



The multidimensional impacts of heatwaves on human ecosystems: A systematic literature review and future research direction

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ARTICLE INFO

Keywords:

Heatwave
Social, economic, and environmental impacts
Policy adaptation
Systematic literature review

ABSTRACT

Global warming continues to exacerbate heatwave severity, duration, and frequency causing impacts that threaten humanity, and the physical and anthropogenic environment. Although research on heatwave impacts has increased, the majority of studies have focused on social effects relegating to the background other crucial impacts. Such a narrow focus on social impacts limits the realization of a thorough understanding of the net impacts of heatwaves. Using the PRISMA protocol, this study conducts a review of 127 peer-reviewed articles to provide a systematic and comprehensive taxonomy of heatwave impacts highlighting key policies, adaptation strategies and barriers. The review found traceable evidence of heatwaves impact on human and environmental ecosystems via 11 thematic pathways namely, health, food crisis/water shortage, infrastructure/energy use, disaster hazard displacement, labour productivity, living cost, industry loss, infrastructure cost, water resources/marine life, vegetation/wildlife, and ozone/air/particulate pollution grouped under social, economic, and environmental dimensions. These multidimensional impacts of heatwaves necessitate stakeholder synergies in pooling resources and integrating diverse types of information to tackle impacts and develop inclusive policies and adaptation strategies for better heat resilience.

1. Introduction

Intensifying human activities (e.g., emission of greenhouse gasses, deforestation, excessive mining of natural resources, among others) are simultaneously altering the earth's climate past warming thresholds with significant impacts on humanity and the ecosystem (Mora et al., 2018; Zuo et al., 2015, Erdiaw-Kwasie et al., 2024). Borg et al. (2023) add that the frequency, duration, and intensity of heatwaves are expected to increase, presenting substantial costs to societies. For instance, the European heatwave of 2003 resulted in over 70,000 deaths (Adnan et al., 2022; Rousi et al., 2022). In France, the 2006 heatwave caused 2065 excess deaths (Fouillet et al., 2008) whereas the 2017 heatwaves in China led to 16,299 deaths (Yan et al., 2022). A time series analysis by Brimicombe et al (2024) found that heatwaves accounted for an estimated 44,909 deaths in children under 5 years across 13 countries in Africa. Similarly, evidence of the destructive effects of heatwaves on

human mortality and morbidity has been observed in other places such as Australia (Adams et al., 2022; Sharples et al., 2021; Scalley et al., 2015), UK (Abrahamson and Raine, 2009; D'Ippoliti et al., 2010; Stedman, 2004), USA (Davis et al., 2020; Kent et al., 2014; Zhang et al., 2015), Canada (Bustinza et al., 2013; Bishop-Williams et al., 2015), and India (Rahman et al., 2022; Nori-Sarma et al., 2019).

While lacking a universal definition due to the diversity of world climatic conditions and adaptation characteristics of the global population, heatwave definitions are contingent on anthropogenic forces as well as on local acclimatization and climatic parameters such as maximum temperature (T_{max}), minimum temperature (T_{min}), and relative humidity (Cowan et al., 2014; Adnan et al., 2022). Generally, several scholars (see Perkins and Alexander, 2013; Roetzel et al., 2010) agree that heatwaves are prolonged periods of excessive heat or hot weather usually associated with heat stress. While Cowan et al. (2014) highlight that heatwave events are 2–4 °C warmer than T_{max} , Adnan

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<https://doi.org/10.1016/j.envsci.2025.104024>

Received 2 October 2024; Received in revised form 10 February 2025; Accepted 13 February 2025

Available online 28 February 2025

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et al. (2022) highlight that in certain places such as Southern Australia heatwave temperatures can be 15 °C warmer than T_{\max} . Based on the scope of our review, the study draws from the definition offered by the Federal Emergency Management Agency (FEMA) “A heat wave is simply a period of unusually hot weather that typically lasts two or more days. The temperatures must be outside the historical averages for a given area” (FEMA, 2024). Evidence shows that heat waves can burden health and emergency services (McEvoy et al., 2012; Kuczyński and Staszczuk, 2020), low crop and livestock yields (Zhao et al., 2017; Nawab et al., 2018), drought and water stress (Rinaudo et al., 2012; White et al., 2023), food crisis (Larcom et al., 2019; Vitali et al., 2015), and other disaster hazards such as floods, landslides, and wildfires (Cordner et al., 2011; Chen et al., 2022; White et al., 2023). While less researched, these heatwave impacts threaten human existence and comfort.

Although heatwave research has grown significantly in the past two decades, in tandem with rising global temperature, which is averagely expected to increase by 4.8 °C by the end of the century (Adnan et al., 2022), reviews that use a systematic approach to provide a comprehensive view of heatwave impacts from social, economic and environmental perspectives remain lacking. Rather, existing reviews on impact assessments focus on the health aspects and its associated policy responses relegating to the background other essential impacts that similarly require rapid and proactive responses. The above suggests that the impacts of heatwaves have been studied in isolation and the focus substantially narrowed, as illustrated by the review articles in Table 1. Given that future predictions of heatwaves suggest an increase in intensity, duration, and frequency (IPCC, 2021; Borg et al., 2023), it is timely to systematically review and develop a comprehensive taxonomy of heatwave impacts, existing policies, mitigation strategies, and barriers to implemented strategies. Also, this systematic review is relevant since several scholars (Adnan et al., 2022; Zuo et al., 2015; Mora et al., 2018) agree that a narrow focus on one or a few heatwave impacts may obscure additional negative heatwave impacts, resulting in an incomplete or inaccurate assessment of heatwave implications.

To provide a comprehensive taxonomy of heatwave impacts, this review engaged in a systematic literature search to (1) identify and cluster impacts into social (health, infrastructure, energy, food, water, and disaster hazards), economic (living cost, labour productivity, industry loss, and infrastructure cost), and environmental (vegetation, wildlife, water resources, marine life, air, ozone, and particulate pollution) perspectives, (2) reports on the existing policies for dealing with heatwave conditions emphasizing which effect cluster (social, environmental, or economic) has received considerable policy attention and which has not, (3) highlights specific mitigation strategies and (4) identify existing barriers within each effect cluster.

This systematic literature review makes two main contributions to the existing body of knowledge. First, using a systematic literature review, we develop a cumulative index of heatwave social, economic, and environmental impacts demonstrating the extent to which humanity is/will be exposed to diverse concurrent heatwave effects. This study differs from existing reviews in that it provides an overview of the interconnections between the identified heatwave impact clusters as well as how the acclimatization capabilities of the local population and vulnerable groups can determine the type and severity of impacts. Second, in reviewing the literature, the most discussed policies, mitigation strategies, and barriers are identified across all three heatwave impact clusters. The study asserts that the effectiveness of mitigation strategies and policies varies across countries due to the existence of context-specific barriers. Thus, this review highlights that countries that possess effective systems and integrate essential stakeholders in pooling together resources can substantially achieve best-case scenarios.

The rest of the paper is organised as follows, Section 2 highlights the methodology, followed by Section 3, which presents the characteristics of selected articles. Section 4 offers content analysis and a discussion of essential aspects of heatwave definition, policies, impacts, mitigation strategies, and barriers and Section 5 presents the discussion. Section 6

presents the conclusion underlining future research directions and limitations.

2. Methodology

This review engages in the (1) search for literature, (2) identification of records, and (3) screening and inclusion of records following the guidelines of the PRISMA protocol developed by Moher et al. (2015). These steps are explained in detail below.

2.1. Search strategy

The Scopus, Web of Science, and PubMed databases were used in the search for related articles from the start of the database entries to 11/08/2023. A systematic approach was employed in this review since it ensures a thorough investigation and appraisal of a particular body of literature. Additionally, systematic reviews, according to Paul et al. (2023), are an important technique to synthesise the findings of a certain body of research investigations because of its comprehensiveness, reproducibility, and objectivity. Thus, this review adopts a systematic approach to synthesise records extracted from the databases. These databases were chosen due to their accumulation of essential sources of academic literature on heatwaves and its related impacts (Adnan et al., 2022; Zuo et al., 2015; Mason et al., 2022).

2.2. Identification of records

In this identification phase, we include several terminologies sourced from existing literature (Adnan et al., 2022; Zuo et al., 2015; Mason et al., 2022) to guarantee inclusiveness and ensure that relevant articles are captured in the search. Thus, we used a combination of search keywords listed in Table 2 to form search strings. The search string used to retrieve research publications was ((heatwave* OR "extreme heat" OR "marine heatwave" OR "excess heat factor" OR temperature) AND (health OR food OR water OR infrastructure OR energy OR "human displacement") AND (industry OR cost OR labour OR labor OR productivity) AND ("Marine life" OR vegetation* OR wildlife OR "Air quality" OR ozone OR pollution)). The symbol "*" captures words that begin with the prior prefix. The search returned 4772 publications, 1461 from Scopus, 2401 from Web of Science, and 910 from PubMed, as shown in Fig. 1. The search was done using the TITLE-ABS-KEY function in Scopus, the ALL Fields function in Web of Science, and the Title/Abstract function in PubMed.

2.3. Screening and inclusion of records

4772 records were examined in the initial screening using the inclusion and exclusion criteria. In the first screening, duplicates (n = 410), editorial/serial/books (n = 138), review (n = 151), and conference papers (n = 86) were excluded leaving 3987 articles for the second screening.

During the second screening, articles that do not emphasise heatwave impacts (n = 1821), studies that do not have a clear heatwave definition (n = 73), articles that are out-of-scope (e.g. focus on other climate change hazards) (n = 1964), and without full text (n = 15) were excluded. In this phase, 3873 records were excluded leaving 114 articles for further examination. Using the snowballing strategy, 13 additional relevant articles were identified by searching the references of the chosen articles. Fundamentally, 127 articles were examined, chosen, and included for the evaluation based on the criteria listed in Table 3.

3. Characteristics of selected articles

Research on heatwave impacts across the globe has been on the increase since the last decade (Adnan et al., 2022). The selected 127 articles for this review were all published between 1988 and 2023. Fig. 2

Table 1
Previous literature review on heatwave impacts on ecosystems.

Author	Source Title	Review Type	Classification of articles by impacts										
			Social				Economic				Environmental		
			Health	Food/ water security	Infrastructure/ Energy use	Disaster displacement	Living cost	Industry loss	Infrastructure damage cost	Labor productivity	Water resources/ Marine life	Vegetation/ Wildlife	Air/Ozone and particulate pollution
Zuo et al. (2015)	JCP	Narrative	√		√	√				√		√	
Adnan et al. (2022)	ER	Systematic	√								√		
Mason et al. (2022)	BMCHSR	Systematic	√										√
Smith et al. (2021)	S	Narrative						√			√		
Cheng et al. (2019)	ER	Systematic/ Meta-analysis	√										
Lowe et al. (2011)	IJERPH	Narrative	√										√
Xu et al. (2016)	EI	Systematic/ Meta-analysis	√										
Campbell et al. (2018)	HP	Systematic	√										
Li et al. (2015)	IJERPH	Systematic	√										
Arsad et al. (2022)	IJERPH	Systematic	√										
Åström et al. (2011)	M	Systematic	√										
Current study	-	Systematic	√	√	√	√	√	√	√	√	√	√	√

Note: Journal of Cleaner Production (JCP), Environmental Research (ER), BMC Health Services Research (BMCHSR), Science (S), International Journal of Environmental Research and Public Health (IJERPH), Environment International (EI), Health & Place (HP), Maturitas (M)

Table 2
Keyword combinations included in search strings.

Heatwave related	Social impacts related	Economic impacts related	Environmental impacts related
Heatwave*	Health	Industry	Marine life
Extreme heat	Food	Cost	Vegetation*
Excess heat	Water	Labor	Wildlife
Marine heatwave	Infrastructure	Labour	Air quality
Temperature	Energy	Productivity	Ozone
	Human displacement		Pollution

Note: * - captures words that begin with the prior prefix

presents the increasing trend of articles on heatwave impacts. The highest publications were in 2022 (12, 10%), 2014 (11, 9%), 2018 (10, 8%), 2019 (10, 8%), and the years with the lowest publications were 2001, 2004, 1990, and 1988 with 1 (0.8%) publication each. Additionally, Fig. 3 illustrates that while the impacts of heatwaves vary, the majority of existing study has placed a major focus on the social impacts (103, 58%), then economic impacts (49, 28%), and then the environmental impacts (25, 14%). Specifically, the widely investigated effects were the health impacts (58, 33%), the infrastructure/energy use

impacts (19, 11%), food crisis/water shortage (17, 10%) and the least studied heatwave effects were on infrastructure cost (7, 4%), vegetation/wildlife (8, 5%), and water resources/marine life (8, 5%). It is important to note that, in Fig. 3, some articles reflected multiple heatwave impacts and thus, have been grouped under their respective impact clusters.

Additionally, publications from 74 journals were included in this systematic review. Among these journals, *Environmental Research and International Journal of Environmental Research and Public Health* had 8 (6%) publications each, followed by *Environmental Health Perspectives*, *International Journal of Biometeorology*, *Environment International*, *Science of the Total Environment*, *Environmental Health*, and *Global Health Action* with 7 (6%), 6 (5%), 5 (4%), 5 (4%), 4 (3%), and 3 (2%) publications, respectively. The remaining journals had less than 3 publications each (See Appendix 1 for the full journal and author lists). The selected 127 studies employed two main research methods. While 115 (90%) studies applied a quantitative method, 12 (10%) used a qualitative approach.

Additionally, preliminary analysis indicates that the selected studies were conducted across 28 countries. *Australia* was the country with the highest number of publications 35 (24%), followed by the *United States of America* and the *United Kingdom* with 24 (16%) and 11 (7%) publications, respectively. *France* came next with 10 (7%) publications,

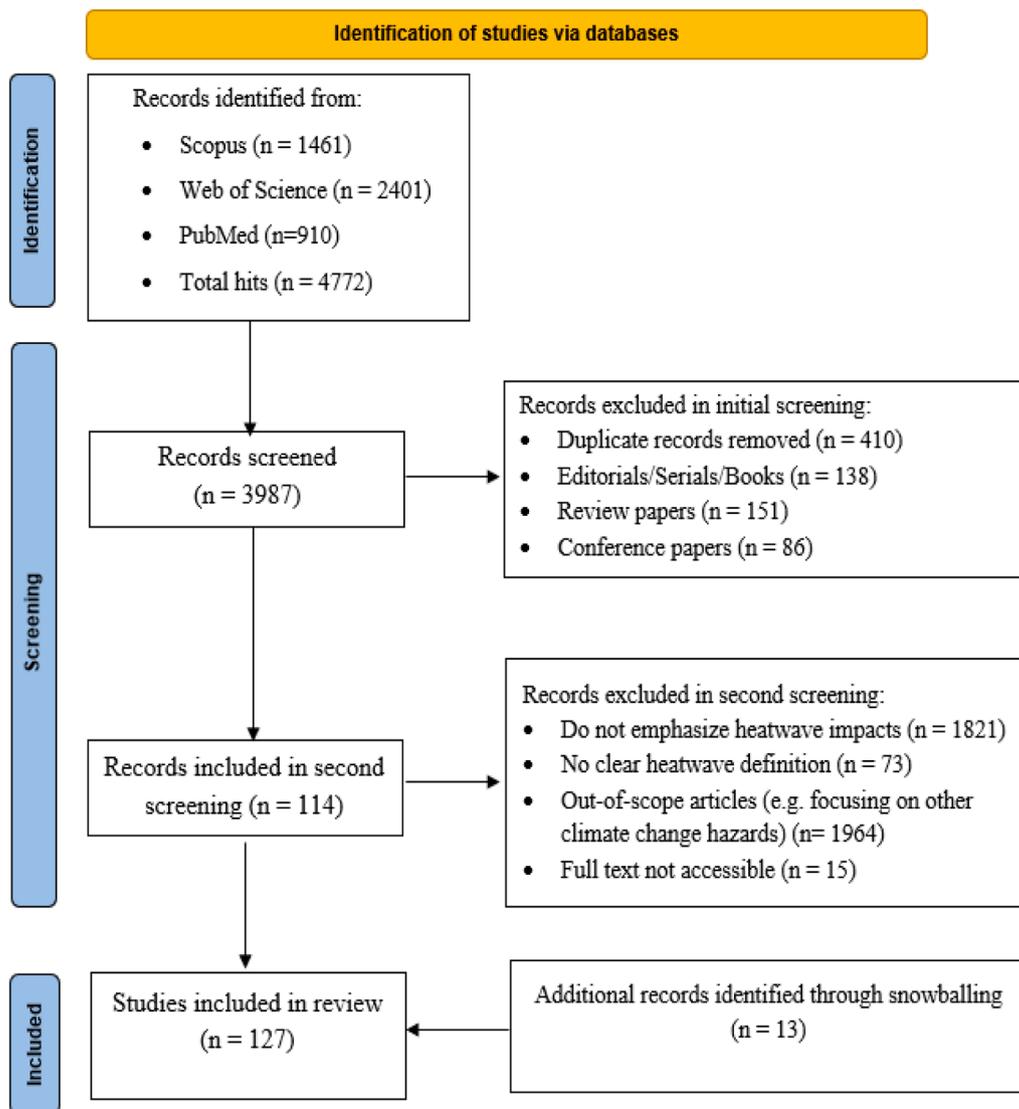


Fig. 1. PRISMA flow chart of shortlisted articles.

Table 3
Article inclusion and exclusion criteria.

Aspect	Inclusion criteria	Exclusion criteria
Language	Articles written in English	Articles that use other languages (e.g. French, Chinese, German, Arabic, Spanish, etc.)
Document Type	Peer-reviewed articles	Editorials, review articles, conference papers, book chapters, serials, grey literature, and commentaries
Availability	Full-text available	Full-text not available
Focus	<ul style="list-style-type: none"> a) Heatwave must be the central theme of the article b) The article must highlight at least one of the impacts-social, economic, and environmental c) The article should clearly define heatwave 	<ul style="list-style-type: none"> a) Articles focusing on other climate change hazards b) Articles that do not highlight heatwave impacts c) Articles that lack a clear heatwave definition

followed by *China, Spain, Canada, Italy, Germany, India, Hungary, Switzerland, and Portugal* with 9 (6 %), 9 (6 %), 7 (5 %), 7 (5 %), 5 (3 %), 4 (3 %), 3 (2 %), 3 (2 %) and 2 (1 %) publications, respectively. The

remaining countries *Brazil, Ghana, Greece, Israel, Korea, Malaysia, Netherlands, Pakistan, Poland, Saudi Arabia, Slovenia, South Africa, Turkey, and Vietnam* followed with 1 (0.7 %) publication each, as presented in Fig. 4. Finally, 5 (3 %) studies did not indicate the context or country of the study.

4. Content analysis

Generally, there are two content analysis approaches: manual and automated (Matthes and Kohring, 2008; De Graaf and van der Vossen, 2013). While both approaches have their pros and cons, several scholars (Evans et al., 2007; De Graaf and van der Vossen, 2013) recommend that a combination of automated and manual approaches in content analysis provides researchers with added value in discovering insights. Following this recommendation, this review employs both automated and manual content analysis approaches. In the automated approach, we use the Leximancer software to identify essential themes and concepts. This software was used due to its effectiveness in analysing larger volumes of data and providing maps that serve as starting points for detailed analysis, as presented in Fig. 5 (Sotiriadou et al., 2014). Fig. 5 presents the essential themes and concepts in the 127 selected articles with theme

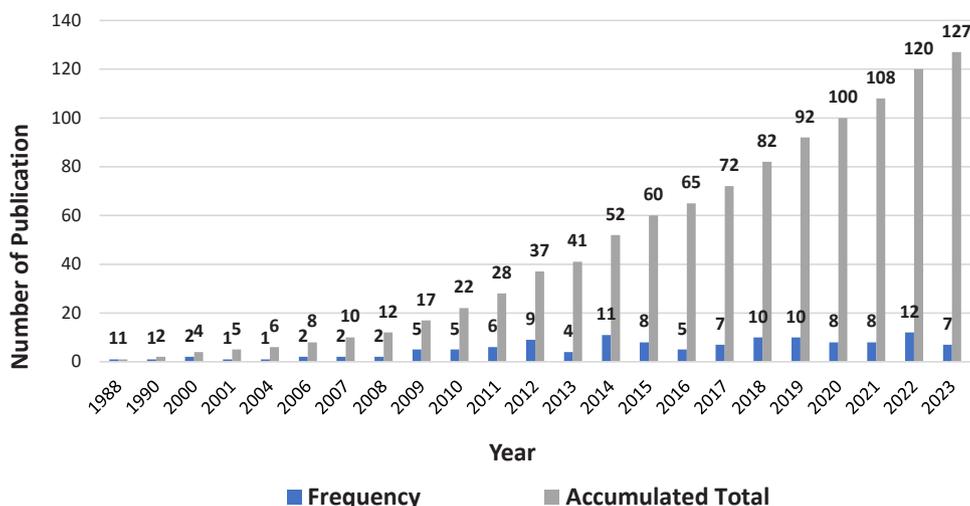


Fig. 2. Publications by year and frequencies.

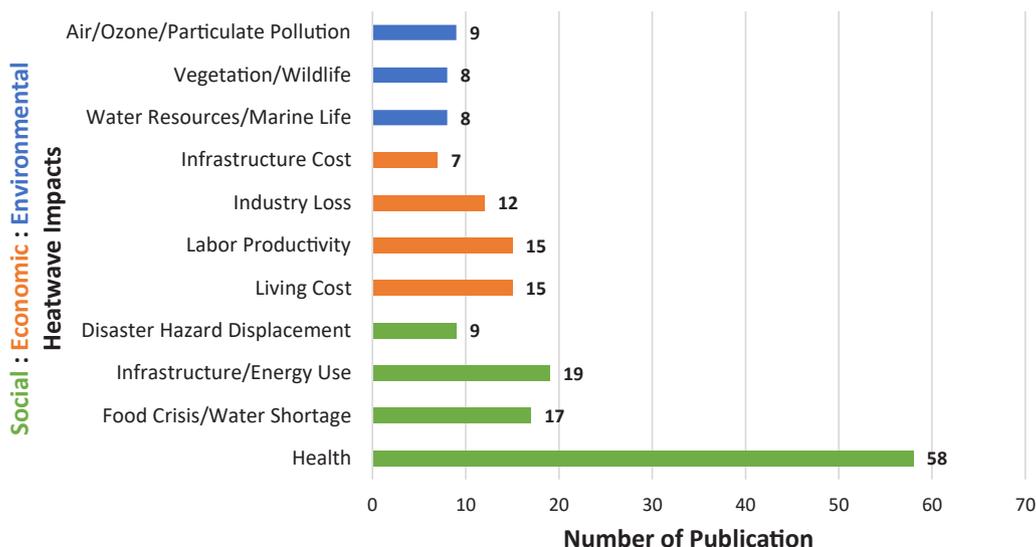


Fig. 3. Publications by impacts.

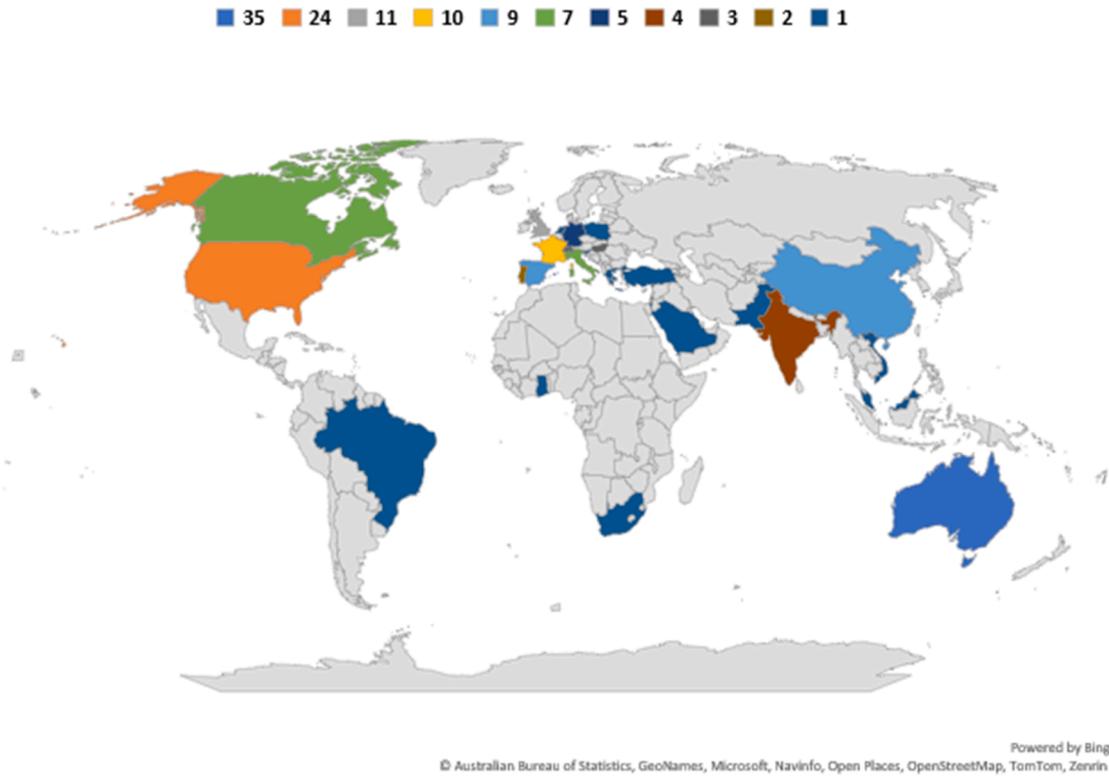


Fig. 4. Publications by country.

size and concept visibility set at 30 % and 20 %, respectively to ensure clarity. From the map, there are 12 main interconnected themes: heatwave, health, climate, population, air, work, water, weather, ozone, energy, species, and marine. Of the 127 selected articles, the heatwave theme was the strongest with interlinked concepts of temperature and stress. The health theme followed with age as an interlinked concept, then the climate theme with interlinked concepts of global and growth. The population theme was the next strongest with risk as a concept, then air with urban as a concept. The work theme, being the next strongest, was followed by the water theme with interlinked concepts of quality and production, and then the weather theme with capacity as a concept.

The next strongest themes were energy, ozone, species, and marine as indicated by the hits and relevance values in Fig. 5.

These identified themes based on the 127 selected articles suggest that heatwave impacts are wide and varied. However, most existing studies tend to be more oriented toward the health implications of heatwaves as indicated by the high number and percentage of hits (10518) and relevance (91 %), respectively. The automated analysis further supports our assertion that heatwaves have other less researched essential impacts such as on water, energy, work, ozone, species, marine, and air, among others, which are essential factors that keep humanity thriving. This further strengthens the need to comprehensively

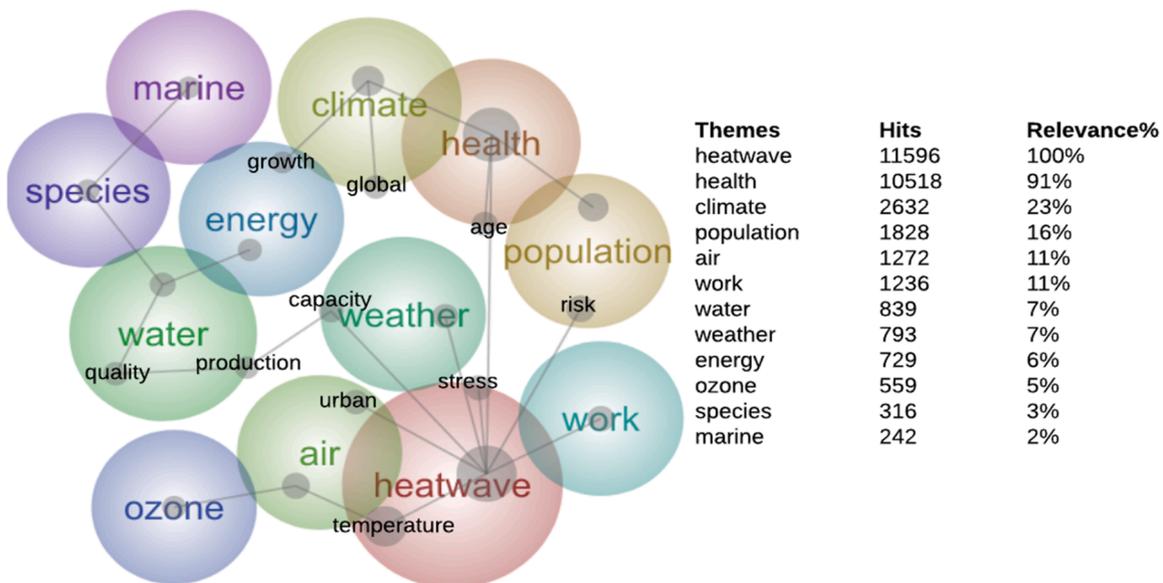


Fig. 5. Leximancer concept map of selected studies.

examine the broad and heightened impacts of heatwaves on humans, societies, and the environment, as done by this review.

In the manual content analysis, we critically analyse the 127 selected articles to report insights that cover the following essential aspects: (1) the definition of heatwaves, (2) heatwave policies, (3) the social impacts (health, infrastructure, energy, food, water, and disaster hazards), economic impacts (living cost, labour productivity, industry loss, and infrastructure cost), and environmental impacts (vegetation, wildlife, water resources, marine life, air, ozone, and particulate pollution) of heatwaves, (4) the current mitigation strategies, and (5) existing barriers.

4.1. Definition of heatwaves

There are several definitions for heatwaves indicating the lack of consensus in their conceptualization. Zuo et al. (2015) establish that varying acclimatization characteristics, climatic conditions, socio-demographics, and other anthropogenic forces contribute to the contextual variations in heatwave definitions. For instance, in the USA while Fuhrmann et al. (2016) assert in North Carolina that heatwaves occur when the heat index is expected to reach between 40 °C and 42 °C (104 °F and 107.6 °F) for 2 or more hours or between 38 °C and 40 °C (100.4 °F and 104 °F) for 3 or more days, Davis et al. (2020) explain that in Virginia, heatwaves are 3 or more days with $T_{\max} \geq 33$ °C. Likewise, in Australia, Wang et al. (2012) emphasise that in Brisbane, heat and extreme heat warnings are issued when the heat index is anticipated to exceed 36 °C and 40 °C, respectively for 2 or more days. In Adelaide, South Australia, a heatwave is defined as 5 days and 3 days with $T_{\max} > 32$ °C and 40 °C, respectively (Zuo et al., 2015). Williams et al. (2012) also highlight that in Perth, Western Australia, a heatwave is defined as 3 or more days with $T_{\max} > 35$ °C. Sun et al. (2014) in Pudong, China, asserted that heatwaves are heat days that last for 2 or 3 days. The authors further defined heat days as days with daily mean temperatures exceeding the 90th (29.67°C), 95th (30.70°C) and 99th (33.05°C) percentiles of the year. For the UK and Germany, heatwave events occur when the average maximum temperature is exceeded by 5 °C for 5 days and when the daily $T_{\max} > 30$ °C for at least 5 consecutive days, respectively (Adnan et al., 2022). Given the contrasts in the definition of heatwaves across countries, the 127 articles selected satisfied one of the following heatwave definitions: (1) single days or hours where the 90th, 95th, and 99th percentile of heat distributions in the locality were exceeded, and (2) 2 or more days with $T_{\max} > 27$ °C or above the 90th percentile of heat distribution in the region.

While some scholars (Radnović and Čurić, 2012; Zuo et al., 2015; De Boeck et al., 2010) agree that the conceptualisation of heatwaves should be based on absolute thresholds (e.g. 5 °C) and average daily temperature, other scholars (Tong et al., 2014; Zhang et al., 2015; Bobb et al., 2014) criticize and indicate this approach as unreliable due to its lack of considerations for climatic variability, population vulnerability, and mortality rates. Adnan et al. (2022) and Buzási (2022) add that heatwave conceptualisation should integrate heat exposure (timing, intensity, and duration) as well as adaptive capacity (ability to respond/adapt to negative heatwave impacts). Despite the above debate regarding the thresholds that should factor in heatwave conceptualisation, a consensus on a standard metric for defining and assessing heatwave remains lacking. Thus, highlighting the essential need for global collaboration among countries, stakeholders, and scholars in providing a comprehensive definition and conception of heatwave.

4.2. Heatwave policy/program

Renowned institutions such as the IPCC, the Bureau of Meteorology (BOM), and the World Meteorological Organisation (WMO) unanimously forecast increases in heatwave frequency and intensity. Adding to this, scholars also highlight that with greater heatwave intensity and frequency comes dire impacts (Adnan et al., 2022; Zuo et al., 2015;

Casanueva et al., 2019). As a response to the estimated escalation of heat conditions, many countries have adopted several policies and programs to reduce impacts on the population, especially vulnerable groups. A review of policies and programs across impact clusters in the study's sampled countries is found in Table 4. From heatwave action plans to heat-health warning systems (HHWS) and heat-health action plans (HHAPs), several countries have tried to implement effective heatwave response measures (Abrahamson and Raine, 2009; Zhang et al., 2012) based on meteorological forecasts and the cause-and-effect correlations between the thermal environment and human health (Casanueva et al., 2019; Scalley et al., 2015; Steul et al., 2018).

The review of the heatwave policies and programs indicates that the health impacts of heatwaves have garnered considerable attention. This is not surprising given that scholars (Casanueva et al., 2019) emphasise that heatwave action plans and warning systems are established based on public health indicators during heat conditions and on the vulnerability of regional populations to extreme weather. Casanueva et al. (2019) further indicate that most of the existing heatwave plans, HHWS, and HHAPs fail to achieve effective outcomes due to ineffective coordination among key stakeholders (health agencies, meteorological institutes, and other health service providers). Adding to this, the authors highlight that many deaths and injuries occur before HHWS alerts are triggered thereby suggesting the lack of proactiveness on the part of local authorities and other essential health service providers in issuing pre-alerts that can reduce negative health impacts.

Furthermore, a critical look at Table 4 shows that current heatwave policies and programs are significantly biased towards social impacts, specifically health. While the focus on health is necessary, it is also important to note that these impact clusters are interdependent in that a heatwave effect on the environment has social implications. For instance, Islam et al. (2022) in the Australian context, posited that heatwaves led to bushfires that had devastating air pollution effects, resulting in thousands of people being admitted to emergency departments of hospitals. Similarly, Stedman (2004) in the UK context found positive correlations between heatwaves, ambient ozone and particulate matter (PM10) concentrations, and excess death. The connections between these impact clusters indicate the need for heatwave policies and programs that extend beyond social impacts to also integrate economic and environmental impacts. Additionally, the thresholds of heatwave policies and programs should be set having a detailed understanding of the short and long-term heightened effects of heatwaves on social, economic, and environmental systems.

4.3. Impact clusters of heatwaves: social, economic, and environment

Systematically reviewing the literature, we found 11 thematic impacts (health, food crisis/water shortage, infrastructure/energy use, disaster hazard displacement, labour productivity, living cost, industry loss, infrastructure cost, water resources/marine life, vegetation/wildlife, and ozone/air/particulate pollution) of heatwaves. These 11 main identified impacts were grouped into 3 main clusters (social, economic, and environmental) to demonstrate the wide-ranging impacts of heatwaves. For brevity, the cluster impacts of heatwaves and the sub-categorized specific impacts are explained below making use of at least one case example. These clusters and specific heatwave impacts, mitigation strategies and barriers are illustrated in Fig. 6.

4.3.1. Social impacts of heatwaves

Health. Heat poses a significant threat to human health, especially for vulnerable groups. In the sampled studies, we found that heatwaves in addition to increasing mortality and morbidity rates (Guirguis et al., 2014; Nori-Sarma et al., 2019) significantly add to heart and renal failures (Davis et al., 2020; Gill et al., 2007), injury rates (Khalaj et al., 2010; Adams et al., 2022), heat exhaustion (Schaffer et al., 2012; Davis et al., 2018), sunburns (Smoyer-Tomic and Rainham, 2001; Fuhrmann et al., 2016), asthma (Xu et al., 2013, Islam et al., 2022), mental

Table 4
Country-specific heatwave policies and programs.

Heatwave policy/ program	Country	Social	Economic	Environmental
The Heatwave Plan: This plan is a heat-health watch system that operates between 01/06 and 15/09 each year in England. During this period health and social care service providers raise awareness regarding severe hot weather. Essential responsibilities highlighted in the plan are distributed between the Department of Health and Social Care.	UK ^{1,2,116}	√	X	√
Heat Prevention Plan: The main components of the national program for the prevention of heat health effects are the: city-specific heat health watch warning systems; local network for the distribution of the warning bulletin; national prevention guidelines; local registries of at-risk subgroups of the population; a rapid real time mortality surveillance system; and evaluation of warning systems and prevention programs introduced.	Italy ^{32,42,116}	√	X	X
Plan National Canicule: This plan is a heat-health watch system that operates between 01/06 and 15/09 each year. The plan includes a new weather alert service, a	France ^{52,42,116}	√	X	X

Table 4 (continued)

Heatwave policy/ program	Country	Social	Economic	Environmental
registry of people at risk, and response guidelines for hospitals and voluntary aid workers. Mapping out a four-level system, the plan aims to safeguard vulnerable groups against heatwave effects while also boosting cooperation between emergency services, health service providers, and security services.				
Heatwave Action Plans (HAP): These plans implemented in warm regions of Switzerland, especially in the summer, generally consist of early warning systems, monitoring of vulnerable groups, timely public and medical advice, and strategies to improve adaptation to hot weather to reduce heatwave-related health effects. These plans are also used by the Swiss Federal Office of Public Health, health authorities, and health professionals in information campaigns to promote public awareness of heat threats.	Switzerland ^{43,52116}	√	X	X
Heat Health Action Plans (HHAP): The action plan emphasizes the dissemination of heat risk-related information via heat health	Germany ^{114,115,116}	√	X	X

(continued on next page)

Table 4 (continued)

Heatwave policy/program	Country	Social	Economic	Environmental
warning systems implemented by the German Weather Service. This information aims at reducing heat-induced morbidity and mortality, especially in hospitals and care homes/centres for the elderly.	Portugal, Spain, Hungary, and Slovenia, United States of America ^{113,30,116}	√	X	X
Heat Health Warning Systems (HHWS): These are national warning systems targeted at reducing heat-related impacts on human health using meteorological forecasts on temperature, mortality surveillance, keeping a register of vulnerable groups, and awareness campaigns.	Canada ^{117,118}	√	X	X
Heat Response Plan (HRP): This response plan is aimed at managing the risk and preparing for extreme heat events through heat alert and response systems (HARS). HARS is implemented by public health and emergency management officials to protect the health of citizens, especially vulnerable citizens, communities, or regions.	Australia ¹¹⁹	√	X	X

Table 4 (continued)

Heatwave policy/program	Country	Social	Economic	Environmental
response to heatwaves as well as provide a vivid understanding of warning systems and practices that mitigate heatwave risks and support at-risk groups. Several heatwave warnings are disseminated by the Bureau of Meteorology and supported by local health workers and social service officials.				

Exemplary studies used in Table 4 and Fig. 6: 1. Abrahamson and Raine, (2009); 2. Abrahamson et al., (2009); 3. Adams et al., (2022); 4. Khalaj et al., (2010); 5. Toloo et al., (2014); 6. Davis et al., (2020); 7. Toloo et al., (2015); 8. Xu et al., (2019); 9. Xu et al., (2013); 10. Sun et al., (2014); 11. Schaffer et al., (2012); 12. Knowlton et al., (2009); 13. Chen et al., (2017); 14. Zhang et al., (2015); 15. Borg et al., (2023); 16. Bishop-Williams et al., (2015); 17. Fuhrmann et al., (2016); 18. Frimpong et al., (2017); 19. Davis and Novicoff, (2018); 20. Maloney and Forbes, (2011); 21. Wondmagegn et al., (2021); 22. Rahman et al., (2022); 23. Stowell et al., (2022); 24. Winquist et al., (2016); 25. Adélaïde et al., (2022); 26. Wang et al., (2014); 27. Oray et al., (2018); 28. Gasparrini and Armstrong, (2011); 29. Son et al., (2012); 30. Kent et al., (2014); 31. Xiang et al., (2014); 32. Michelozzi et al., (2010); 33. Guirguis et al., (2014); 34. Worfolk, (2000); 35. Nori-Sarma et al., (2019); 36. Anderson and Bell, (2011); 37. Xia et al., (2018); 38. Fouillet et al., (2008); 39. Lopez-Bueno et al., (2020); 40. Zhu et al., (2014); 41. Wang et al., (2012); 42. D'Ippoliti et al., (2010); 43. Ragetti et al., (2017); 44. Williams et al., (2012); 45. Tong et al., (2014); 46. Díaz et al., (2018); 47. Yong et al., (2023); 48. Tran et al., (2020); 49. Ma et al., (2015); 50. Rameezdeen and Elmualim, (2017); 52. López-Bueno et al., (2019); 53. Mason et al., (2023); 54. Mastrangelo et al., (2007); 55. Varghese et al., (2019a); 56. López-Bueno et al., (2021); 57. Yan et al., (2022); 58. Hansen et al., (2008); 59. Rauf et al., (2017); 60. Gill et al., (2007); 61. Bustinza et al., (2013); 62. Larcom et al., (2019); 63. Zhao et al., (2017); 64. Carlson, (1990); 65. Nawab et al., (2018); 66. Vitali et al., (2015); 67. Dunn et al., (2014); 68. von Biela et al., (2019); 69. Zhan et al., (2022); 70. Lobell et al., (2011); 71. Manica et al., (2022); 72. Wade et al., (2019); 73. Murdoch et al., (2000); 74. Rinaudo et al., (2012); 75. Van Vliet et al., (2017); 76. Maller and Strengers, (2011); 77. Imran et al., (2019); 78. McEvoy et al., (2012); 79. Kuczyński and Staszczuk, (2020); 80. Nguyen et al., (2012); 81. Islam et al., (2022); 82. Corder et al., (2011); 83. Sharples et al., (2021); 84. Chen et al., (2022); 85. Ayyappan et al., (2009); 86. Balakrishnan et al., (2010); 87. Ke et al., (2016); 88. Chooibneh et al., (2016); 89. Lemonsu et al., (2015); 90. Gómez-Martín et al., (2014); 91. Sibitane et al., (2022); 92. Barnett-Itzhaki et al., (2023); 93. Kalisa et al., (2018); 94. Honey et al., (2021); 95. Gordon et al., (1988); 96. Zanotelli et al., (2022); 97. Piatt et al., (2020); 98. Zou et al., (2021); 99. McPherson et al., (2021); 100. Zampieri et al., (2023); 101. Giamalaki et al., (2022); 102. Brown et al., (2021); 103. Mouthon and Daufresne, (2006); 104. Mouthon and Daufresne, (2015); 105. Piccolroaz et al., (2018); 106. Chowdhury et al., (2012); 107. Vieno et al., (2010); 108. Zong et al., (2022); 109. Pu et al., (2017); 110. Pascal et al., (2021); 111. Basagaña et al., (2011); 112. Stedman, (2004); 113. Zhang et al., (2012); 114. Steul et al., (2018); 115. Matthies and Menne, (2009); 116. Kovats and Kristie, (2006); 117. Price et al., (2013); 118. Smoyer-Tomic and Rainham, (2001); 119. Scalley et al., (2015); 120. White et al., (2023); 121. Wu et al., (2018); 122. Wang et al., (2023); 123. Rogers-Bennett and Catton, (2019); 124. Cowan et al., (2014); 125. Varghese et al., (2019b); 126. Varghese et al., (2020a); 127. Varghese et al., (2020b)

disorders (Hansen et al., 2008; Wang et al., 2014), dehydration (Davis et al., 2018; Price et al., 2013), heat stress (Zhang et al., 2012; Guirguis et al., 2014), and increased hospital admissions thereby pressuring health workers (Xiang et al., 2014; Tran et al., 2020). Of these health effects, mortality, morbidity and heart and renal failure were the most observed. This is because heatwaves impair essential body functions

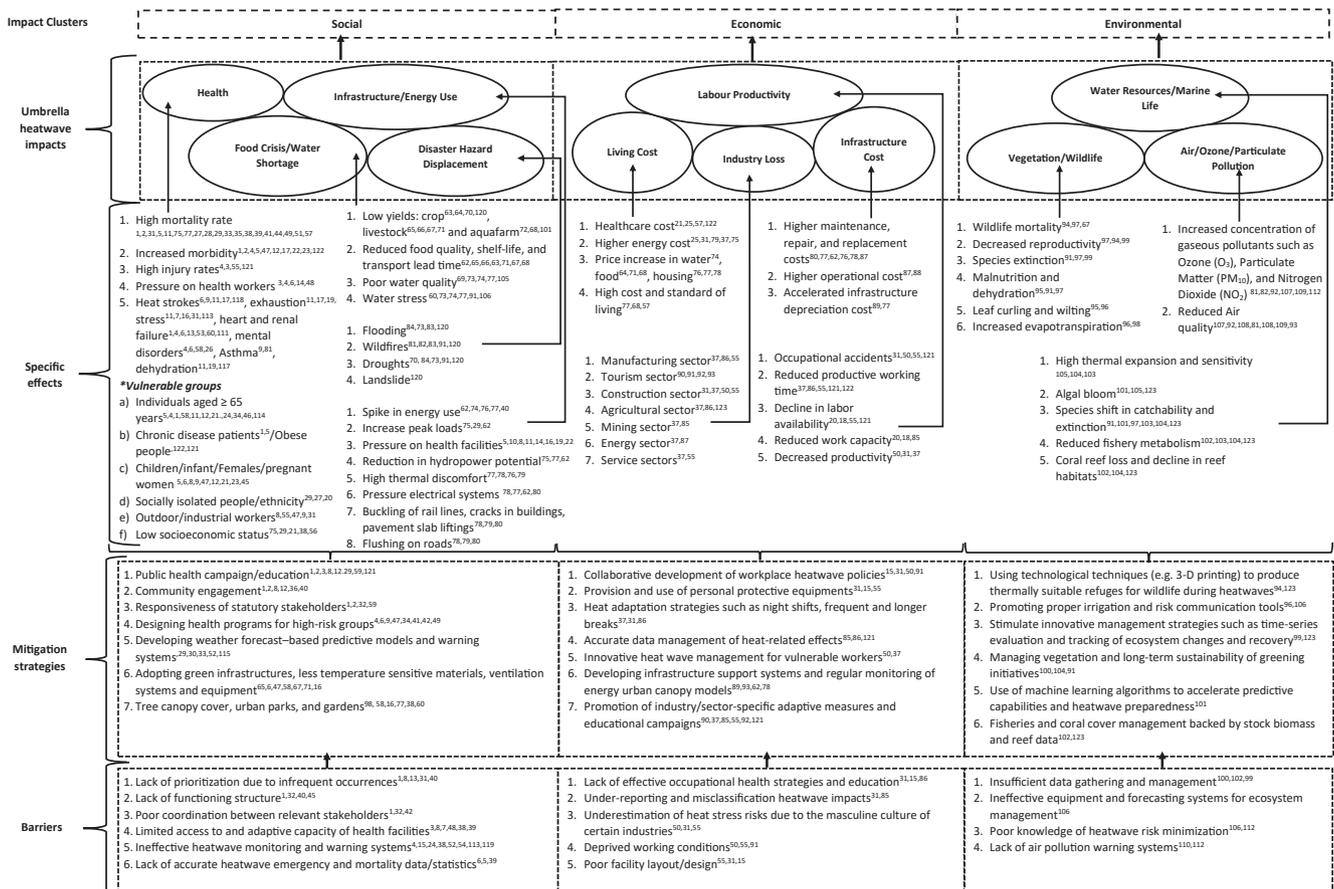


Fig. 6. A graphical synthesis of the social, economic, and environmental impacts of heatwave.

such as thermoregulation, tubular reabsorption, glomerular filtration, and tubular secretion (Basagaña et al., 2011). Adding to this, while Hansen et al. (2008) further reveal that heatwaves increase fatalities associated with symptomatic mental disorders such as dementia and Alzheimer’s disease in the elderly above 65 years, Xu et al. (2013) disclose that heat effects increase emergency admissions of children (0–4 years) with asthma. Mora et al. (2018) emphasise that heat effects cause increases in pathogens and vectors and facilitate the transmission range of diseases leading to excess death and chronic illnesses.

Furthermore, we found that certain groups were more sensitive to heatwaves. These groups even in regions with relatively modest temperatures tend to be in danger of heat effects (Knowlton et al., 2009). As presented in Fig. 6, we found that people aged 65 and above coupled with children and infants are more vulnerable to heat-induced diseases and heat effects (Díaz et al., 2018; Steul et al., 2018; Toloo et al., 2014; Wondmagegn et al., 2021). These groups are very vulnerable due to the inability of their bodies to adjust to sudden temperature changes. For example, Zhang et al. (2015) assert that due to ongoing medications or existing chronic complications that impair the body’s thermoregulation abilities, the majority of older people are unable to quickly adjust to heat effects. Likewise, Stowell et al. (2022) highlight that heatwaves affect the metabolic abilities of children such as sweating thereby impeding their ability to cool down presenting high risks of heat-induced illness. Adding to this, heat effects were found to be detrimental for individuals with chronic health conditions such as cardiovascular and respiratory diseases due to the likely intensification of these conditions during heatwave periods (Adams et al., 2022; Rahman et al., 2022). Obese people due to high thermal discomfort and heat stress are considered vulnerable to heatwaves (Wang et al., 2023; Rogers-Bennett and Catton, 2019).

Various studies also reported that people with low socio-economic

status as well as socially isolated groups and remote ethnicities are also vulnerable to heatwave impacts (Son et al., 2012; Maloney and Forbes, 2011; Van Vliet et al., 2017; Oray et al., 2018). López-Bueno et al. (2021) emphasise that low socio-economic status individuals are unable to afford the energy, material, and rent costs of buildings with proper insulation against exterior temperatures making them more vulnerable to heatwaves. Abrahamson et al. (2009) further highlight that people who stay alone or those not near city centres tend to suffer during heatwaves because of a lack of care and access to adequate health facilities. Additionally, outdoor workers and sportsmen tend to be more susceptible to heatwaves via heat stress (Xu et al., 2019; 2013). According to Xu et al. (2019), workers such as farmers apart from engaging in physically demanding jobs are also exposed to extreme outdoor heat during heatwave periods. Similarly, Xiang et al. (2014) found that injuries among industrial workers increased significantly by 6.2 % during heatwaves asserting industrial workers as a vulnerable group.

The review further reveals a correlation between gender and heatwave vulnerability. While Lu et al., (2021) indicate that men are exposed to extreme heat more than women due to the majority being outdoor and industrial workers, Li et al. (2022) indicate that pregnant women when exposed to extreme heat in their second and third trimesters risk having a stillbirth and preterm birth. Adnan et al. (2022) added that extreme heat exposure increases heat discomfort, dehydration, and low uterine blood flow in pregnant women putting them at high risk of preterm and stillbirth. From the discourse, a better understanding of heatwave health impacts and population vulnerable groups can advance heatwave alertness, response, and mitigation.

Food crisis and water stress. The review finds that food systems and water security were impacted by heatwaves, including the effects on the yields, quality, shelf-life, and transportation lead times were observed for food. Likewise, water quality and water stress were the most

observed heatwave impacts on water accessibility (See Fig. 6). Crop, livestock, and aquafarm yields were adversely impacted by heatwaves. Carlson (1990) investigating the effect of heat stress on corn production found that periods of higher heat stress (e.g. $\geq 30^\circ\text{C}$) led to a significant reduction in corn yields due to a decline in plant-available soil moisture. Vitali et al. (2015) found that heatwaves positively and negatively correlated with dairy cow mortality, and milk production quantities, respectively. Adding to this Schlenker et al. (2009) highlight

that one single day above 38°C reduced annual agricultural yields by 5 % in the USA. Changes in natural land covers also induced by heatwaves were identified as a contributing factor for rapidly reducing soil moisture and low agricultural yields (Mora et al., 2018). Further presenting results from an aquafarm, Wade et al. (2019) found that heatwaves did not only trigger a temperature-induced cessation of voluntary feeding but also led to poor osmoregulation, and liver and renal functions in salmon. von Biela et al. (2019) highlighted that during heatwave periods, the length and energy density of Pacific sand lance significantly declined by 38 % and 13 %, respectively, suggesting a substantial decline in nutritional value.

Moreover, Nawab et al. (2018) add that heatwaves via heat stress reduce the quality of chicken products. According to the authors, heat stress is an important environmental factor affecting chicken feed intake which in sequence affects meat and egg quality, growth rate, body weight, and fertility. Nawab et al. (2018) further noted that high ambient temperature has resulted in high mortality of poultry and spoilage of chicken products during transportation. Zhan et al. (2022) also noted that under high heat effects, chicken eggs reduce in weight and quality consequently reducing their shelf-life. Godde et al. (2021) further note that in addition to heat stress during transportation, heatwaves can worsen conditions for food storage, distribution, and safety via the rapid spread of microbes and fungi especially in humid settings. Adding to this, McEvoy et al. (2012) highlight that heatwaves due to their impacts on logistics systems and transportation infrastructures increase transportation lead times further resulting in more food spoilage, especially for fresh and perishable produce.

The review reveals that heatwaves affect the quality and available quantity of fresh water (See Fig. 6). Hotter and drier conditions caused by heatwaves, according to Murdoch et al. (2000), can have a significant effect on surface water quality. This is because elevated air temperature or droughts instigated by heatwaves can exceed ecosystem tolerance thresholds triggering water-quality degradation. Similarly, Gill et al. (2007) posit that extreme heat increases surface runoff of rainwater. These runoffs lead to flash floods that carry heavy metals, pesticides, and fecal pathogens that contaminate water supplies (Mora et al., 2018; Murdoch et al., 2000). Gordon (1988) also emphasises that heatwaves lead to drought conditions which in turn reduce water storage levels stimulating water stress concerns. Mora et al. (2018) suggest that heatwaves apart from droughts can trigger other hazards such as bushfires, flooding, and heavy rains that threaten available drinking water sources via contamination. An example is the 1999 heavy rain in New York that washed wastewater into aquifers resulting in several deaths and illnesses (Epstein, 2004; Mora et al., 2018).

Infrastructure and energy use. The review highlights several impacts of heatwaves on critical health, transportation, and energy infrastructures. Zhu et al. (2019), for example, highlight that while the increased use of air conditions helped deal with heat stress and discomfort during heatwaves in China, it worsened the heat island effect by increasing energy consumption and condensing heat to the air. McEvoy et al. (2012) found that the Australian heatwave of 2009 had a substantial effect on electricity/energy peak loads and electrical systems. Adding to this, Van Vliet et al. (2017) highlight that heat effects reduce hydropower and electrical system performance due to inefficient generator cooling. Apart from the significant spike in energy use, heatwaves also cause expansions in concrete and steel structures which subsequently damage transport infrastructures such as the buckling of rail lines, flushing on roads, and damage to traffic light systems (McEvoy

et al., 2012; Nguyen et al., 2012).

Sun et al. (2014) further insinuate that heatwaves put substantial pressure on health facilities due to the increase in hospital admissions. Kuczyński and Staszczuk (2020) in addition to indicating that heatwaves cause expansion stress which contributes to cracks in buildings, also insinuate that heatwaves contribute to high thermal discomfort in several buildings thereby necessitating the need for more cooling materials and devices in building designs. McEvoy et al. (2012) add to the above effects connoting that heatwaves have caused power lines to sag because of overheating resulting in wide and long-lasting blackouts. Zuo et al. (2015) summarize the discourse by asserting that heatwaves critically challenge the durability of existing critical infrastructures and thus, require proactive responses to avoid periods of critical infrastructure failures.

Disaster displacement hazards. We found that heatwaves initiate a chain of catastrophic events that not only include thousands of attributable deaths but also displace people from their homes and places of habitual residence. Flooding, wildfires, droughts, and landslides were the main observed heat-induced hazards. Providing a vivid depiction of heat-induced hazards in the Pacific Northwest regions of Canada and the USA, White et al. (2023) indicate that while the 2021 June heatwave stimulated a rapid snow and glacier melt which led to river flooding, it also substantially increased wildfires that resulted in displacement. Sibitane et al. (2022) posit that heat effects via evaporation contribute to the drying up of dams and river bodies presenting intense periods of droughts and water stress motivating many to relocate to new places. Adding to this, White et al. (2023) indicate that heatwaves can cause landslides due to permafrost thawing. Similarly, Islam et al. (2022) highlight that extreme heat in Australia caused a wildfire which burned over 13 million hectares damaging about 2400 buildings, polluting the air, and displacing many. This demonstrates that heatwaves can trigger a chain of hazardous events that have devastating effects on human displacement.

4.3.2. Economic impacts of heatwaves

Living cost. The review suggests that higher temperatures, increased humidity, and frequent extreme weather have significant impacts on living costs. We observe specific effects of heatwaves on healthcare costs, energy/electricity costs, and price increases in water, food, and housing, ultimately resulting in high costs and high standards of living. Wondmagegn et al. (2021) found in Adelaide that low and severe heatwaves contributed to health costs of emergency admissions by AU \$242.8 and AU\$289.3, respectively. The authors further indicated that these health costs in the future could be greater given the growing number of vulnerable groups. Adélaïde et al. (2022) add by indicating that the health effect costs of heatwaves between 2015 and 2019 in France totalled €25.5 billion.

Likewise, Kuczyński and Staszczuk (2020) and Ke et al. (2016) assert that heatwaves increase electricity consumption for air conditioning and cause price hikes due to severe power outages, respectively. Imran et al. (2019) explain that higher temperatures increase energy and water demands. These increased demands result in price increases due to excess demand over supply. Godde et al. (2021) stress that heat effects will impact food quality, limit water availability, and impact logistics networks which in turn will increase the prices of basic goods and services. Adding to this, McEvoy et al. (2012) reveal that housing prices and rent are anticipated to increase due to the need for less temperature-sensitive materials as well as sophisticated designs that will minimize heatwave impacts. From the discourse, developing tailored policies to tackle heatwave-induced prices may help better protect vulnerable groups in society.

Infrastructure cost. Reviewing the economic impacts, we found that heatwaves result in high infrastructure maintenance, repair, and replacement costs, higher operational costs, and accelerated depreciation costs. Ke et al. (2016) in the electricity sector highlight that heatwaves negatively impact power grids and hence, increase operational

costs for greater output. Similarly, on an intense heatwave day (30th January 2009) in Melbourne an explosion at a railway transmission station coupled with a power failure caused city loop train services to cancel leaving several commuters stranded. These issues required substantial amounts to restore train operations and repair damaged equipment (McEvoy et al., 2012). McEvoy et al. (2012) add that during heatwaves, disrupted transport repairs and labour costs are more costly than usual because essential repairs take place at night to avoid daytime heat stress and when repairs happen during daytime, workers use enormous amounts of water to cool down buckled rails thereby increasing repair costs. Lemonsu et al. (2015) also claim that heatwaves via increasing urban heat islands impact the durability of urban infrastructures. McEvoy et al. (2012) further suggest that heatwaves cause rail and road networks to depreciate quickly thereby needing essential repairs and maintenance a few years after construction. The discourse above suggests that heat effects pose relevant infrastructure costs and a better understanding of approaches to minimising such costs can bolster urban resilience to heatwaves.

Labour productivity. The review further identifies heatwave impacts on labour productivity. We found that heatwaves via occupational accidents, reduced productive working hours, decline in labour availability, and decreased work capacity decrease overall productivity. The International Labour Organization explain that labour productivity declines significantly when temperatures exceed 24–26 °C. Godde et al. (2021) further explain that due to heat stress, the work capacity of labourers performing moderate and high intensity tasks declines by 50 % and between 31 % and 38 %, respectively when temperatures are above 33–34 °C. Kjellstrom et al. (2010) insinuate that given the increasing frequency of heatwaves and global warming, labour productivity may decrease by about 11–27 % by 2080 in hot regions such as Asia and the Middle East if essential industrial policies and initiatives are not acted upon.

Also presenting insights from sub-Saharan Africa, Frimpong et al. (2017) find devastating effects of heat stress on production systems in that outdoor workers who are key inputs for such systems suffer detrimental heat-related health consequences and hence, many workers decline working on high heat days leading to labour availability issues. Xiang et al. (2014) in South Australia found that occupational injuries and illness were significantly higher on heatwave days. The authors found that daily claims increased significantly by 6.2 % during heatwaves. Adding to this, Rameezdeen and Elmualim (2017) assert that the association between heat effects severity and labour productivity is dependent on the characteristics of the worker and the work (e.g. the work environment, type and intensity of the work, and the adaptability of the worker to heat conditions). Thus, workers who are found vulnerable to heat effects could be prioritized in setting work health and safety policies.

Industry loss. Heatwaves have cascading macroeconomic impacts on several industries all resulting in substantial economic losses, as indicated in Fig. 6. Xia et al. (2018) posit that a 14-day heatwave which occurred in China's Jiangsu Province led to a total economic loss of 27.49 billion Yuan. Of this loss, 63.1 % was from the manufacturing sector due to labour availability and productivity issues. Likewise, Sibitane et al. (2022) indicate that heatwave days adversely impact tourists, tourism operations, and tourism sector employees. Gómez-Martín et al. (2014) add that due to the 2003 heatwave, Spain's tourist sector in 2003 recorded no growth after seven consecutive periods of over 2 % sector growth. McEvoy et al. (2012) also found that among the several sectors, the electricity/energy sector was found to be the most vulnerable due to faults with transmission, load shedding, blackouts, and explosions at major power stations that occur during heatwave periods. In the agricultural sector, Rogers-Bennet and Catton (2019) found that heatwaves resulted in the closure of commercial fisheries worth over \$44 million. Apart from these, heatwaves have also been found to have negative impacts on the service and mining sectors all leading to a substantial decline in sectorial growth (Varghese et al.,

2019b; Xia et al., 2018; Ayyappan et al., 2009; Rogers-Bennett and Catton, 2019). Such effects suggest the need for policies and initiatives that ensure rapid recovery from heatwave impacts.

4.3.3. Environmental impacts of heatwaves

Vegetation and wildlife. While heatwaves impact on human mortality and morbidity have been widely observed, less is known regarding impacts on wildlife and vegetation. The review finds that heatwaves significantly impact wildlife feed quality, reproductivity, and mortality. A study conducted by Gordon et al. (1988) in South Australia, for example, found that the population of koalas decreased by 63 % during heatwaves and drought conditions. This sharp decline was associated with poor nutrition and dehydration. Similarly, Piatt et al. (2020) reported the death and dying conditions of about 1 million common murre (seabirds of the North Pacific) during the 2014–2016 marine heatwaves due to starvation. The authors further expose that the heatwave increased reproductive failures in multiple bird colonies across California and Alaska.

While other impacts have been observed on other animals such as turtles (Sibitane et al., 2022), flying foxes (Ratnayake et al., 2019), and bats (Honey et al., 2021) among others, heatwaves also significantly impact vegetation. Zanotelli et al. (2022) indicate that heatwaves affect the water and carbon balances of vegetation distinctively. For example, while forest trees during periods of extreme heat mostly close the stomata to preserve soil water and improve the functionality of wood vessels, grasses release all water available until they wither. Despite the varying response to heatwaves, vegetation is largely compromised regarding photosynthesis and gross primary production rates. Particularly, the current and anticipated heat-induced loss of vegetation, natural covering, and wildlife warrant monitoring and development of rapid management responses to preserve wildlife and promote vegetation restoration.

Water resources and marine life. The review finds that the increasing frequency of heatwaves has not only impacted water resources but has given marine species little time to recover driving some species to extinction and decline in catchability. Additionally, several scholars assert that marine heatwaves have increased thermal expansion and sensitivity of water resources (Piccolroaz et al., 2018; Mouthon and Daufresne, 2015; Mouthon and Daufresne, 2006). Specifically, such thermal expansion and sensitivity causes the volume of water to increase leading to water level rise which in turn leads to flooding, contamination, and spread of pathogens and diseases (Piccolroaz et al., 2018; Mora et al., 2018). Giamalaki et al. (2022) posit that heatwaves in addition to triggering shifts in range and extinction of several species promote the growth of algal blooms (rapid growth and accumulation of algae that produce toxic effects on marine species and people). Such natural phenomena coupled with increasing sea surface temperatures also affect precipitation, drought conditions, storms, and air temperature (Piccolroaz et al., 2018; Giamalaki et al., 2022) and as such, require crucial policy attention. Rogers-Bennet and Catton (2019) further emphasise that the rapid decline in coral reef habitats pushes species out of range and drives local extinction. According to the authors, heatwaves in Northern California have reduced bull kelp canopy by over 90 % stimulating the mortality of abalones by 80 % and reducing fisheries metabolism. The dangers posed by heatwaves on water resources and marine life require collaborative efforts from scientists and policymakers in developing climate-resilient proactive and recovery strategies for preserving water and marine ecosystems.

Air, ozone, and particulate pollution. The review finds that during heatwaves concentration of gaseous pollutants increases leading to reduced air quality. For instance, during the August 2003 heatwaves in France and the UK, concentrations of ozone (O₃) significantly increased by over 50 % (Kalisa et al., 2018; Zong et al., 2022; Pu et al., 2017). Islam et al. (2022) presenting evidence from New South Wales note that heatwaves increase the travelling distance of particulate matter (PM_{2.5} and PM₁₀). Kalisa et al. (2018) found that heatwaves do not only

positively impact O₃ and PM₁₀ but also increase Nitrogen dioxide (NO₂). Zong et al. (2022) indicate high concentrations of O₃, PM₁₀, and NO₂ and exposure to the same stimulate human respiratory concerns such as aggravation of chronic respiratory conditions and damage to lung cells. In addition to the direct increases in gaseous pollutants and greater travelling distance, heatwaves via other indirect means have also impaired air quality. Islam et al. (2022), for instance, highlight that heatwaves also via smoke from heat-induced bushfires affect the body's respiration abilities and can also cause heavy rains and floods. Given the inextricable link between heatwaves, air quality, and human health, it is essential to adopt additional measures and policies that tackle and are specific to air pollutant concentrations as a proactive response to mitigating heatwave impacts.

4.4. Mitigation strategies and associated barriers

In providing a wide-ranging observed impact of heatwaves on human and environmental ecosystems, this review also highlights essential mitigation strategies implemented and the associated barriers across all three clusters of heatwave impacts (See Fig. 6). In responding to the social impacts of heatwaves, this review finds that public health campaigns and education, promoting community engagement, and improving heatwave warning systems are fundamental (Abrahamson et al., 2009; Zhang et al., 2012). Adding to this, other scholars indicate that orientation towards green infrastructure that uses less temperature-sensitive materials with improved ventilation can prove essential, especially for high-risk or vulnerable groups (Davis et al., 2020; Hansen et al., 2008). Alternatively, the use of tree covers, urban parks, and gardens has also been essential in ensuring adaptation to heatwaves (Zou et al., 2021; Adnan et al., 2022). Despite the above social mitigation strategies, the review highlights that essential barriers such as lack of prioritization due to heatwave infrequency, lack of functioning structures and poor coordination between key stakeholders impede mitigation strategy outcomes (Abrahamson and Raine, 2009; Zhu et al., 2014). The review also highlights that several mitigation strategies also fail due to the limited access and capacity of health infrastructures, ineffective monitoring and warning systems, and lack of reliable heatwave emergency statistics (Toloo et al., 2014; Borg et al., 2023).

Exploring the mitigation strategies in the economic cluster, several researchers highlight the need for collaborative efforts in developing workplace or industrial heatwave policies, providing protective equipment, and using other heat adaptation strategies such as night shifts as well as longer and frequent breaks on heatwave days to help tackle concerns of labour availability and productivity (Borg et al., 2023; Xiang et al., 2014). Additionally, accurate management of data on heat-related effects, management of vulnerable workers, promotion of support systems, and educational campaigns have been suggested as essential in reducing heatwave economic impacts (Ayyappan et al., 2009; Lemonsu et al., 2015; Wu et al., 2018). The barriers that impeded mitigation strategies in this cluster included an underestimation of heat stress risks, ineffective occupational campaigns on heatwaves, under-reporting of impacts, poor facility layouts, and poor working conditions (Xiang et al., 2014; Sibatane et al., 2022; Balakrishnan et al., 2010).

Furthermore, the review finds that the mitigation strategies implemented to preserve the environment from the dire impacts of heatwaves comprise the use of technological approaches to building thermally suitable refuges for wildlife, ensuring proper regulation for vegetation, and tracking heatwave induced environmental changes (Chowdhury et al., 2012; Rogers-Bennett and Catton, 2019; Honey et al., 2021). Giamalaki et al. (2022) further suggest that machine learning algorithms can significantly help in heatwave preparedness and response thereby ensuring long-term sustainability of the environment. Brown et al. (2021) also insinuate that to preserve the marine ecosystem, key stakeholders can acquire and effectively manage fisheries and coral reef data and use the same in making essential heatwave decisions. The key

barriers identified in this cluster have to do with insufficient data gathering and management of the same, poor knowledge of minimising heatwave risks, and the unavailability of essential equipment that can help in effective forecasting and warning systems for environmental ecosystem management (Chowdhury et al., 2012; Zampieri et al., 2023; McPherson et al., 2021).

5. Discussion

There is a diverse portfolio of actions countries use to cope with heatwave impacts worldwide. Based on this broad literature review, it was evident that, although there has been significant progress in research and thinking on heatwave adaptation over the past few decades, it remains strongly focused on assessing future impacts, responses, and vulnerabilities to heatwaves on human ecosystems. In recent years, the focus has shifted from a static view of heatwaves based on long-term averages and projections to an increased understanding of their characteristics, drivers, and multi-dimensional impacts. As part of our analysis, we sought to contribute to studies on the multidimensional impacts of heatwaves on human ecosystems. Taking a broader look at studies and policies that capture the multifaceted impacts of heatwaves and the entwined nature of country-led heatwave policy interventions, we examined how heatwave characteristics affect the human ecosystem more generally and how those affect policy. Using three broad dimensions of heatwaves, we explored the state-of-the-art regarding analysing and assessing the impacts of heatwaves on human ecosystems. A broad range of human ecosystems have been altered as a result of heatwaves, including social (health, food crisis, human displacement, water shortages), economic (cost of living, operation costs, industry losses), and environmental (wildlife dangers, deforestation, pollution).

Synergies between various parameters of heatwave impacts can result in direct and indirect, immediate and long-term effects on a wide variety of scopes. The recognition of heatwaves' explicit dimensions in social, economic, and environmental systems outlined above provides a pathway to understanding how heatwaves interact with our human ecosystems and their resilience. A critical step towards developing aggregated interventions to mitigate heatwave impacts involves understanding the interrelationships among the multiple dimensions beyond the individual characteristics and impacts across human ecosystems. The mitigation of food shortages from heatwaves, for example, is necessary to maintain labour productivity and minimise industry losses. Likewise, the effective performance of water systems during heatwaves ensures the continuous functioning of natural ecosystems of the human environment to facilitate the preservation of water resources and minimise animal and vegetation mortality caused by dehydration and increased evapotranspiration. In line with previous research (Bao et al., 2015; Reid et al., 2009; Wilhelmi and Hayden, 2010;), our analysis offers insights into developing more specific and operational objectives for identifying synergies, conflicts, and tradeoffs across all dimensions of heatwave impacts.

It is increasingly believed that effective responses to heatwave call for polycentric and multilevel governance arrangements (Campbell et al., 2018). Several studies have emphasized the importance of interactions between clusters of heatwave impacts and the need to identify conditions that may promote such interactions (Mayrhuber et al., 2018; Zhao et al., 2018; Zuo et al., 2015). Taking a systematic approach to these interactions is necessary. There was an emphasis in several of the studies we reviewed on the need for a comprehensive approach to cope with and mitigate heatwave impacts, while also pointing out the need to ensure new heatwave policies align with the multidimensional impact of heatwaves within a given jurisdiction. In the studied policies, we identified trade-offs involving social, economic, and environmental aspects of heatwave impacts, which further complicate attempts to establish a comprehensive and straightforward relationship between the interventions and the desired outcomes. Our assessment supports putting more emphasis on the differential impacts of heatwaves and overcoming

implementation challenges and implications (Guo et al., 2018; Toloo et al., 2013; Abunyewah et al., 2024), despite the fact that the number of policies has been used as one proxy for evaluating the effectiveness of heatwave policies. The point is particularly relevant for heatwave policy research that examines how interacting interventions at multiple scales can be effective (Campbell et al., 2018; Lowe et al., 2011). By taking a broad, more networked perspective on social, economic, and environmental issues associated with heatwaves, we can effectively combat their substantial impacts and consequences at all levels. In this context, it is important to examine not just the innovation of an individual policy, but how country-level heatwave policies respond to the seemingly inherent tradeoffs or interactions among its social, economic, and environmental impacts in order to assess the lasting heatwave impacts. Taking into account the size and complexity of the heatwave problem, it is indeed true that an aggregated policy approach and interventions across scales and jurisdictions are necessary to understand how and whether they assist or hinder collective action against heatwave. This may initially take the form of reviewing the existing policies, especially concerning economic and environmental aspects that impact heatwave mitigation and response and developing a robust policy coordination framework.

A stakeholder-inclusive approach to heatwave issues facilitates a better understanding of how to combat its multidimensional impacts. In developing inclusive interventions against heatwave impacts, Bhave et al. (2016) emphasize stakeholder collaboration as an important aspect of decision-making. According to Adger et al. (2011) and Abunyewah et al. (2023), regardless of the scale of analysis of heatwave impacts, vulnerable groups are the most affected, and the views of these groups must be incorporated into intervention strategies. Our synthesis reveals that as ecosystems provide critical services to people and their livelihoods such as food and water, it is important to address the immediate risk of heatwaves through strategies that benefit vulnerable groups and enhance inclusive decision-making processes, so heatwave mitigation can be sustainable. It is easier to include specific considerations and needs of vulnerable groups and communities in heatwave adaptation mandates, frameworks and institutional arrangements after identifying them. Heatwave policies that fail to take the needs of vulnerable groups into account during decision-making processes, policy formulation, and implementation may make it harder for countries to ensure that heatwave adaptation and mitigation interventions are equitable (Klinsky et al., 2017; Reckien et al., 2017; Thomas and Twyman, 2005; Zander et al., 2024) and that benefits and burdens of heatwave policies are equally distributed.

These precepts support substantial investment in adaptation and mitigation measures to prevent heatwaves from stifling progress in building sustainable human ecosystems. There are many options available for adapting to and recovering from heatwaves, and more are being developed every day. Heatwaves must be addressed in their broadest sense as well as incorporated into the development of human ecosystems throughout the globe. Enhancing technology and management systems to build more heatwave-smart ecosystems is one part of this but will not be sufficient on its own to achieve sustainable human ecosystems. As a result of heatwaves, the entire human ecosystem needs to adapt, with social, economic, and environmental policies being paid close attention to. It is essential to work toward a heatwave-smart ecosystem designed to address all dimensions of human ecosystems affected by heatwaves.

5.1. Limitations and future research

There are limitations to our study. Heatwave impacts remain poorly understood despite a growing literature on climate change over the past few decades. It will help to some extent if we get better evidence to expand our knowledge base. Thus, we propose four main research priorities. First, even though the economic and environmental aspects of heatwave impacts remain important, we found an abundance of literature and policies that focused on the social impacts. As an example, a

synthesis of heatwave policies and programs from countries such as the UK, Italy, Australia, the USA, and Germany confirmed that the social impacts of heatwaves were the primary focus of existing policies. It is imperative that heatwave studies address economic and environmental impacts concurrently with the social dimension' among different development policy strategies going forward. Second, we know little about how mitigation strategies interact with heatwave impacts. Among the studies included in our review, we found that food crises caused by heatwaves are associated with higher living costs and lower labour productivity. In terms of economic and environmental outcomes, social interventions have relatively large effects, but we found no empirical studies that examined specific interactions. It is therefore necessary to examine the indirect effects of heatwaves on a cross-dimensional basis through more comprehensive analytical approaches and sophisticated modelling, which should include links to the political economy.

Third, collecting empirical evidence on heatwave effects across the ecosystem's social, economic, and environmental aspects will enable a more holistic understanding of heatwaves. A better understanding of the human dimensions of heatwave impacts needs to be integrated into human ecosystem planning in the future. Human ecosystems are ultimately driven by people's behaviour and responses to perceived and real climate changes in their local environments—as these factors will play a key role in addressing the multi-dimensional impacts of heatwaves at both the national and local levels. Fourth, the review includes only peer-reviewed journal articles that have been selected according to pre-determined inclusion criteria in order to minimize bias. In assessing the articles, objectivity and transparency were the main objectives. The study was limited by the fact that a limited number of articles met the inclusion criteria. In part, the limited number of articles can be attributed to the novelty of the research area, but also to the narrow inclusion criteria that excluded several relevant articles. Data and publications relevant to the topic could also be found in publications in languages other than English.

6. Conclusion

The rise in heatwave frequency, intensity, and duration compounds impacts on human and environmental ecosystems. In this review, we identified and grouped the broad effects of heatwaves into social, economic, and environmental impacts. While there have been substantial heatwave studies across the globe, the majority of these heat-related studies have placed focus on social impacts neglecting other crucial economic and environmental effects. This extensively narrowed focus on social impacts impairs understanding and may not reflect the complete or wide-ranging impacts of heatwaves on humans, and physical and anthropogenic environments. This review therefore uses an integrative analysis to find that there are key social, economic, and environmental effects (See Fig. 6) that need rapid policy attention. The analysis of the selected articles further reveals interrelationships between the dimensional impacts of heatwaves thereby connoting that policy or mitigation responses or focus on a particular dimension may be insufficient in tackling impacts.

Despite this, the review of existing heatwave policies across various countries (See Table 4) highlights an essential focus on social impacts. Given the interconnections between the impact clusters, we suggest that existing adaption and mitigation strategies that are skewed towards social impacts may impede achieving sustainable heatwave resilience in the face of global warming. This is because, for instance, if heatwaves trigger bushfires the impact will not only be disaster hazard displacement, loss in vegetation cover and wildlife mortality but will also trigger health consequences due to smoke and an increase in gaseous pollutants which in turn will also lead to more hospital admission increasing health costs and pressure on infrastructures. The evidence presented here suggests that heatwave impacts are not mutually exclusive and thus, requires an integrated and inclusive approach to resolving impacts. This may require nations to review their policy frameworks to address the

impacts of heatwaves through understanding the complex interactions between the human ecosystem's social, economic and environmental aspects.

Moreover, while several studies emphasize mitigation strategies that promote proactive responses to heatwaves, the essential barriers that impede current adaptation strategies have been overlooked. Thus, in our assessment of the literature, we highlight some barriers mentioned in the reviewed papers (See Fig. 6) and recommend future studies to provide more evidence on the barriers to enhance effective social, economic, and environmental responses toward heatwave resilience. Overall, this review illustrates that heatwave impacts are evident across social, economic, and environmental dimensions and thus, pose heightened threats to humanity and environmental ecosystems. This warrants collaborative efforts among stakeholders in pooling resources and integrating diverse types of information from these clusters to develop inclusive policies and adaptation strategies for better heatwave resilience.

CRedit authorship contribution statement

Udage Kankanamge Amila Kasun Sampath: Writing – review & editing, Writing – original draft. **Gajendran Thayaparan:** Writing – review & editing, Writing – original draft, Validation, Formal analysis, Data curation, Conceptualization. **Erdiaw-Kwasie Michael Odei:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Baah Charles:** Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Okyere Seth Asare:** Writing – review & editing, Writing – original draft, Project administration. **Abunyewah Matthew:** Writing – review & editing, Writing – original draft, Validation, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2025.104024.

Data availability

Data will be made available on request.

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