West Nile fever. About 3% of symptomatic cases and 0.5%–1% of total cases present a neuroinvasive form possibly leading to serious consequences, up to death, in about 10% of cases [9–11].

Before 1998, there were only few documented cases of West Nile Virus (WNV) in Europe, and none in Italy [12]. Since then, the disease has dramatically increased, leading to 475 human neuroinvasive forms in Italy alone during the decade 2008–2018. This surge has shown no sign of curbing: in 2018, 2083 cases and 180 deaths were recorded in Europe, 577 and 46 of them respectively in Italy [13, 14]. In the 2024 transmission season, Italy has reported 455 locally acquired human cases (of 1436 in Europe) and 21 deaths (of 125 in Europe) related to WNV infection, thus making it the most affected European country for several years already, followed by Greece (217 cases with 34 deaths) [15].

Public attention is increasingly focusing on this spread as its causes are still unknown, although climatic and environmental factors are prime suspects, as observed for other infectious diseases [16–19]. One of the major suspected causes is climate change [20]. As a matter of fact, similar trends have been noted between the increasing impact and severity of climate change and the WNV epidemics in the same territories [21]. It has been shown that the increased spread of vectors in European countries has been caused also by the increase in temperatures linked to global warming, which has expanded suitable areas and lengthened the survival period of the vectors [22–24]. Although some evidence on the association between climate change and WNV spread has been recently reported, literature on a comprehensive overview and comparison of the climatic and environmental factors involved is missing. Some recent reviews have approached the topic in a rather exploratory way, including studies referring to a large time interval to extremely different territories and in some cases considering several arboviruses together. Also because of the low comparability of the data, they were limited to describing the presence or absence of associations, without going into detail [25, 26].

This systematic review aims to analyse the existing epidemiologic evidence investigating the association between the spread of WNV or its vectors, and climatic or environmental factors, focusing on Italy as the most affected country in Europe [15].

METHODS

Review Registration and Research Question

We performed a systematic review of the literature on the association between climate and environmental factors and WNV and its vectors epidemiology in Italy. The recommendations of the PRISMA (The Preferred Reporting Items for Systematic reviews and Meta-Analyses) guidelines were followed and the study protocol was registered in PROSPERO (no. CRD42023430636) [27].

The research question following the PECOS (Population, Exposure, Comparison, Outcome, Study design) statement was "What is the association between climatic or environmental factors and WNV infection prevalence/WNV vectors distribution in Italy?". Inclusion criteria were as follows: Italian human and non-human population (P), climatic and environmental factors associated with climate change (E), comparison between such factors, i.e., low or no exposure (C), increase in WNV cases or vectors spread (O) and non-experimental and experimental studies (S).

Literature Search and Screening

We searched four literature databases (PubMed, Web of Science, Embase, and Scopus) up to 22 January 2025, using MeSH terms related to WNV and its vectors (*Cx. pipiens* and *modestus*) as reported in detail in **Supplementary Table S1**. We considered only original research studies with qualitative or quantitative analysis in English or Italian language, and we also screened the references lists of the retrieved articles for additional eligible studies. Two of us (AL and PV) independently screened the title, abstract and full text of the studies. We used the freely available systematic review tool Rayyan[1] for listing the selected papers and references retrieved were saved in Endnote (Clarivate Analytics, 2024).

Inclusion and Exclusion Criteria

We considered as eligible for our review only original studies assessing the geographical distribution of vectors or WNV infection in humans or non-human hosts in Italy, also considering climatic, environmental, or geographical factors (**Supplementary Material** on the selection process). We did not include case studies and literature reviews, other reports and guides published by relevant organizations, unpublished manuscripts, conferences proceedings, notification of outbreaks, and clinical descriptions of diseases.

Data Extraction

From the selected articles, we extracted data about first author, publication year, study design, region of the study, vector species, reservoir and hosts (humans, non-human hosts–i.e., birds or other animals - and bird species), type of data presentation (e.g., abundance or probability map), analytical approach, data sources, climatic and environmental factors, and WNV activity indicator. Both vector and WNV related outcomes were considered as WNV activity indicators. Vector related outcomes included abundance, expansion, growth rate, infection rate and geographical suitability for mosquitos. WNV related outcomes included abundance, incidence, force of infection (FOI), spillover risk, circulation, and transmission rates of the virus.

Quality Assessment

To evaluate quality of the selected publications, a 12-items quality assessment tool was used and adapted, based on methods applied

[1]https://www.rayyan.ai/

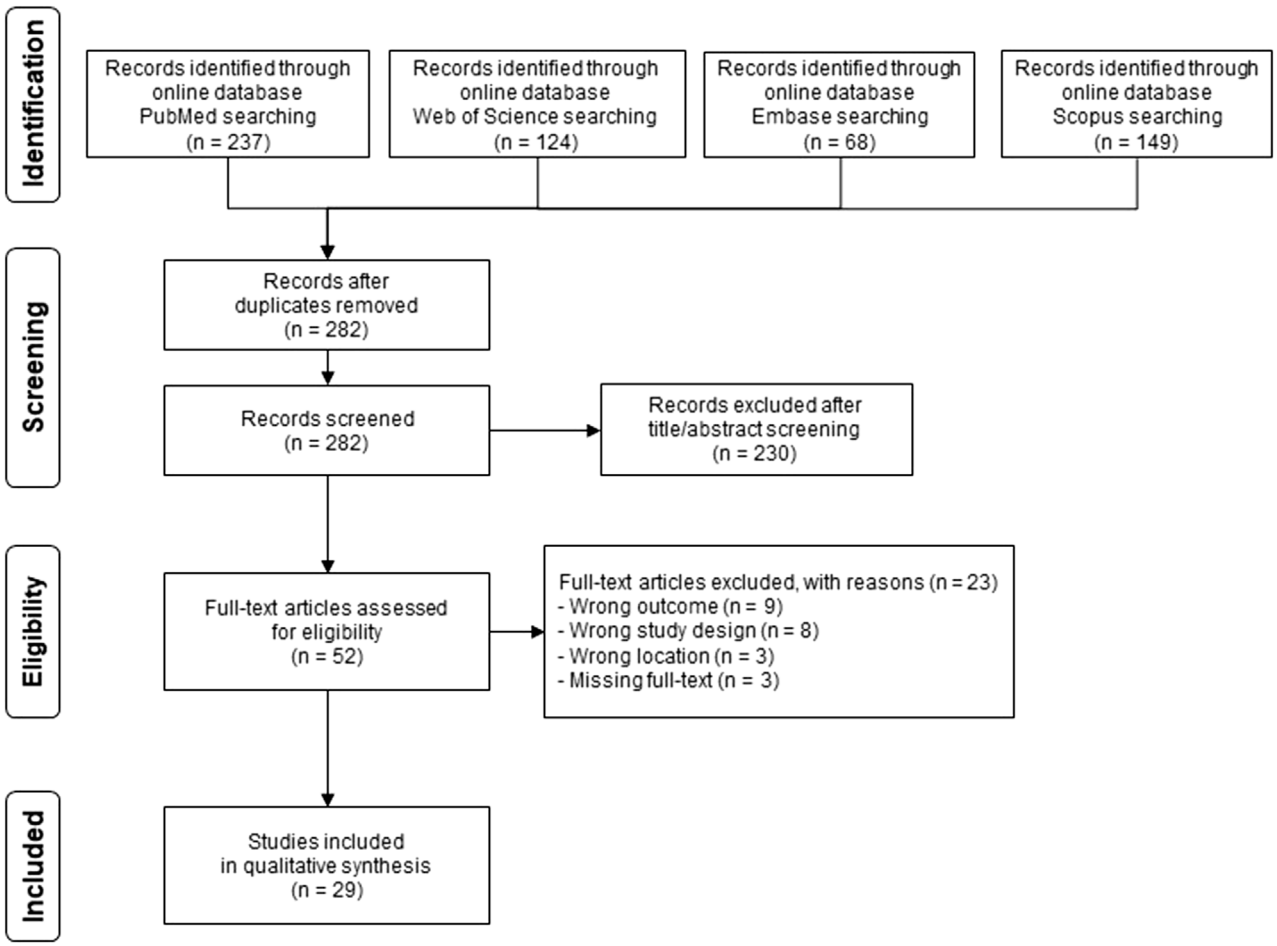

FIGURE 1 | PRISMA flow chart of the inclusion process (systematic review, Italy, 2011–2025).

in similar reviews [26]. Quality was scored as a binary variable (yes/no scoring as 1/0). The sum of positive items yielded the final evaluation, with higher scores meaning higher quality (maximum score: 12). The items evaluated included: description of the most relevant background, clear description of the objectives, appropriate study design, description of data collection procedures, sources for data collection, description of the study period, description of the place of study, description of the analytical approach and methods, description of data analysis, clear description of the results, results coinciding with objectives, adequate conclusions.

Data Analysis

In order to compare results, we implemented a graphical representation showing the number of studies investigating each factor and the direction (positive or negative) of the association emerged, if any. Each factor was assigned a specific circle. The size of the circle was weighted according to the number of studies that investigated that specific factor, while on the x-axis was the percentage of such studies in which the factor was found to be associated with the outcome. Furthermore, within the circle was the relative frequency, in percentage, in the sign of the associations found (grey for positive and black for negative). We used Mapchart[2] and Excel (Office Package, Microsoft Corp., Redmond, WA, 2024) to produce tables, figures, and maps.

RESULTS

Study Inclusion

The database search yielded 578 potentially eligible articles (**Figure 1**). After exclusion of 296 duplicates, we performed title and abstract screening of the 282 remaining items. Out of 52 articles selected for full-text evaluation, we eventually included 29 papers in our review. Reasons for exclusions were an outcome unrelated to WNV or disease (n = 9), study design not reporting original data (n = 8), missing full text (n = 3) or not specifically considering Italy (n = 3), as reported in **Figure 1**.

[2]https://www.mapchart.net/

TABLE 1 | Summary information of the studies selected for review (systematic review, Italy, 2011–2025).

General information				Host infected			WNV	Vector		Study place	
First author (year) [reference number]	Study design	Analytical approach[a]	Study quality	Human	Birds	Equines	Effect on WNV studied	Analyzed *Culex* species	Effect on vectors	Analyzed region	Type of maps[b]
Bisanzio et al. [28]	Ecological	SM/AM	9					both[c]	Abundance	Piedmont	AM, PM
Calzolari et al. [29]	Ecological	SM	11					*pipiens*	Vector infection	Emilia-Romagna, Lombardy	AM
Calzolari et al. [30]	Cross sectional	SM/DM	9					*pipiens*	Vector infection	Padan Plain	AM
Candeloro et al. [31]	Ecological	PM	9		X	X	WNV circulation			Italy	PM
Carrieri et al. [32]	Longitudinal	AM	11					*pipiens*	Abundance	Bologna Province	
Conte et al. [33]	Ecological	AM/PM	10	X		X		both[c]	Suitability	Italy	PM
De Angelis et al. [34]	Case Time Series	AM	12	X			Incidence			Northern Italy	AM
De Freitas Costa et al. [35]	Ecological	TM/DM	11		X		Birds Transmission	both[b]		Italy	
Fesce et al. [36]	Ecological	TM/PM	10		X		Birds Transmission	*pipiens*	Vector infection	Lombardy	
Fornasiero et al. [37]	Ecological	AM	12					both[c]	Growth rate, Abundance	Veneto, FVG[d]	
Groen et al. [38]	Cross sectional	PM	8					*pipiens*	Abundance	Emilia-Romagna, Po Delta	
Jian et al. [39]	Ecological	AM	10					*pipiens*	Growth rate, Abundance	Rovigo Province	
Marcantonio et al. [40]	Ecological	AM/PM	11	X			Incidence			All Europe	AM
Marini et al. [41]	Longitudinal	DM	10					*pipiens*	Abundance	Eastern Piedmont	
Marini et al. [42]	Case control	DM	10					*pipiens*	Abundance	Trento and Belluno Provinces	
Marini et al. [43]	Ecological	DM/TM	9	X	X		Spillover Risk	*pipiens*	Abundance	Veneto	
Marini et al. [44]	Ecological	TM/AM	9				Birds Transmission	*pipiens*	Abundance	Emilia-Romagna	AM
Marini et al. [45]	Ecological	AM	10	X			Abundance			All Europe	AM
Marini et al. [46]	Ecological	AM	8	X			Force of infection			All Europe	AM
Moirano et al. [47]	Ecological	AM	11	X			Incidence			Northern Italy	AM
Moirano et al. [48]	Case Crossover	AM	10	X			Incidence			All Europe	AM
Mughini-Gras et al. [49]	Ecological	PM	10			X	Abundance			Italy	AM, PM
Mulatti et al. [50]	Ecological	AM	8		X	X	Abundance			Padua, Rovigo, Venice Provinces	PM
Mulatti et al. [51]	Longitudinal	AM	10					*pipiens*	Expansion	Veneto, FVG[d]	AM
Rizzoli et al. [52]	Cross sectional	AM	12		X			*pipiens*	Abundance	Veneto	
Roiz et al. [53]	Cross sectional	AM	11					*pipiens*	Abundance	Trentino (Arco, Riva del Garda)	
Rosà et al. [54]	Ecological	AM	11					*pipiens*	Abundance	Piedmont	
Serres et al. [55]	Ecological	PM	12	X			Outbreaks			All Europe	PM
Trajer et al. [56]	Ecological	AM	10	X			Abundance			Italy	

[a]*Analytical approach: predictive models (PM), association models (AM), spatial models (SM), transmission models (TM).*
[b]*Type of maps: abundance map (AM), predictive map (PM).*
[c]*Both* Cx. pipiens *and* modestus.
[d]*FVG (Friuli-Venezia Giulia).*

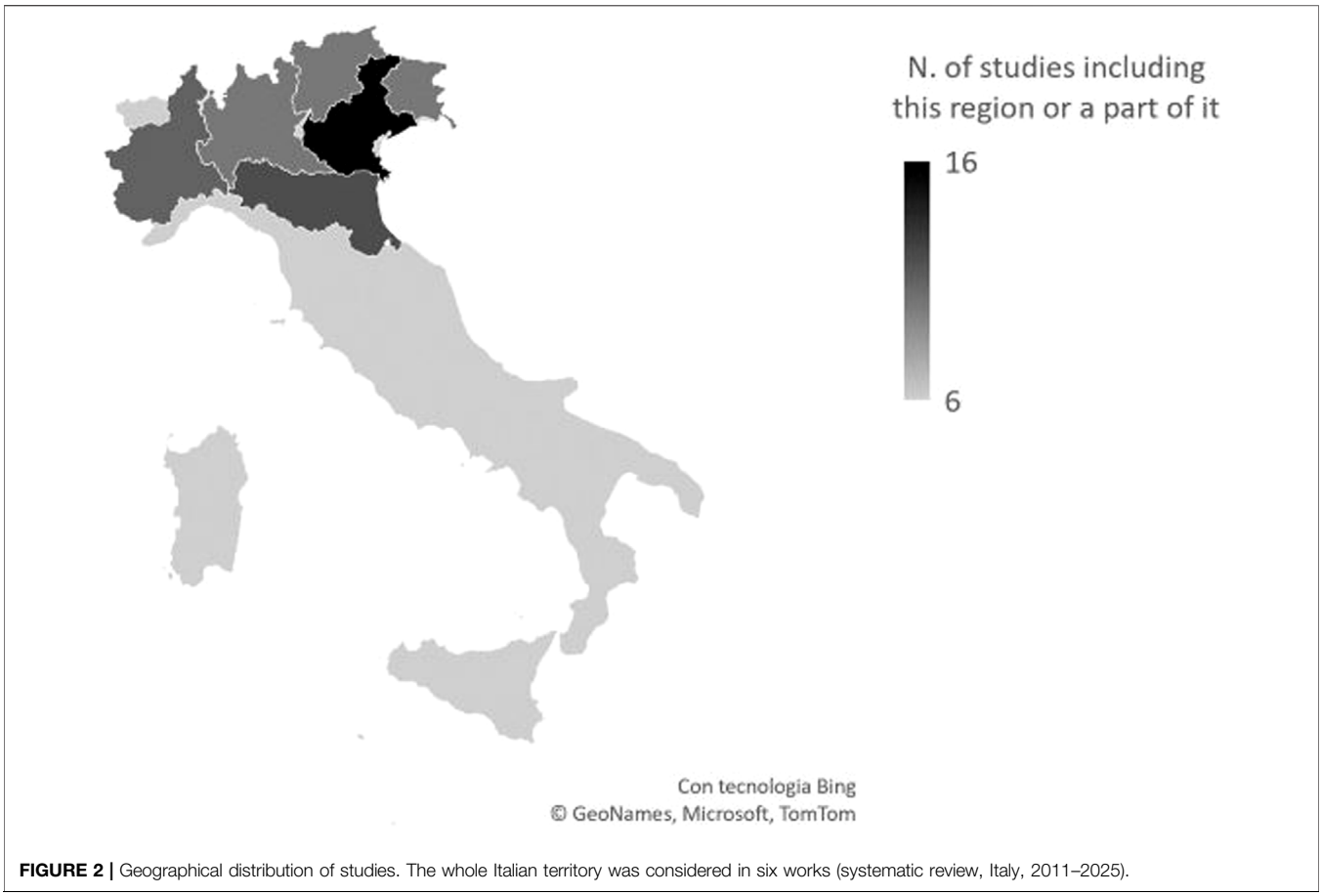

FIGURE 2 | Geographical distribution of studies. The whole Italian territory was considered in six works (systematic review, Italy, 2011–2025).

Study Characterization

The main characteristics of the studies included are summarised in **Table 1**. All articles were published between 2011 and 2025. The most frequently used statistical model types were association/correlation models (n = 14) followed by predictive models (n = 4). Other models were spatial models (n = 1), density/abundance models (n = 2), and multiple models (n = 8). Among the latter, generally spatial (n = 2) or transmission models (n = 4) were mixed with other types. Two studies mixed association and predictive models.

Considering quality assessment, the average score was 10 points. The most frequent gaps in the score were related to a lack of clear and complete description of the objectives (11 studies) and of the results (10 studies), while 6 studies did not accurately report the study or data collection period and five did not have exhaustive conclusions (**Supplementary Table S2**).

The analysed outcome was WNV in 12 studies, the vector in 14, while 3 studies assessed both endpoints. Of those related to WNV, 2 studies analysed the total number of cases in humans [45, 56], one study in horses [49] and one study in horses, birds and mosquitoes [50]. Four studies evaluated the incidence of WNV infection in humans [34, 40, 47, 48], and 3 others viral transmission between mosquitoes and birds [35, 36, 44]; one study the circulation of the virus in animals [31], the FOI [46], the spillover risk [43] and outbreaks [55].

In contrast, the studies that reported the spread of the vector as an outcome analysed absolute abundance in 10 studies [28, 32, 38, 41–44, 52–54], abundance together with growth rate in 2 studies [37, 39], the percentage of vector infection in 3 studies [29, 30, 36], and expansion [51] and geographical suitability [33] in one study each.

As depicted also in **Figure 2**, eight studies analysed the entire country, and 3 studies Northern Italy only. The remaining 16 studies focused on specific Northern Italy areas, namely, 7 studies the so-called Triveneto (Friuli-Venezia Giulia, Veneto, Trentino), 2 studies Emilia-Romagna, and 2 studies both Emilia Romagna and Triveneto. Finally, 3 and 2 studies assessed the Piedmont and the Lombardy region, respectively.

Climatic and Environmental Factors

Associations of WNV transmission and vector epidemiology with climate and environmental factors emerged in the studies, are described below (**Figure 3**; **Supplementary Tables S3, S4**), as follows:

Temperature

Temperature was the most investigated factor as it was considered in 27 studies. In many of these it proved to be a

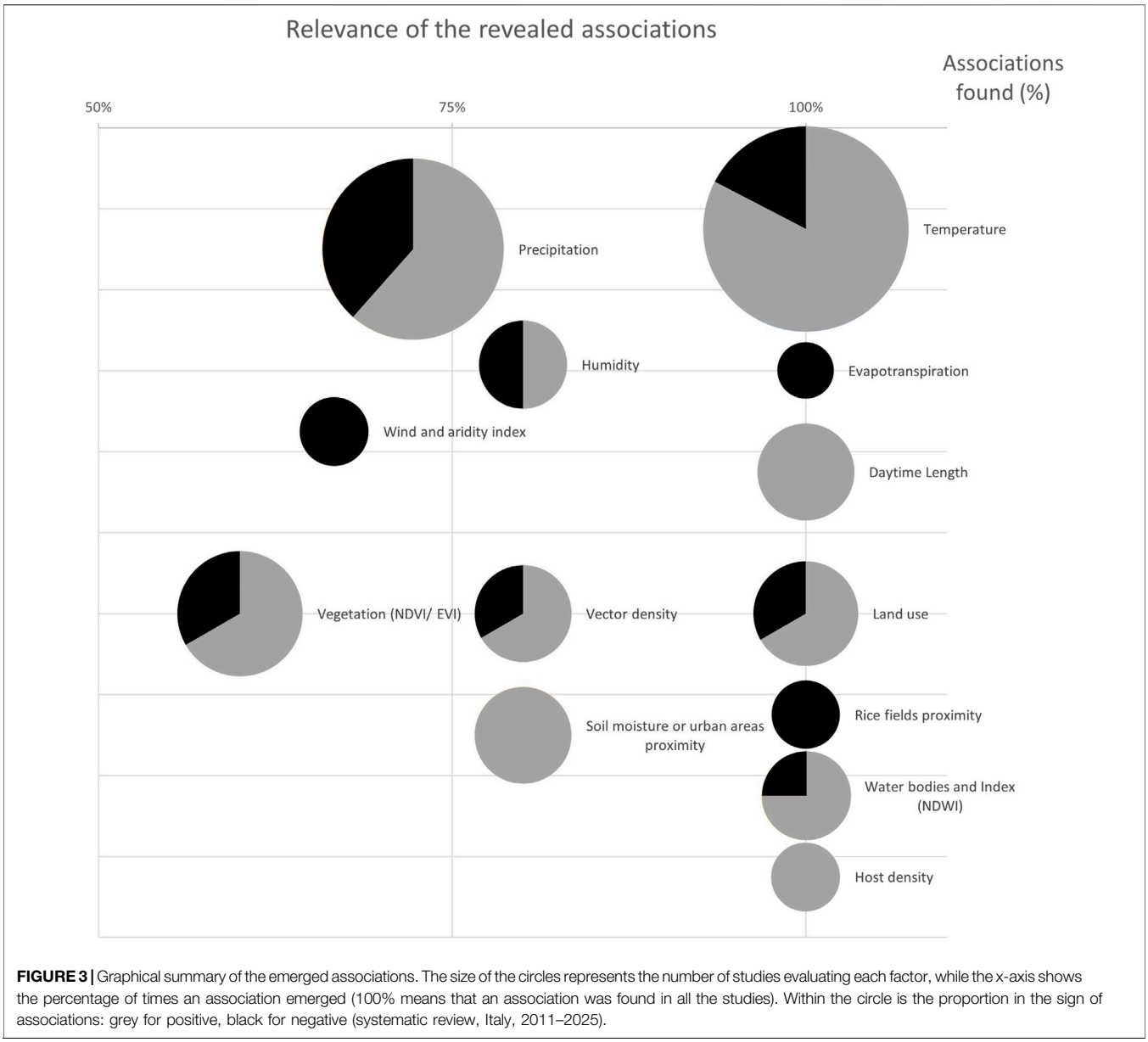

FIGURE 3 | Graphical summary of the emerged associations. The size of the circles represents the number of studies evaluating each factor, while the x-axis shows the percentage of times an association emerged (100% means that an association was found in all the studies). Within the circle is the proportion in the sign of associations: grey for positive, black for negative (systematic review, Italy, 2011–2025).

key factor in the spread of WNV and its vector, with a high rank in predictive models [28, 31, 49, 50] and showing almost always positive associations (24 out of 27 studies). Only 3 studies reported a negative association between temperature and vector abundance, 2 of which were related to the rise in temperature in the preceding days [37, 51]. Conversely, one study reported the competition with mosquitoes of the genus *Aedes* (*Ae.*), which was greater at higher temperatures [42]. All other associations that emerged were positive. In particular, positive associations between the average temperature of a preceding period of 1 week or more, up to more than a month, and abundance of the vector, infection rate of the vector or incidence of WNV in the population were found [29, 34, 38, 47, 48, 53, 56].

High spring temperatures have been shown to anticipate the first seasonal WNV cases, to lengthen the epidemic season and to be positively associated with vector or WNV abundance in summer, or with FOI [32, 41, 44–46, 54]. The mean temperature during summer months positively correlated with vector abundance and disease incidence [32, 40]. In one paper, summer temperatures ranging from 15°C to 28°C were positively associated with the occurrence of WNW cases in humans [55]. A predictive model showed that the warmer temperature in Italy compared to other European countries are associated with viral circulation despite the low vector-host ratios (number of mosquitoes per bird), and the high dilutions, i.e., high proportion of mosquito bites on competent birds that are able to replicate the virus to infect mosquitoes [35]. In another study a

negative association emerged between late summer heat and vector abundance, but with a longer period of vector activity [54].

Temperature was found to be, on average, higher in WNV endemic areas than in neighboring areas, and a predictor of the risk of outbreaks [30, 36, 55]. Finally, collinearity emerged with both mean day length [39] and humidity [38].

Precipitation

Rainfall was evaluated in 21 studies, with conflicting results. In 5 of these, rainy days or the precipitation amount were not associated with expansion, growth, abundance, or infection rate of the vector, nor with FOI [29, 37, 39, 46, 51]. In other studies, however, a positive association emerged between heavy rainfall in the previous month and WNV incidence [47]; overall a positive association or predictive value was found in 5 other studies [32, 40, 41, 48, 55]. According to one study, rainfall decreased competition with *Ae. albopictus* mosquitoes, increasing the number of *Cx. pipiens* [42]. In 4 studies, spring precipitation was positively associated with vector abundance during the summer season, although it may delay its onset and shorten its duration [32, 40, 41, 54]. Summer rains, on the other hand, were associated with outbreaks probability, a greater presence of vectors in the following months and a longer duration of the epidemic [32, 54, 55]. Finally, according to 4 studies intense rainfall was negatively associated with both the abundance of the vector up to 7 weeks later, and the monthly cases amount; furthermore, rain was found to be lighter in virus endemic areas than in neighboring areas [30, 34, 38, 53, 56].

Humidity

Humidity was evaluated in 5 studies, resulting not associated with vector expansion in one of them [51]. Negative associations were found with vector abundance 3–4 weeks later [38] and with incidence of WNV infection in humans 1–9 weeks later [34]. In other research, high relative humidity in May, July and August was positively associated with summer abundance of the vector [32] and relative humidity levels from 70% to 85% positively influenced the probability of occurrence in human cases of WNV infection [55].

Wind

The role of wind was assessed in 2 studies, being not associated with vector abundance in one study [39], while negatively correlated towards it from May to August in the other one [32].

Evapotranspiration

Evapotranspiration is the loss of water from the soil both by evaporation from the land surface and by transpiration from the plants growing on it [57]. It was evaluated by 2 studies: one study reported a negative association between evapotranspiration in May and vector abundance in the subsequent first three summer months, while the other one pointed out a strong negative association with vector infection rate [30, 32].

Daytime Length

Daytime length was positively associated with vector abundance, expansion and spillover risk in all the 6 studies that analysed it [35, 37, 39, 40, 43, 51].

Thermal Excursion and Hydroclimatic Balance

These two factors were both analysed once. Thermal excursion, particularly that of April and May, was found to be negatively associated with vector abundance in the early summer period. In contrast, the hydroclimatic balance (calculated as rainfall minus evapotranspiration) was positively associated with the abundance of the vector from May to September [32].

Vegetation Index (NDVI/EVI)

The Normalized Difference Vegetation Index (NDVI) is a satellite-based measure calculated from the near infrared and visible wavelength values reflected by the plants. It is indicative of vegetation density and values range from −1, corresponding to area with no or low vegetation like water bodies or areas covered by cement, and +1 corresponding to high density vegetation like forest; the Enhanced Vegetation Index (EVI) is similarly calculated, but it corrects for some distortions in the reflected light caused by the particles in the air as well as the ground cover below the vegetation [58]. Vegetation index was evaluated in 10 studies [28, 30, 31, 33, 37, 39, 40, 49, 50, 55], 2 of which observed a positive association with vector growth and abundance [37, 39]. Two studies concluded that there was no association between vegetation and WNV incidence [40] or outbreaks [55], while another observed more dense vegetation outside the area of virus circulation [30].

Presence of Standing Water or Wetlands

The presence of standing water was analysed in 2 studies [40, 55]. One of these concluded that it was not a predictor of virus incidence [40] and another assessed that the presence of open water areas, wet crops or wetlands was a positive predictor for outbreaks [55].

Water Index (NDWI) or Aridity (De Martonne Index)

The normalised difference water index (NDWI) is used to delineate open water features and enhance their presence in remotely-sensed digital imagery [59]. It was analysed in 2 studies and was found to be positively associated with earlier onset and longer duration of seasonal vector presence [54], while its spring and summer values were negatively associated with WNV incidence [40]. Only one study assessed aridity (De Martonne aridity Index, calculated as the ratio between the annual average precipitation and the annual average temperature increased by 10°C [60]) as a function of vector abundance, showing a negative association [37].

Altitude

The role of altitude was a considered in 4 studies [28, 33, 49, 50], of which only one analysed the individual contribution of this variable, defining it as very important in delineating a suitability area for the vector [33].

Human Use of the Environment (Land Use)

Human land use was taken into account 5 times [28, 40, 46, 49, 55], being once negatively associated with FOI [46]. In other studies inhabited forests and more so irrigated croplands were found to be positive predictors for WNV incidence [40] and

urban areas were positive predictors for outbreaks [55]. Furthermore, the presence of areas untouched by humans (such as protected areas) was not associated with vector abundance [52] and agroforestry areas, arable lands or arid shrublands were not predictive for the probability of outbreaks [55]. In the last study a set of variables evaluated through Corine Land Cover map was used to characterise the distribution of mosquitoes, but without defining which of them contributed most in predicting their presence [49].

Host Density

Host density, animal or human, was used as a variable in 3 studies [46, 49, 55], with 2 of them reporting a positive association: between density of individuals over 65 and FOI [46], and between human population density and probability of outbreaks [55].

Distance to Specific Areas

Emerging as non-predictive on FOI in one study [46], distance to specific areas was analysed in 4 other studies by:

a. Distance from rice fields [28, 39, 54], resulting having a negative association with vector abundance in all 3 studies.
b. Distance from damp soil/soil moisture [31, 39, 55], resulting in a negative association with vector abundance [39] and a high predictive value 80 days before WNV circulation [31]. The level of soil moisture has a positive predictive role for probability of outbreaks [55].
c. Distance from urban areas [28], negatively associated with vector abundance for *Cx. pipiens*.
d. Distance from forest areas [55], positive predictor for probability of outbreaks.
e. Distance from pastures [55], not predictive for outbreaks.

Other (Vector and Infection Dynamics)

Vector density, analysed in 7 studies, outlined 3 positive associations with consequently vector abundance, with transmission of WNV from birds to humans, or from mosquitoes to birds [32, 35, 41, 44], one non-linear association with mosquito positivity for WNV when tested by real-time PCR [29] and two negative associations with vector expansion after the reaching of a ceiling effect [37, 51]. WNV incidence in previous years was not associated with FOI [46]. In contrast, competition with *Aedes* mosquitoes was negatively associated with *Cx. pipiens* abundance [42]. Finally, infection dynamics in birds appeared to have a high impact on transmission to humans [36].

DISCUSSION

The most widely evaluated factors were temperature and precipitation (in 27 and 21 studies respectively), although consistent results were reported for the former only. An association between temperature and the spread of WNV or its vector emerged in 100% of the studies, being positive in 83% of them. Conversely, precipitation provided evidence of any association in only 2 out of 3 studies, with a positive direction in 62% of them and a negative direction in 38%. Environmental factors linked to the water cycle and humidity gave more contrasting results as the associations were generally not consistent, although the limited number of studies hamper any definitive conclusion. Conversely, greater consistency emerged from climatic factors such as wind, aridity, evapotranspiration, generally negatively associated, and hydroclimatic balance positively, with the outcomes.

Vegetation index was the third most frequently studied factor, being associated in 67% of the included studies to one of the outcomes of interest, positively with vector abundance or growth rate, and negatively or not associated with WNV incidence, presumably also due to fewer people in these areas. In contrast, WNV spread was positively associated with human use of the environment (irrigated croplands and settled forests) [40], which was instead negatively associated with FOI [46]. On the other hand, soil exempt from human use was not associated with vector abundance [52]. Moreover, distance from rice fields, damp soils and urban areas were found to be negatively associated with vector abundance [28, 39, 54], and the density of over 65 inhabitants positively with FOI [46]; all signs that human activities close to suitable areas have an impact on disease dynamics.

Finally, day length was found to be positively associated with outcomes, effectively confirming their seasonality, while temperature excursion negatively. Vectors and transmission dynamics appeared to be associated in a complex and non-linear manner with the spread of infection [35, 36, 42].

Our results are somewhat consistent with previous reviews that showed a high heterogeneity of the factors evaluated as well as of their associations with WNV [25, 26]. Conversely, we confirmed a strong positive association of temperature (especially at the onset of the warm season), of daylight hours and of anthropogenic impact with the spread of WNV and its vectors. In addition, our results further highlight that strong relevance of temperature in the spread of WNV and its vector. Thus, temperature increase linked to global warming in recent decades is expected to grow the number of cases of WNV in Europe and particularly in Italy. This effect does not seem to be related to the temperature peaks typical of the warmer months, but rather to the overall increase in its average values as well as to its reduced variation over days and seasons, yielding to the increase of both mosquitos and WNV presence [22–24]. These climatic modifications in Italy are already particularly evident and quickly escalating, accompanied by a sharp increase in cases, as shown in recent studies [61].

The relatively little influence of water cycle factors on the emerged outcomes can be explained in several ways. Indeed, the abundance of rainfall can lower the temperature, delaying the onset of the infectious season, and discourage both humans from going outside and mosquitoes from circulating, thus lowering the probability of contact. Conversely, dry periods accompanied by a scarcity of natural standing waters may push vectors, and birds, towards anthropogenic bodies of water close to inhabited areas, and paradoxically increase contagions as a result, as happened in the dry season of 2022 [62]. On the other hand, the abundance of rainfall in the warm months, and very full reserves from the

spring rains, may increase the vector's breeding sites, lengthening the season and increasing its abundance and WNV outbreaks probability [32, 54, 55].

However, rain and other factors linked to the water cycle have an overall contrasting effect. The region where WNV most affects Italy corresponds to the Padan Plain, a humid area with numerous watercourses and high human activity. Thus, abundant rainfall is not necessary to provide suitable breeding sites for *Culex* mosquitos. This could also explain why there is such a high disparity of WNV cases between the north and the south of the country. Southern regions are characterised by generally warmer temperatures and a more arid, uninhabited and windy landscape, all factors negatively associated with the outcomes considered [63].

The high level of human activity in northern Italy seems to be another relevant factor for the increase of WNV in Italy. In fact, while purely natural sites, where birds and watercourses abound, are positively associated with the presence of the vector, but negatively or not associated with the spread of WNV, those partially used by humans are positively associated with the spread of the virus, although negatively with FOI. The latter discrepancy could be explained by the fact that agricultural areas or settlements close to forests are places with a low population density. Indeed, the density of inhabitants over 65 years of age is positively associated with FOI, also due to their greater susceptibility to infection [64]. However, the presence of anthropic land use is a determining factor for the spread of WNV, the occurrence of which increases when approaching rice fields, urban areas and wet soils.

Limitations and Strengths

The main limitations of this review concern the lack of uniformity in the selected studies. Indeed, these differ widely, both in terms of exposure and outcome variables collected, and even more so in terms of types of data analyses used. The wide variability of the studies constitutes a major impediment to the quantitative comparison and meta-analysis of the results, but sometimes even to the qualitative one, making them even inconsistent with each other in some cases. In addition, the low use of certain variables limits the interpretation of their effect, just as the inclusion of variables differing in quantity and type in the predictive models makes them difficult to compare with each other. In the future, it is hoped that evidence coming from upcoming literature will lead to more uniformity in the variable considered for each factor, so that results can be best compared with each other. Despite the poor comparability of the studies, results highlighted by this review are promising and already manage to outline an association between factors related to climate warming, anthropization of natural places, and the spread of WNV, along the lines of already existing reviews [25, 26]. This work, however, by focusing on a smaller but highly representative area, succeeds in going into greater detail on the variables analysed, providing new and more concise evidence, thereby providing important contributions to existing knowledge.

CONCLUSION

In conclusion, climatic and environmental factors contribute through complex interactions of different intensity to the spread of WNV and its vectors. Global warming appears to be a determining factor for the recent sharp increase in cases in Northern Italy, through both the increase in average temperatures and the lengthening of the epidemic season. Factors linked to the water cycle seem to have little influence in an area characterised by great human population density and both agricultural and industrial activities, where there is plenty of breeding grounds for the vector. All these characteristics are associated to a high incidence of WNV or vector abundance, especially in contact areas between human and natural environments where there is no shortage of reservoirs of the virus and moist soil. In coming years, particular attention should be paid to very hot spring seasons, a warning sign for intense summer epidemics, and to human activities near natural environments or wet crops. Consequently, the future impact of WNV infection will depend on both policies against global warming, and protection of natural environments aimed at reducing the human invasiveness towards them.

AUTHOR CONTRIBUTIONS

AL, MG, PV, and LT: conceptualization, investigation; AL, MG, and PV: methodology; AL: project administration; MV: resources; LP, MM, AB, ER, MV, SP, and TF: supervision, writing - review and editing; AL and TF: visualization; AL and MG: writing – original draft. All authors contributed to the article and approved the submitted version.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.ssph-journal.org/articles/10.3389/phrs.2025.1607444/full#supplementary-material

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Advancing Climate Mitigation, Adaptation, and Equity Simultaneously: The Transformative Potential of Investments in Gender Equality

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Background: Climate change negotiations often stall because of debates about equity. The SDGs affirm all countries' responsibilities to act on climate and high-income countries' initial $100 billion annual financing commitment; the SDGs also affirm fundamental human rights that are foundational to both equality and a strong economy. Nevertheless, climate investments historically have neglected people-centered climate solutions that would powerfully advance these interconnected goals.

Analysis: Realizing girls' equal rights in education, women's equal rights at work, and freedom from gender-based violence would fulfill fundamental human rights while markedly accelerating climate mitigation and adaptation. Mechanisms include increased reproductive autonomy, higher adoption of sustainable fuels and regenerative agriculture, increased resilience to climate disasters, and greater gender parity in leadership.

Policy Options: A variety of options are available for countries to invest in gender equality simultaneously with nature- and energy-based solutions. These include carbon markets, debt-for-equity swaps, and existing UNFCCC financing mechanisms. The climate impacts of people-centered solutions are estimable.

Conclusion: Successfully addressing climate will require investments in gender equality. Bilateral and multilateral bodies can build on existing data to achieve this through a variety of climate mechanisms.

Keywords: equality, gender, climate change mitigation, climate change adaptation, policy

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BACKGROUND

Advancing equal rights has been central to global goals since the founding of the United Nations. The very first line of the Universal Declaration of Human Rights, adopted in 1948, proclaims unequivocally that "the equal and inalienable rights of all members of the human family is the foundation of freedom, justice and peace in the world." Likewise, advancing equality is fundamental to nearly all of the Sustainable Development Goals (SDGs) agreed to by 193 countries in 2015, while two goals are dedicated solely to equality: SDG 5, "Achieve gender equality and empower all women and girls," and SDG 10, "Reduce inequality within and among countries."

Realizing equal rights is essential because of their intrinsic value—but it's also a prerequisite to overcoming major global challenges. Among the most urgent is climate change: inequalities within and across countries have stymied progress on meeting IPCC targets. Climate change talks and agreements have often stalled amidst debates about equity, with low-income countries emphasizing their need for economic growth and the responsibility of high-income countries—which have historically been the largest emitters and have grown as a result—to cover the costs of mitigation and adaptation [1].

The urgent need is for all countries to mitigate and adapt going forward and for lower-income countries to still be able to grow, while those with the most emission-driven growth support the costs. The SDGs provide a framework for this by simultaneously: 1) holding all countries accountable for combatting climate change while holding wealthier countries accountable for markedly increasing available funding (SDG 13), and 2) urging and supporting all countries to realize fundamental human rights that are foundational to both equality and a strong economy, including access to nutrition (SDG 2), health (SDG 3), education (SDG 4), and decent work for all people (SDG 8).

Nevertheless, climate investments historically have not supported these interconnected goals, instead prioritizing investments in technology. Indeed, technology is crucial to mitigation and to a lesser extent may help with adaptation. But neither can be solved without investments in people. Carbon emissions are the product of emissions per person and the number of people. The human elements that shape the impact of mitigation efforts include both -popularly recognized factors such as what energy people are able to access and choose to use, as well as less widely recognized factors such as how people farm, whether people live free from violence, and whether they have reproductive autonomy. Similarly, whether people have the time, resources, and information to adapt to the risks and conditions of climate change will shape both households' and countries' resilience. Moreover, while investments in people-centered climate solutions have been insufficient overall, investments in women and girls—who are the disproportionately affected by climate change across countries—have been even lower.

This policy brief argues for more action and investment to support gender equality, a long-established fundamental right that is foundational to successful human solutions to climate change mitigation and adaptation. The brief will: 1) provide an overview of some of the evidence that advancing gender equality can accelerate mitigation, 2) illustrate how gender equality matters to adaptation, and 3) describe what taking gender equality seriously would mean for the global and regional mechanisms currently designed to address climate change.

The evidence and recommendations in this policy brief are based on an in-depth review of the evidence relevant to approaches that can address urgent climate mitigation and adaptation needs and simultaneously advance equal opportunity. We first mapped potential pathways for climate change mitigation and adaptation. We then conducted a comprehensive literature review to evaluate potential approaches that would both accelerate climate mitigation and adaptation and advance equity goals. Given that previous scientific consensus efforts have highlighted the importance of gender equality in education and health to climate mitigation, we paid particular attention to the research evidence on the full range of mechanisms with respect to gender equality. Finally, we ran test simulations to determine the feasibility of estimating the climate impact of gender equality interventions with similar rigor and methods to those used for other interventions included in climate markets and funding.

ANALYSIS

Reducing Emissions

Investing in education has long been recognized as a powerful engine for equity and development. The World Bank estimates that if girls' educational attainment were equal to that of boys, global human capital wealth could increase by US$ 15 trillion to US$ 30 trillion, while UNICEF has shown that child mortality would be cut in half if girls completed secondary education—and these are just two examples of many. Yet education also has a powerful—and less recognized—role to play in mitigation and adaptation. A large global network of scientists and researchers focused on climate change solutions estimated that universal access to education and reproductive health would reduce greenhouse gas (GHG) emissions by nearly 70 gigatons by 2050, with 55% of the impact from low- and middle-income countries and 45% from high-income countries [2]. To put these impacts in context, the initiative forecasted that universal education and voluntary family planning would lead to a greater reduction in carbon emissions by 2050 than:

- All transportation solutions combined (including electric vehicles, decarbonizing aviation, and decarbonizing shipping).
- Deploying both onshore and offshore wind turbines.
- Tropical forest restoration [3].

To be clear, energy and nature-based solutions are critical—and governments and industries must reduce dependence on fossil fuels. At the same time, these investments need to be complemented by human investments. Research suggests that investments in reducing gender inequality in education and work and preventing GBV would all advance mitigation. In this section we survey the mechanisms and evidence, with particular attention to girls' education as one powerful example.

Impacts on Reproductive Autonomy

Access to education increases girls' health knowledge, access to services, and autonomy in decision-making [4–6]. Young women with greater educational attainment, on average, also express a preference for delaying childbearing and having smaller families [7]; some evidence likewise suggests lower fertility preferences for men who stay in school longer [8], or whose wives have more education [9]. Access to education also reduces child marriage [10], which is a major threat to girls' health and opportunities and a key driver of adolescent pregnancies. Recent estimates from UNESCO suggest that achieving universal secondary education would virtually end child marriage—and that ending child marriage would lower fertility rates by a third, as girls are able to stay in school and reach adulthood before starting a family [11].

Gender equality in other spheres likewise matters to reproductive autonomy—a fundamental right on its own. A study of 23 African countries found that laws prohibiting domestic violence reduced women's unmet need for family planning by over 20% [12]. At the same time, young women's greater access to employment opportunities has been associated with a desire to delay childbearing and have fewer children, coupled with a desire to pursue more education and training and continue working after marriage [13, 14].

Importantly, reproductive autonomy includes the right to make independent decisions about family size, whether that means fewer or more children [15]. In practice, however, the greater threat to women's reproductive autonomy globally is the inability to decide to have fewer children or to have children later in life [16]. Realizing this fundamental right in turn benefits climate, as delayed births and fewer unwanted pregnancies lower emissions by slowing population growth [17, 18].

Impacts on Fuel Use

Higher educational attainment also leads to higher incomes. The impacts on emissions depend on how higher income is used. One case in point is fuel use.

Biomass and waste burning—which create substantial carbon emissions while also threatening human health through their impacts on air quality—account for a majority of household energy consumption in Africa, as well as substantial shares in small island nations, South and Central America, and Asia [4]. However, evidence suggests that greater educational attainment can contribute to households adopting more sustainable fuels. For example, a systematic review examining factors that shape adoption of improved cookstoves and/or cleaner fuels for cooking found that higher educational attainment and higher income were associated with higher uptake in nearly all studies [19]. Moreover, women are generally more likely than men to choose clean fuels [20], and take-up among women with greater education is even higher [21]. Women's equal opportunities in employment can likewise support greater uptake of these technologies by increasing women's income [22].

Impacts on Agricultural Practices

More sustainable agricultural practices have a powerful role to play in reducing emissions, preserving biodiversity, and ensuring food security. Studies from a range of countries have found that higher educational attainment is associated with higher take-up of regenerative agricultural practices.

In Brazil, for example, farmers with higher levels of education were more likely to adopt crop-livestock integration [23]. In Pakistan and Ethiopia, more educated women farmers were more likely to adopt a range of conservation and climate-smart agricultural (CSA) practices than women with less education [24, 25]. Across Malawi, Mozambique, and Zambia, research found that one additional year of formal education increased the likelihood of a farmer adopting land, soil, and water conservation measures by 13% [26]. Notably, while studies find increased uptake of sustainable agricultural practices among farmers with higher levels of education regardless of gender, in some countries, men's uptake is higher, potentially due to men's greater access to resources—underscoring why reducing barriers to education for all must be an imperative for both equity and climate.

Impacts on Leadership and Climate Action

Girls who are able to complete their education have greater opportunities to take on public and private sector leadership roles as adults. Likewise, women who face less discrimination at work and lower risks of violence at home are more likely to be able to attain and retain leadership positions. Greater gender equity in leadership in turn supports more climate-conscious decision-making.

For example, studies spanning a wide range of countries have documented a positive relationship between more gender-equal representation in parliament and lower carbon emissions [27]. A review of studies focused on the private sector likewise found that greater gender equity in top positions was associated with firms achieving higher environmental performance ratings and providing more transparent sustainability disclosures [28]. Currently, however, just 31% of managers, 7% of Fortune Global 500 CEOs, and 25% of national parliamentarians globally are women—illustrating the significant untapped potential for impact on both gender equity and climate action [29].

Supporting Resilience to Climate-Related Disasters

Alongside mitigation, all countries must adapt. Across countries, climate-related disasters are already causing billions of dollars of damage each year, and disproportionately harming economically vulnerable communities. Yearly rankings of countries' vulnerability to climate change consistently report that LMICs in Africa, alongside small island nations, are facing the greatest collective risks across six key dimensions: food, water, health, ecosystem service, human habitat, and infrastructure [30]. The scale and intensity of wildfires, floods, and other climate disasters are also increasing in high-income countries, where they disproportionately affect women and marginalized communities [31]. Higher educational attainment has been linked with higher rates of survival following natural disasters. Greater access to education enhances access to information and is associated with higher levels of disaster preparedness, as well as better access to support and resources following a disaster [32, 33]. Educating girls may be particularly impactful: one analysis estimated that increasing the share of girls finishing lower secondary school in sub-Saharan African from roughly 30%–70% would reduce deaths from climate disasters between 2040 and 2050 by 60% [34]. Greater household income--facilitated by women as well as men having access to employment---also improves resilience following disasters [35].

POLICY OPTIONS

Increasing Climate Investments in Gender Equality

Some crucial policy changes that matter to climate and equality can be made without substantial funding; modest resources are needed to ensure successful implementation. Examples include ensuring that it is illegal to discriminate based on gender in

hiring, promotion, and other aspects of work. Currently 84 countries lack at least one of these basic protections [36].

Advancing equality in other areas will require investment. The cost of tuition for secondary education is a major obstacle to the attendance of girls and low-income children [10, 37]. Yet 57 countries do not provide tuition-free secondary education [36]. The benefits of girls' education to national economies will make it affordable for governments to fund secondary education themselves in the long run. In the short run, weak economies and limited budgets are obstacles for a number of countries—and supporting girls' education with funds from the mechanisms below could help countries turn a corner on emissions and on equality.

Given its powerful impact on climate mitigation, girls' education should receive climate funds as well as other sources of funding. Government-operated compliance markets are currently valued in the hundreds of billions, and continue to grow [38, 39]. If gender equality in education received the same portion of the voluntary and regulatory carbon market as the percentage of emissions it could reduce, this could lead to a 50-100X increase in financing.

Investing in girls' education should be part of the $100 billion initial global commitment in SDG 13 to increase funds available to low-income countries to mitigate and adapt, which was since updated to $300 billion at COP29. Moreover, given that many of the countries with high numbers of girls out of school are also highly indebted, debt-for-equity swaps modeled on current debt-for-nature swaps hold potential to provide significant additional return on investments. Community-based programs could be part of the voluntary market.

Data on Climate Value of National Policies and Programs

Investments in girls' education, ending child marriage and GBV, supporting gender equality at work and in leadership should not be limited to their "carbon value." Each is invaluable in its own right because of how it can directly transform the quality of life of half of the people on the planet—and in turn the health and wellbeing of their children, partners, parents, and communities.

At the same time, carbon investments should not ignore the value of gender equality as a carbon solution and carbon investments can be an important funding source because of how high the carbon value is. The 70-gigaton reduction in emissions that scientists estimated gender equality would lead to is itself likely an underestimate. While it considered the impacts of girls' and women's greater reproductive autonomy on countries' resource use [2], this estimate did not factor in the range of other mechanisms by which girls' education can powerfully support climate change mitigation and adaptation. Among these are higher adoption of sustainable fuels, increased resilience to climate disasters, higher take-up of regenerative agriculture, and greater gender parity in leadership, which may increase climate action by companies and governments.

The global estimate of climate benefit will need to be broken down to country- and program-level estimates. While there will be some challenges, estimating the carbon value of advancing gender equality is no more difficult than estimating the value of land preservation. Take increasing girls' graduation from secondary school as an example. Just as there have been multiple estimates of the global impact of gender equality in education on GDP growth [40, 41], we can estimate the impact of increasing girls' graduation on carbon emissions. These estimates can be made robustly by examining how carbon-relevant outcomes have changed in countries that lower barriers to girls' education versus countries that do not. The same can be done with reducing workplace discrimination, child marriage, and domestic violence because we have longitudinal data on these policies [36]. Combining this with outcome data on many of the drivers of carbon emissions at a household level, we can estimate the distribution of both the environmental benefits and the implementation costs of each policy at the country level.

This would allow low-income countries to apply to carbon funds to increase the resources available to them to make secondary school tuition-free, or to invest additional resources in programs to end child marriage and GBV and support equal opportunity at work.

CONCLUSION

Both current climate realities and long-term trajectories make clear that all countries need to mitigate and all countries need to adapt. Doing so equitably necessitates increasing investments in solutions that not only reduce emissions and facilitate resilience but also level up access to opportunities, economic resources, and health across countries and across populations. Gender equality is central amongst these.

At present, however, the climate funding going to gender equality has largely been symbolic, despite the fact that investments in gender equality can yield both short- and long-term gains in climate mitigation, as well as for adaptation. It's long past time for substantial investments to be made in supporting gender equality, which can powerfully advance climate mitigation and adaptation and simultaneously improve economies, human health, and intergenerational wellbeing. Ensuring girls have an equal chance to complete secondary education and beyond, that women have equal opportunities at work, and that all women and girls can live free from violence is long overdue, and the reasons to take action are as numerous as they are pressing.

AUTHOR CONTRIBUTIONS

JH, AS, AO, and LG-M contributed to the conceptualization and framing of this policy brief. AS, LG-M, and AO contributed to the review of the literature in the field. AS and JH drafted the manuscript. LG-M and AO critically reviewed and made recommendations on revisions.

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CONFLICT OF INTEREST

The authors declare that they do not have any conflicts of interest.

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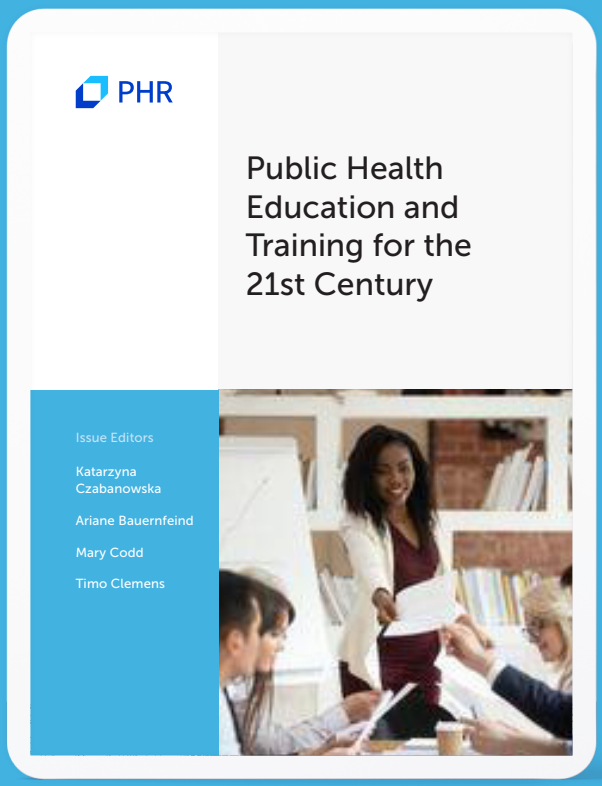

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