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Review article

Housing conditions and the health and wellbeing impacts of climate change: A scoping review

Angela Cartwright [a,b,*], Saman Khalatbari-Soltani [a,c], Ying Zhang [a,d]

[a] School of Public Health, Faculty of Medicine and Health, University of Sydney, Edward Ford Building, A27 Fisher Rd, University of Sydney, NSW, 2050, Australia
[b] Asthma Australia, L13 Tower B, 799 Pacific Hwy, Chatswood, NSW, 2067, Australia
[c] ARC Centre of Excellence in Population Ageing Research (CEPAR), School of Public Health, Faculty of Medicine and Health, University of Sydney, Edward Ford Building, A27 Fisher Rd, University of Sydney, NSW, 2050, Australia
[d] China Studies Centre, University of Sydney, Level 7 Jane Foss Russell Building (G02), 156 City Road, The University of Sydney, Darlington, NSW, 2006, Australia

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ABSTRACT

Housing conditions are emerging as an important consideration in climate change adaptation. Housing modifications have the potential to improve health outcomes by reducing exposure to changing weather conditions and extreme events. This scoping review aimed to explore the existing evidence examining the contribution of housing conditions to the impacts of climate change on health and identify any research gaps. Literature searches were conducted in Scopus and PubMed from January 2013 to September 2023 and data were analysed using thematic analysis. The review included 38 articles consisting of original studies, reviews, and reports, with broad geographical coverage. The most common focus among included articles was on heat-health impacts; housing conditions found to improve heat-health health outcomes included air conditioning, ventilation, and window shading, and there was support for multifaceted housing adaptations rather than single fixes. Ventilation was found to be a priority for improving indoor air quality, while inappropriate insulation and excessive air tightness were found to increase indoor heat and reduce indoor air quality. The scoping review reveals a need for more empirical and qualitative research into indoor heat in homes, climate change hazards other than heat, and intervention studies to inform climate change adaptation policies around housing and improve public health outcomes.

1. Introduction

Climate change is the greatest threat to health this century (Watts et al., 2018). More frequent and severe extreme weather events, such as floods and heatwaves, directly impact human health by increasing morbidity and mortality (McMichael and Lindgren, 2011). Climate change also indirectly impacts health through phenomena such as droughts and sea level rise, which can reduce food and water security and displace populations (McMichael and Lindgren, 2011; Romanello et al., 2022). A 2021 systematic synthesis of 94 systematic reviews highlighted the adverse impacts of climate change on ten health outcome categories, including respiratory, cardiovascular, neurological, mental health, pregnancy and birth outcomes, infectious diseases, skin conditions and allergies, and mortality (Rocque et al., 2021). Additionally, climate change is responsible for substantial economic losses, such as those associated with extreme weather events and lost livelihoods (Romanello et al., 2023).

Climate change has been described as a risk multiplier (Calabro and Hoffman, 2021). It exacerbates existing social, health, and economic inequities through interactions with social factors including poor housing (Khine and Langkulsen, 2023). Improving housing conditions has the potential to influence these inequities and has been recognised as an important focus for climate change mitigation and adaptation (Hales et al., 2007; Haverinen-Shaughnessy et al., 2018). Mitigation refers to efforts to reduce climate change, e.g., increasing home energy efficiency, while adaptation seeks to reduce or prevent the adverse impacts of climate change, e.g., increasing the resilience of homes to disasters (World Health Organization, 2021).

This scoping review focuses on adaptation of housing conditions and climate change health impacts. Housing is a critical social determinant

* Corresponding author. L13 Tower B, 799 Pacific Hwy, Chatswood, NSW, 2067, Australia.
E-mail addresses: acartwright@asthma.org.au (A. Cartwright), saman.khalatbarisoltani@sydney.edu.au (S. Khalatbari-Soltani), ying.zhang@sydney.edu.au (Y. Zhang).

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of health, as safe and secure housing is associated with good health, while precarious and inadequate housing (e.g., poor housing conditions) is associated with poor health (Australian Institute of Health and Welfare, 2016; Mason et al., 2021; McKinnon et al., 2020). People spend over 90% of their time indoors, with the majority of that time spent inside homes, and people at greater risk of experiencing climate change health impacts—including young children, older adults, and people with chronic health conditions—can be indoors up to 100% of the time (McKinnon et al., 2020; Institute of Medicine, 2011; Klepeis et al., 2001; Zhang et al., 2021; Liang et al., 2021). Time spent indoors may be increasing due to extreme weather conditions (Gronlund et al., 2018).

In addition, housing conditions contribute to poor health outcomes through a range of pathways, including dampness and mould (Knibbs et al., 2018), indoor air pollution (Adamkiewicz et al., 2011), poor housing quality (Alidoust and Huang, 2021), and excessive hot or cold temperatures (Jacobs, 2011). Improvements to housing conditions have been found to result in positive health outcomes (Jacobs et al., 2010). The positive and negative impacts of housing conditions affect many areas of human health, including respiratory disease, mental health conditions, and skin and eye conditions, as well as general health (Thomson et al., 2013). Of note, certain groups are more likely to experience adverse health outcomes associated with poor housing conditions, including older adults, women, children, Indigenous peoples, people living in low socioeconomic areas, and people with chronic health conditions (Lien and Tabata, 2022; Sly, 2021; Standen et al., 2022). Housing conditions can influence the health impacts of climate change by reducing or increasing exposure to environmental hazards caused by climate change (Hales et al., 2007). However, housing is a complex area, and modifications may lead to unintended consequences which can worsen rather than improve health outcomes, e.g., increasing air tightness with the aim of preventing heat loss may increase indoor airborne hazards (Macmillan et al., 2016; Shrubsole et al., 2014).

The relationships between housing conditions and health, and climate change and health, are separately well-researched (Rocque et al., 2021; Alidoust and Huang, 2021). However, to date, the availability of evidence on the role of housing conditions in the associations between climate change and health is unclear. To address this critical knowledge gap, and the need for evidence to inform adaptation policies, we conducted a scoping review of existing literature to explore the evidence considering the contributions of housing conditions to the health impacts of climate change. Additionally, we aimed to identify gaps that need to be addressed in future research.

2. Methods

This scoping review was prepared following Arksey and O'Malley's (Arksey and O'Malley, 2005) framework to systematically identify and assess literature relevant to the relationship between housing conditions, climate change, and health. The framework provides guidance on conducting comprehensive scoping reviews and has five stages from identifying the research question to collating, summarizing, and reporting the results. We selected the scoping review approach because the topic is broad, covering multiple potential climate change and extreme weather hazards and their health impacts, as well as the role of various housing conditions in these relationships. The chosen approach allowed us to scope the available literature, identify themes, and identify gaps and future research needs.

2.1. Literature search

We searched Scopus and PubMed from January 2013 to September 2023, with the final search conducted on September 21, 2023. The search strategy involved three concepts: housing conditions, conditions and events related to climate change or extreme weather, and health outcomes. We finalised the search in consultation with an expert librarian at the University of Sydney to ensure that our search strategy is comprehensive and captures relevant studies. Our initial scoping search indicated the term hous* yielded sufficient relevant results, while adding synonyms such as residen*, home*, and room* reduced the relevance of results to the research question. For the climate change concept, synonyms were used for climate-related conditions and events to capture relevant studies. A range of general health terms was used. The search terms are listed in Table 1 and Appendix A.

2.2. Eligibility criteria

We included peer-reviewed original studies, reviews, and reports that addressed all three key concepts of any indoor housing conditions (e.g., indoor temperature and mould), climate change or extreme weather events or conditions, and health outcomes. There was no restriction on study designs or on country. Our inclusion criteria required that articles must be available in full text and in English so that full text reviewing could be undertaken, and from the last 10 years, as the topic of housing, health, and climate change is an emerging area.

As the scope of the review focused on housing as an adaptive measure to health impacts of climate change, we excluded studies focused on home energy sources where there was no link to climate change-driven health impacts, outdoor environment (e.g., neighbourhood conditions, location, or building orientation), relocation resulting from climate disasters, and social behaviour conditions (e.g., overcrowding or mosquito net use). Commentaries, letters, and books or book chapters were not included.

2.3. Study selection

One reviewer (AC) conducted an initial search of the databases and identified and removed duplicate articles. Three reviewers (AC, YZ, and SK-S) conducted title and abstract screening to identify articles for full text screening that appeared to meet the study inclusion criteria. At least two reviewers conducted full text screening of each article that appeared to meet inclusion criteria. Disagreements were discussed and resolved with the third reviewer. One reviewer (AC) undertook a reference check of certain papers at the full-text stage to identify additional articles for inclusion. The reviewers used Microsoft Excel and Google spreadsheets

Table 1
Key words and search strategy.

Keywords	Terms used
Housing conditions	hous*
Climate change	climate change
	warming
	bushfire*
	wildfire*
	flood*
	heavy rain*
	drought*
	heatwave*
	heat
	cold
	temperature extreme*
	extreme* temperature
	hurricane*
	cyclone*
	thunderstorm*
Health outcomes	health*
	wellbeing
	morbidity
	mortality
	hospitali?ation*
	illness
	disease
	emergency
	injury
	death
	accident

to document decisions and reasons.

2.4. Data extraction

One reviewer (AC) extracted data from the included articles and recorded it in a data collection form in Microsoft Excel. The information extracted from original studies consisted of publication year, country the study was conducted in, population, study aims, study type, indicators of the three key concepts of climate change, housing conditions, and health outcomes, method of ascertainment of the indicators, and the main findings of the study. The information extracted from reviews and reports consisted of publication year, aims, methods, and main conclusions.

2.5. Data synthesis

One reviewer (AC) thematically analysed data to identify key themes across the studies and any gaps in the evidence. A narrative approach was taken, given the broad scope of the review and the heterogeneity in study designs, methods, and measurements.

3. Results

3.1. Study characteristics

The scoping review included 38 articles in total (Fig. 1), comprising 30 original studies (Standen et al., 2022; Lane et al., 2023; Chen and Qin, 2022; Sy et al., 2022; Adegebo, 2022; Teyton et al., 2022; Larson et al., 2021; Bhatta and Pahari, 2021; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Ahrentzen et al., 2016; Hatvani-Kovacs et al., 2016; Lu et al., 2016; Li et al., 2023; Jiao et al., 2023; Hu et al., 2022; López-Bueno et al., 2022a, 2022b; Klein et al., 2014; Sailor et al., 2021; Bradatan et al., 2020; Taylor et al., 2018; Phung et al., 2016; Eisenman et al., 2016; Gronlund et al., 2015; Hernández et al., 2018; Williams et al., 2019; Ma et al., 2014; Ehsan et al., 2021), six reviews (Gronlund et al., 2018; Howden-Chapman et al., 2023; Kownacki et al., 2019; Barnes, 2018; Vardoulakis et al., 2015; Fisk, 2015), and two reports (Romanello et al., 2021, 2022). Detailed characteristics of the original studies are summarised in Table 2 and aims of the studies presented in Supplementary Table S1. One original study evaluated the impacts of an intervention (Lane et al., 2023). The remaining original studies were observational, and the most common study designs were cross-sectional (Sy et al., 2022; Adegebo, 2022; Larson et al., 2021; Bhatta and Pahari, 2021; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Hatvani-Kovacs et al., 2016; Lu et al., 2016; Bradatan et al., 2020; Ehsan et al., 2021) and ecological (Standen et al., 2022; Hu et al., 2022; López-Bueno et al., 2022a, 2022b; Klein et al., 2014; Sailor et al., 2021; Phung et al., 2016; Eisenman et al., 2016; Ma et al., 2014). There were four cohort studies, of which two were prospective (Teyton et al., 2022; Williams et al., 2019) and two were retrospective (Chen and Qin, 2022; Jiao et al., 2023). The six reviews employed narrative approaches (Gronlund et al., 2018; Howden-Chapman et al., 2023; Kownacki et al., 2019; Barnes, 2018; Vardoulakis et al., 2015; Fisk, 2015) while the two reports narratively summarised research on a wide range of indicators of climate change impacts and health outcomes (Romanello et al., 2021, 2022) (Table 3).

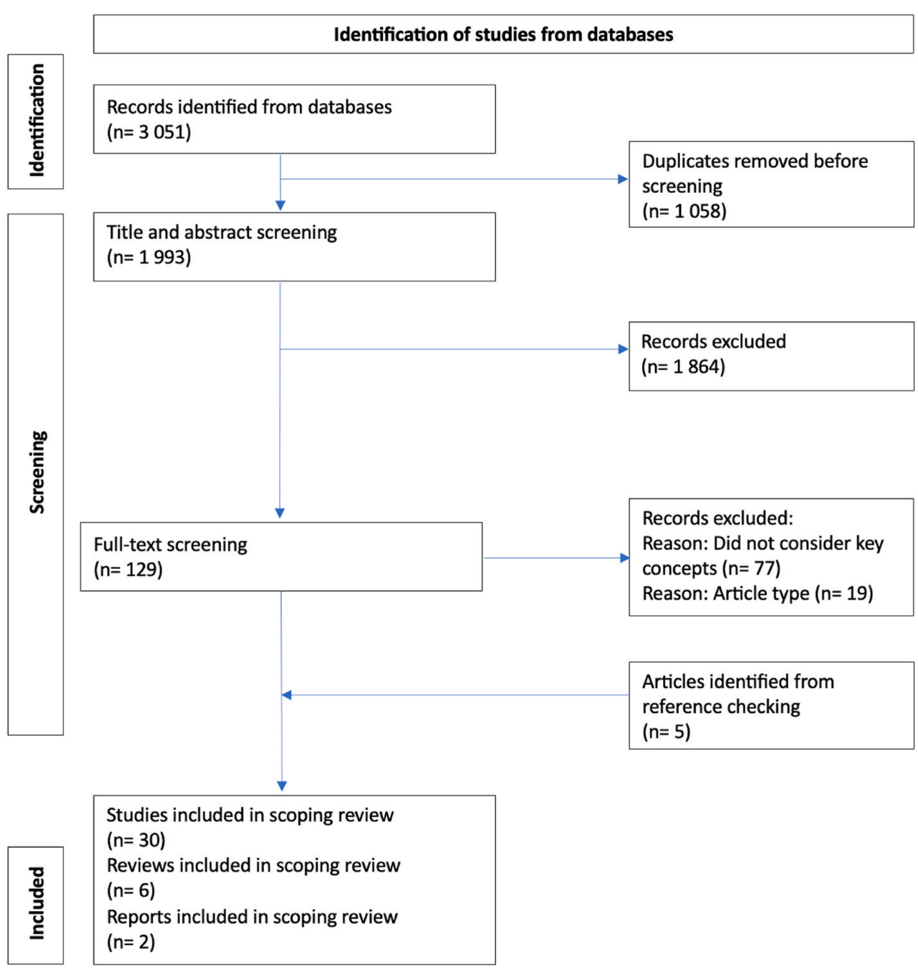

Fig. 1. Literature search flow diagram.

Table 2
Summary of original studies included in the scoping review.

First author, year	Country	Study design	Study population and sample size	Climate change/ extreme weather hazard(s)	Housing condition(s)	Health outcome(s)	Main findings
Adegebo, 2022	Nigeria	Cross-sectional	Urban population of five local government areas of Ibadan. n = 400	Heat, measured using data from Nigerian Meteorological Agency and Forest Research Institute of Nigeria archives, 1971–2018 (relative humidity and daily minimum, daily maximum, and monthly mean temperature).	Housing wall materials, housing roof materials, housing type, and use of fan or air conditioner (self-reported).	Heat-health symptoms (dehydration, heat exhaustion, sweating, heat rash, heat exhaustion, sleep disturbance, headache, restlessness, dizziness, and inadequate sleep) (self-reported).	Multivariate analysis indicated sociodemographic characteristics including housing wall materials, housing roof materials, and housing type jointly had a significant influence on self-reported health and wellbeing effects of heat exposure.
Ahrentzen et al., 2016	United States	Case-crossover	Low-income older residents of an affordable housing complex in Phoenix which was retrofitted in 2010. n = 57	Extreme hot and dry conditions, measured using sensor data (temperature in kitchen, bedroom, and living area; relative humidity in living area) and blower door tests (air infiltration).	Home retrofits, undertaken for an intervention to increase energy efficiency (including new ceiling fans; air conditioning; window upgrades; roof insulation).	General health and quality of life; emotional distress; amount of sleep (self-reported before renovation and 3 months and about one year after renovation).	Reducing the number of temperatures extremes in apartments was linked to improvements in reported health (improved quality of health and life, reduced emotional distress, and increased number of sleep hours).
Bhatta and Pahari, 2021	Nepal	Cross-sectional	Residents of Nepalgunj Sub-metropolitan. n = 366	Heat, measured using heat index based on weather station data (daily relative humidity and maximum and minimum temperatures) and National Oceanic and Atmospheric Administration's National Weather Service method, June–December 2019.	Roof construction material and cross ventilation (self-reported).	Heat stress (dry skin/ rashes, rapid pulse, dizziness, muscle cramps/spasms, heavy sweating, breathing difficulty, headache, unconsciousness, seizure, hyperthermia, confusion, and vomiting) (self-reported).	61% of participants reported heat-related symptoms during June to December 2019 (with high enough heat index to make heat-health related issues possible), of whom 14% attended a healthcare facility, and 9% had severe heat symptoms. Roof construction and cross-ventilation were significantly associated with symptoms.
Bradatan et al., 2020	Honduras	Cross-sectional	Households with at least one child aged under 5 in Honduras (2011-12). n = 8430	Rainfall and temperature or heat anomalies, measured using gridded data from the Climate Research Unit, 1981–2012.	Flooring type (dirt, mud, plank, tile, or granite), measured using 2011-12 Honduras Demographic and Health Survey data.	Child health outcomes (cough, diarrhoea, and infant mortality) measured using self-reported data and mother's births history.	Climate anomalies were associated with child respiratory illness but not infant mortality or diarrhoea in children. Households with dirt floors had the highest prevalence of all three outcomes.
Cardoza et al., 2020	United States	Cross-sectional	Residents of Detroit surveyed in 2016–17. n = 101	Heat (unclear definition).	Availability and type of air conditioning in the home (self-reported).	Heat-related illness (symptoms related to heat exhaustion: muscle cramps, dizziness, tiredness, weakness, throbbing headache, nausea or vomiting, fainting, and paleness) (self-reported).	Residents with poorer health and no air conditioning had greater risk of heat-related illness during extreme heat events. People without air conditioning were 4.66 times as likely to have heat-related illness as people with central air conditioning after adjusting for health status and age.
Chen and Qin, 2022	China	Cohort – retrospective	Participants aged ≥45 years in the China Health and Retirement Longitudinal Study in 2011, 2013 and 2015. n = 50 059	Extreme temperature shocks, measured using United States National Oceanic and Atmospheric Administration data archives (hot and cold exposure days; hot exposure days in	Air conditioning and heating equipment (self-reported).	Health level, ability to complete daily activities and functional daily activities, and number of chronic diseases (self-reported). Cognitive ability, measured using tests.	Long term exposure to extreme heat and cold significantly affected individuals' health. Cooling and heating equipment were effective in alleviating the health impact of heat and cold exposure, respectively.

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Table 2 (*continued*)

First author, year	Country	Study design	Study population and sample size	Climate change/ extreme weather hazard(s)	Housing condition(s)	Health outcome(s)	Main findings
				summer; cold exposure days in winter).			
Ehsan et al., 2021	Pakistan	Cross-sectional	Residents of 5 low-income communities in Faisalabad. n = 292	Heat, measured using discomfort index based on sensor data (indoor wet and dry bulb temperatures) and outdoor weather station data, April–August 2016.	Ventilation (windows or vents) and fan, air conditioner, or evaporative cooler in home (self-reported).	Heat-related health complaints (diarrhoea, dehydration, headache, eye infection, fever, nosebleed, muscular fatigue, skin allergy, and mild temperature) (self-reported).	Discomfort levels were higher in houses without ventilation. The most common heat-related health complaints were fever (24%), headache (22%), diarrhoea (22%), and dehydration (16%).
Eisenman et al., 2016	United States	Ecological	Maricopa County. n = not relevant	Extreme heat, measured using published gridded historical temperature data (maximum temperatures with a three-day lag period).	Air conditioning, measured using data from Maricopa Assessor. Thermal properties of homes, measured using a published building thermal index.	Mortality (from all internal causes and heat-related illnesses), measured using data from the Arizona Department of Health Services, 2005–2010.	There were more deaths from all internal causes on heat days (814) than control days (770), and more heat-related deaths on heat days (Teyton et al., 2022) than control days (Romanello et al., 2023). Not having home air conditioning significantly predicted all internal cause mortality in the bivariate model. Social vulnerability factors moderated the protective benefits of air conditioners in multivariate models. Home thermal protection was not associated with mortality.
Gronlund et al., 2015	United States	Case-crossover	Residents aged ≥65 years of 8 Michigan cities. n = not provided	Extreme heat, measured using National Climactic Data Centre data (daily minimum, maximum, and mean temperature; daily dew point).	Housing age, measured using Decennial Census Long Form and American Community Survey data (2012).	Mortality from natural causes, including heat-related, measured using death records from Michigan Department of Community Health.	Extreme heat was associated with cardiovascular mortality, while the association with respiratory mortality was inconsistent. Housing age may independently increase older people's vulnerability to cardiovascular mortality during extreme heat.
Hatvani-Kovacs et al., 2016	Australia	Cross-sectional	People aged ≥18 years in Adelaide. n = 393	Heatwaves in February 2015, measured using Australian Bureau of Meteorology weather station data (daily minimum and maximum temperatures) and participants' reported strength of heatwaves.	Housing characteristics (house type; heat stress resistant features [type of air conditioning, wall or roof insulation, and double-glazed windows]; adaptive techniques [nocturnal and natural ventilation], retrofitting) (self-reported).	Heat-related health symptoms (self-reported).	Heat stress resilient buildings increased adaptation capacity and decreased adverse health effects during heatwaves. Air conditioning increased dependence, reduced passive adaptation, and did not necessarily reduce health problems. Only people with air conditioning in their whole house had reduced health issues during heatwaves. People with pre-existing health conditions were among the most likely to experience health issues.
Hernández et al., 2018	United States	Qualitative	Residents of 3 public housing developments impacted by	Hurricane.	Floor (self-reported).	Health impacts (described by participants).	Participants described long-term mental health impacts of exposure to the storm, however

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Table 2 (*continued*)

First author, year	Country	Study design	Study population and sample size	Climate change/ extreme weather hazard(s)	Housing condition(s)	Health outcome(s)	Main findings
			Hurricane Sandy. n = 65				these were not linked to housing conditions.
Hu et al., 2022	United States	Ecological	27 states in the United States. n = not relevant	Heat (unclear definition).	General housing conditions (age and air conditioning) and thermal inertia (roof and exterior wall condition; energy efficiency), measured using American Housing Survey and ResStock data.	Heat-related illness and mortality, measured using United States Centers for Disease Control and Prevention Environmental Public Health Tracking Program data (heat-related mortality; mortality rate; emergency department visits; hospitalisations).	Roof condition was significantly associated with heat-related emergency department visits while housing age negatively predicted heat-related mortality. Exterior wall condition was not associated with any heat-related illness outcomes. Neither housing energy efficiency nor air conditioning alone were significantly associated with heat-related illness.
Jiao et al., 2023	United States	Cohort – retrospective	Pregnant women with electronic health records in Southern California (2008-18). n = 190 767	Extreme heat, measured using gridded daily maximum heat index data based on United States National Weather Service algorithm.	Air conditioning in homes, estimated at population level using residential electricity records for climate zones with the strongest heatwaves.	Spontaneous premature rupture of membranes (PROM) during warm season, measured using electronic health record data.	A 9–14% increase in PROM risk was associated with less intense heatwaves. Areas with lower air conditioning penetration had increased risk of heat-related PROM.
Klein et al., 2014	United States	Ecological	People aged ≥65 years in 59 New York City (NYC) Community Districts and 42 United Hospital Fund areas. n = not relevant	Heat waves, measured using National Climatic Data Center hourly meteorological data to calculate heat index, May–September 1997–2006.	Air conditioning, measured using NYC Community Health Survey data. Housing conditions (based on being in dilapidated or deteriorating buildings), using NYC Housing and Vacancy Survey data.	Heat mortality, measured using natural cause death records from NYC Department of Health and Mental Hygiene Office of Vital Statistics.	There was a significant increase in all-cause mortality in people aged ≥65 years on extremely hot days. Neighbourhood-level prevalence of poor housing conditions and low air conditioning were significantly and positively associated with mortality rate ratios.
Lane et al., 2023	United States	Intervention – evaluation	Low-income residents aged ≥53 years of public and private housing in NYC. n = 1447	Extreme heat, summer 2019-20 (unclear definition).	Air conditioning installed in home during intervention compared to control group without air conditioning.	COVID-19 in household and feeling unwell due to hot weather (self-reported).	Non-participants (did not receive air conditioning) (27%) were more likely than participants (received air conditioning) (10%) to report feeling sick in their homes due to hot weather in 2020. Both groups were affected by COVID-19.
Larson et al., 2021	United States	Cross-sectional	Households in Detroit. n = 4803	Home flooding from rainfall (self-reported).	Housing conditions linked to flooding (foundation cracks; mould in basement; mouldy smell; roof condition; leaks; basement needing repair; sink and bath drainage) (self-reported).	Diagnosis of asthma among adults or children in household (self-reported).	Household factors such as poor roof quality and basement wall cracks were more likely to predict pluvial flooding than neighbourhood factors. Asthma cases were associated with home flooding and housing conditions linked to flooding.
Li et al., 2023	Australia	Case-control	Household, Income and Labour Dynamics in Australia (HILDA) survey participants aged ≥15 years (2009-19). n = 1984	Floods, bushfires, and cyclones, measured using HILDA survey data (damage or destruction of home by one of these disasters) (2009-19).	Housing quality, measured using HILDA survey data (reported dissatisfaction with home).	Eight mental and physical health domains (mental health; social functioning; physical functioning; vitality; role limitations due to emotional problems;	Housing damage from climate-related disasters had significant mental, social, emotional, and physical health effects. People residing in poorer quality housing before the climate-

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Table 2 (*continued*)

First author, year	Country	Study design	Study population and sample size	Climate change/ extreme weather hazard(s)	Housing condition(s)	Health outcome(s)	Main findings
						role limitations due to physical health; bodily pain; general health), measured using HILDA survey data.	related disaster experienced greater negative health effects because of the disaster.
López-Bueno et al., 2022a	Spain	Ecological	Rural and urban municipalities in 10 provinces in Spain. n = not relevant	Extreme cold, measured using State Meteorological Agency data (minimum daily and winter minimum temperature) and National Geographic Institute calculations (predictive positive balance, related to aridity).	Housing quality (dwelling in decline and thermal inertia), measured using government cadastral data.	Vulnerability threshold at which a mortality increase is attributable to extreme cold, measured using National Statistics Institute data (daily winter mortality rate due to natural causes).	Only two of the 42 areas analysed in the study experienced no increase in the mortality rate on extreme cold days, compared to eight areas which had increased mortality due to extreme heat. Percentage of housing with poor thermal inertia contributed to increased vulnerability to extreme cold.
López-Bueno et al., 2022b	Spain	Ecological	42 urban and non-urban geographic areas in 10 provinces in Spain with over 10 000 inhabitants. n = not relevant	Heat, measured using State Meteorological Agency data (maximum daily, summer, and summer extreme temperature; historical 'cool summer' climate classification) and National Geographic Institute data (water balance, related to aridity).	Housing quality (dwelling in decline and older dwelling), measured using government cadastral data.	Vulnerability threshold at which a mortality increase is attributable to heat, measured using National Statistics Institute data (daily mortality rate due to natural causes).	Population groups with higher percentages of dwellings in poor condition had higher vulnerability to extreme heat, which is linked to lack of protection from outdoor heat, likely due to poor thermal properties of dwellings. Vulnerability was lower in rural than urban areas which was possibly due to built environment characteristics such as better thermal properties in rural homes.
Lu et al., 2016	China	Cross-sectional	Parents of children attending kindergartens in Changsha. n = 3485	Outside air pollutants (coarse particulate matter; sulphur dioxide; nitrogen dioxide) and weather conditions (outdoor temperature; relative air humidity; wind speed), measured using municipal monitoring station data and Weather Underground website data.	Indoor home environmental factors (building characteristics [age]; mould and dampness [stains on floor or ceiling, odour, dampness on bed or clothing, water damage, and windowpane condensation in winter]; ventilation [window opening, bathroom exhaust fan, and kitchen mechanical ventilation]) (self-reported).	Sick building syndrome (SBS) symptoms, measured based on reporting weekly occurrence of: any general symptoms (fatigue, and headache); mucosal symptoms (itching, burning or irritation of the eyes, irritating, stuffy or runny nose, and hoarse, dry throat); dermal symptoms (dry or flushed facial skin, scaling or itching scalp or ears, and hands with dry, itching, or red skin).	There was not a significant association between SBS symptoms and air pollution or weather conditions. Indoor factors, particularly mould and dampness, were significantly associated with SBS symptoms. Ventilation factors were associated with nose and skin symptoms.
Ma et al., 2014	China	Ecological	17 large cities in China. n = not relevant	Daily temperature and relative humidity, measured using data from meteorological bureau in each city.	Air conditioning and heating in homes, measured using China Statistical Yearbook data.	Daily mortality (from total non-accidental causes and respiratory and cardiovascular disease), measured using data from the municipal centre for disease control in each city.	Both hot and cold temperatures were associated with increased mortality risk. The effects of heat increased with lower prevalence of air conditioning in homes. Number of air conditioning units per household was a significant effect modifier for cold effects.

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Table 2 (*continued*)

First author, year	Country	Study design	Study population and sample size	Climate change/ extreme weather hazard(s)	Housing condition(s)	Health outcome(s)	Main findings
Phung et al., 2016	Vietnam	Ecological	Mekong Delta region. n = not relevant	Heat (daily minimum, maximum, and average temperatures; daily relative humidity; cumulative rainfall), measured using meteorological data.	Poverty housing (measurement methods not stated).	Risk of hospitalisations (for all causes and infectious, cardiovascular, or respiratory disease), measured using linked hospital admission data.	A 1 °C increase in average temperature was associated with increased risks of hospital admissions of 1.3% for all causes, 2.2% for infectious diseases, and 1.1% for respiratory diseases. The relationship to poverty housing was not clearly stated.
Sailor et al., 2021	United States	Ecological	Older people, office workers, and outdoor workers living in homes without functioning air conditioning in Los Angeles. n = not relevant	Extreme heat events, measured using Building Technologies Office of the United States Department of Energy files and weather station observations (dew point temperature and dry bulb temperature).	Indoor thermal conditions in homes without air conditioning, including four levels of window opening behaviour (modelled).	Heat mortality, measured using data from the National Center for Health Statistics.	Being in a home without air conditioning and windows closed was estimated to cause heat exposures 40–60% greater than being outdoors. Having windows closed during day was estimated to considerably increase indoor temperature above outdoor temperature. Improving indoor conditions indicated a significant health benefit.
Standen et al., 2022	Australia	Ecological	Aboriginal population in New South Wales (NSW). n = not relevant	Historical climate exposures (heat, rainfall, drought, and fire danger), measured using NSW Department of Planning, Industry and Environment and Australian Bureau of Meteorology data.	Inadequate housing design and poor housing conditions (measurement methods not stated).	Impact of inadequate housing on Aboriginal health in NSW (measurement methods not stated).	A greater proportion of Aboriginal people than non-Aboriginal people in NSW live in areas with more hot days. Projections indicated this would increase due to climate change and exacerbate the adverse health impacts of poor housing established in earlier literature.
Swain et al., 2019	India	Cross-sectional	Residents of twin cities of Odisha (2017). n = 1099	Extreme heat (unclear definition).	Roof type, cooling mechanisms used (fan, air conditioner or cooler), and adequate ventilation (self-reported).	Heat-related symptoms (heat cramp; heat rash; heat exhaustion; heat syncope; heat stroke) and attendance at health facilities due to heat illness (self-reported).	Over two-thirds of participants had heat illness. Using a fan, cooler, or air conditioner reduced heat illness risk by 60%. A significant association was not found between heat illness and area of residence (e.g., slum areas).
Sy et al., 2022	Senegal	Cross-sectional	Households in the Sahelian zone. n = 1246	Heat waves, measured using Agence Nationale de l'Aviation Civile et de la Météorologie data (maximum, minimum, and average temperatures) and modelling outputs (April, May, and June 2009-19).	Type of housing and construction materials; availability of fan or air conditioner (self-reported).	Extreme temperature impacts on morbidity and mortality, measured using self-reported data and National Health Information System epidemiological data, and health facility consultation data on diseases linked to climate variability (colds and coughs; diarrhoea; arterial hypertension; asthma; heart problems; kidney problems; acute respiratory infection; diabetes; joint pain; skin irritation).	Recurring heat waves led to increases in diseases related to heat, high frequency of visits to health facilities, and excess morbidity (mainly from chronic diseases such as heart disease, diabetes, arterial hypertension, asthma, respiratory affections, hyperthermia, and rheumatism) and mortality. Morbidity and mortality risks were associated with type of housing, construction materials, and presence of fan or air conditioner.

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Table 2 (*continued*)

First author, year	Country	Study design	Study population and sample size	Climate change/ extreme weather hazard(s)	Housing condition(s)	Health outcome(s)	Main findings
							People with a fan or air conditioner and those living in huts or homes made from straw or wooden building materials were less exposed to heat-health effects.
Taylor et al., 2018	United Kingdom	Projective simulation modelling study	West Midlands region. n = 1558 dwellings	Heat, based on simulation model for indoor temperature and temperature anomalies for the West Midlands.	Adaptation measures (external window shutters and energy efficiency building fabric upgrades [floor; roof and wall insulation; triple glazed windows; increased air tightness]) and dwelling archetypes based on simulation model.	Heat mortality, based on published temperature-mortality relationships.	Use of external shutters appeared to be one of most effective measures, reducing heat-related mortality risk by an estimated 30–60%, potentially with decreased effectiveness in extreme heat. External shutters combined with energy efficiency retrofits may reduce mortality risk by 52%. Complete energy efficient adaptation increased mortality risk by 1–14% as solid wall insulation and air tightness can increase indoor temperatures.
Teyton et al., 2022	Canada	Cohort – prospective	People aged ≥60 years living in homes without air conditioning in Monteregie. n = 277	Indoor heat (temperature and humidity), measured using home sensor data during summer 2017-18 (initial reference measurement and two measurements during warmer periods).	Lack of air conditioning, measured based on eligibility for study which was limited to people who did not use air conditioning (self-reported). Housing characteristics (self-reported).	Proximal heat-related physical and mental health symptoms (light-headedness; anxiety; dry mouth; cramps; fatigue; depressive symptoms; nausea; headache; loss of consciousness; more frequent thirst; less frequent urination; dark urine; trouble sleeping) (self-reported).	Increasing temperatures were associated with heat-related health symptoms in the study population which lived in homes without air conditioning, including dry mouth, fatigue, thirst, less frequent urination, and trouble sleeping.
Williams et al., 2019	United States	Cohort – prospective	Low-income residents aged ≥55 years of two public housing units in Cambridge. n = 51	Heat, measured using indoor monitors (dry-bulb temperature and relative humidity) during a heatwave in 2015.	Air conditioning type (central air conditioning; window air conditioning; no air conditioning), measured based on the characteristics of the two public housing units. Opening windows (self-reported).	Sleep and physiological health outcomes (mean galvanic skin response and hourly heart rate), measured with wearable devices. Health symptoms (irritation: sore throat, nosebleeds, and eye irritation; lower respiratory: breathing problems, coughing, and wheezing; upper respiratory: sinusitis, ear pain, common cold, and nasal drip; heat stress: nausea, dry skin, rash, numbness in hands/feet, sweating, and clammy skin; neurocognitive: dizziness, thirstiness, nausea, and headaches; allergies: skin rash and sneezing; mental health: tiredness, depression, anxiety, and irritation) (self-reported).	Nine participants reported 44 heat-related health symptoms, with the highest numbers of symptoms in the hottest units. Higher indoor temperatures were associated with disrupted sleep and increases in galvanic skin response and heart rate. The type of air conditioning contributed to increasing or reducing heat exposure as residences with window air conditioning units were consistently warmer than those with central air conditioning.

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Table 2 (*continued*)

First author, year	Country	Study design	Study population and sample size	Climate change/ extreme weather hazard(s)	Housing condition(s)	Health outcome(s)	Main findings
Wright et al., 2019	South Africa	Cross-sectional	Residents of the City of Johannesburg. n = 580	Extreme heat (unclear definition).	Roof type and air conditioning (self-reported).	Health symptoms during hot weather (sweating; weakness; fatigue and dizziness; muscle cramps) (self-reported).	People living in government-sponsored detached homes, which are often of poor quality, were more likely to report any heat-health effects. People living in houses with asbestos roofs were more likely to report any heat-health effects, although this was not statistically significant.

There appeared to be increasing research interest in the topic with around three-quarters of the included articles published from 2018 onwards. The highest number of original studies was from North America, with a total of 14 studies (Lane et al., 2023; Teyton et al., 2022; Larson et al., 2021; Cardoza et al., 2020; Ahrentzen et al., 2016; Jiao et al., 2023; Hu et al., 2022; Klein et al., 2014; Sailor et al., 2021; Bradatan et al., 2020; Eisenman et al., 2016; Gronlund et al., 2015; Hernández et al., 2018; Williams et al., 2019). The remaining studies were spread out across the globe, with four studies from Asia (Chen and Qin, 2022; Lu et al., 2016; Phung et al., 2016; Ma et al., 2014), and three studies each from Africa (Sy et al., 2022; Adegebo, 2022; Wright et al., 2019), South Asia (Bhatta and Pahari, 2021; Swain et al., 2019; Ehsan et al., 2021), Europe/United Kingdom (López-Bueno et al., 2022a, 2022b; Taylor et al., 2018), and Australia (Standen et al., 2022; Hatvani-Kovacs et al., 2016; Li et al., 2023). While most of the studies defined their population of interest by geographical area (Sy et al., 2022; Adegebo, 2022; Larson et al., 2021; Bhatta and Pahari, 2021; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Hatvani-Kovacs et al., 2016; Hu et al., 2022; López-Bueno et al., 2022a, 2022b; Taylor et al., 2018; Phung et al., 2016; Eisenman et al., 2016; Ma et al., 2014), some studies focused on specific populations, with the most common being older people (Lane et al., 2023; Chen and Qin, 2022; Teyton et al., 2022; Ahrentzen et al., 2016; Klein et al., 2014; Sailor et al., 2021; Gronlund et al., 2015; Williams et al., 2019), people with low income (Lane et al., 2023; Ahrentzen et al., 2016; Williams et al., 2019; Ehsan et al., 2021), and social housing residents (Lane et al., 2023; Ahrentzen et al., 2016; Hernández et al., 2018; Williams et al., 2019).

3.2. *Indicators and measurements of climate change hazards or extreme weather events*

Most of the original studies considered a single climate change hazard, of which heat was the most common (Lane et al., 2023; Sy et al., 2022; Adegebo, 2022; Teyton et al., 2022; Bhatta and Pahari, 2021; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Ahrentzen et al., 2016; Hatvani-Kovacs et al., 2016; Jiao et al., 2023; Hu et al., 2022; López-Bueno et al., 2022b; Klein et al., 2014; Sailor et al., 2021; Taylor et al., 2018; Phung et al., 2016; Eisenman et al., 2016; Gronlund et al., 2015; Williams et al., 2019; Ehsan et al., 2021), and one review focused on heat alone (Kownacki et al., 2019). In contrast, just one study focused on cold alone (López-Bueno et al., 2022a), while two studies (Chen and Qin, 2022; Ma et al., 2014) and one review (Gronlund et al., 2018) considered temperature in general. The only studies to consider single climate change hazards unrelated to temperature focused on hurricanes (Hernández et al., 2018) and home flooding from rainfall (Larson et al., 2021).

Four original studies considered multiple climate change hazards, including heat, rainfall and flooding, bushfires, cyclones, drought, air pollution, and meteorological conditions (Standen et al., 2022; Lu et al., 2016; Li et al., 2023; Bradatan et al., 2020). Four reviews which considered multiple climate change hazards included airborne hazards (Howden-Chapman et al., 2023; Barnes, 2018; Vardoulakis et al., 2015; Fisk, 2015), with three also considering heat (Howden-Chapman et al., 2023; Vardoulakis et al., 2015; Fisk, 2015). While the two reports considered a wide range of climate change hazards, the only hazard relevant to this scoping review was heat (Romanello et al., 2021, 2022).

Climate change and extreme weather hazards were most commonly measured using available meteorological data (Standen et al., 2022; Chen and Qin, 2022; Sy et al., 2022; Adegebo, 2022; Bhatta and Pahari, 2021; Hatvani-Kovacs et al., 2016; Lu et al., 2016; López-Bueno et al., 2022a, 2022b; Klein et al., 2014; Sailor et al., 2021; Phung et al., 2016; Gronlund et al., 2015; Ma et al., 2014; Ehsan et al., 2021), followed by indoor sensors (Teyton et al., 2022; Ahrentzen et al., 2016; Williams et al., 2019; Ehsan et al., 2021), and gridded data (Jiao et al., 2023; Bradatan et al., 2020; Eisenman et al., 2016). Alternative measurement approaches were self-reported exposure to hazards (Larson et al., 2021; Li et al., 2023) and assuming exposure to the hazard based on its coverage (Hernández et al., 2018). One study simulated the effects of the hazard (Taylor et al., 2018). Five studies which focused on heat did not clearly measure or define this hazard (Lane et al., 2023; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Hu et al., 2022).

3.3. *Indicators and measurements of housing conditions*

The presence or absence of air conditioning was the most common housing variable in the included articles, considered alone or in combination with other housing features (Romanello et al., 2022, 2023; Gronlund et al., 2018; Lane et al., 2023; Chen and Qin, 2022; Sy et al., 2022; Adegebo, 2022; Teyton et al., 2022; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Ahrentzen et al., 2016; Hatvani-Kovacs et al., 2016; Jiao et al., 2023; Hu et al., 2022; Klein et al., 2014; Sailor et al., 2021; Eisenman et al., 2016; Williams et al., 2019; Ma et al., 2014; Ehsan et al., 2021; Kownacki et al., 2019; Vardoulakis et al., 2015; Fisk, 2015). In the original studies, air conditioning was measured using self-reported data (Chen and Qin, 2022; Sy et al., 2022; Adegebo, 2022; Teyton et al., 2022; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Hatvani-Kovacs et al., 2016; Klein et al., 2014; Ehsan et al., 2021), second-hand statistical data (Hu et al., 2022; Eisenman et al., 2016; Ma et al., 2014), or based on membership of a cohort or intervention group (Lane et al., 2023; Ahrentzen et al., 2016; Williams et al., 2019). One study estimated air conditioning use based on electricity records and temperature data (Jiao et al., 2023), and another study simulated scenarios which excluded air conditioning use (Sailor et al., 2021).

Other common housing variables considered in the articles which focused on heat were window opening or ventilation (Gronlund et al., 2018; Bhatta and Pahari, 2021; Swain et al., 2019; Hatvani-Kovacs et al., 2016; Sailor et al., 2021; Taylor et al., 2018; Williams et al., 2019; Ehsan

Table 3
Summary of reviews and reports included in the scoping review.

First author, year	Aims	Methods	Main conclusions
Narrative reviews			
Barnes, 2018	To review published evidence on climate change impacts likely to affect allergic and respiratory disease, including home mould and dampness.	Not stated.	- Damp housing due to climate change impacts such as changed seasonal rainfall patterns and sea level rise is likely to increase mould allergies. - Projections using various climate change scenarios estimated up to 3.3 billion people would be exposed to damp conditions amenable to mould growth.
Fisk, 2015	To review evidence on potential health effects of climate change impacts on indoor environments, particularly homes.	Reviewed literature from multiple fields concerning 1. predictions of climate change impacts on outdoor weather, ambient air pollution, sea level, and wildfires; 2. predictions of climate change health impacts linked to indoor exposures; 3. health outcomes related to heatwaves, outdoor ozone, building dampness, and mould; 4. relationship of indoor environmental conditions to building characteristics and outdoor environmental conditions.	- Indoor exposures are substantially responsible for adverse health outcomes resulting from an increase in climate change events such as heat waves, storms, sea level rise, wildfires, and ozone. - Projected effects from exposures that significantly occur indoors include a doubling of heat-related deaths, increased respiratory and cardiovascular hospitalisations during wildfires, and increased mortality and hospitalisations due to ozone. - Increased dampness and mould resulting from heavy rainfall and flooding is likely to have significant adverse respiratory health impacts, including asthma and respiratory infections. - Retrofits to improve building energy efficiency can positively or negatively impact indoor environmental quality and health.
Gronlund et al., 2018	To describe evidence identifying commonalities in heat and cold-related vulnerabilities in areas of Detroit with economic disadvantage, and interventions to improve health outcomes influenced by heat and cold, including housing quality.	Focused on contextual perspective rather that systematically identifying literature. Literature searching of the Web of Science database using search terms relating to temperature, physiology, and housing, focusing on Detroit and cities with a similar climate.	- Results highlight the availability of evidence on the health consequences of hot and cold weather, which disproportionally impact population groups defined by their individual, built environmental, and community characteristics. - Short and long-term interventions to improve housing quality may reduce heat and cold related health problems.
Howden-Chapman et al., 2023	To review evidence about interventions to improve housing and neighbourhood quality associated with equity, health, and wellbeing outcomes.	Focusing on public health interventions that provide robust evidence through randomised controlled trials and natural experiments. Methods not detailed.	- Results demonstrate strong evidence about the health impacts of cold temperatures and effective housing interventions. - Results highlight a lack of empirical data about indoor heat-health impacts compared with outdoor heat. - Knowledge gaps include the health impacts of indoor heat and effective housing interventions.
Kownacki et al., 2019	To describe how severe heat occurs and can be identified in urban indoor environments, and effective actions at the local level to reduce heat stress indoors in Scandinavia.	Reviewed literature from a limited systematic search concerning existing buildings in Scandinavian urban areas and indoor climate and thermal conditions, climate change, heat wave, health, housing, and solutions. Authors included relevant literature from their own collections.	- Results highlight the lack of evidence around indoor thermal environments during heatwaves, despite the likelihood of experiencing heat stress indoors. Most Scandinavian literature focuses on outdoor heat or cold-related thermal comfort. - Indoor temperature can be 50% higher than outdoor temperature. - Solar radiation through windows has the greatest influence on cooling needs and shading devices are effective in reducing indoor heat stress; external blinds more effectively reduce indoor heat than internal blinds.
Vardoulakis et al., 2015	To explore literature concerning health risks associated with indoor environments and climate change, and the positive and negative impacts of climate change policies on housing in the United Kingdom (UK).	Reviewed scientific literature concerning health impacts related to housing likely to result from actions to mitigate or adapt to climate change in the built environment in the UK. Focused on four categories of health risk: indoor temperatures, indoor air quality, indoor allergens and infections, and flood damage and water contamination.	- Climate change is associated with many health risks in homes in the UK. Adverse health effects are more likely among people who are older, have pre-existing illnesses, and have low socioeconomic status. - Well-designed and implemented climate change mitigation and adaptation measures (including ventilation, passive cooling, and energy efficiency measures) in residential buildings can reduce adverse health impacts related to extreme temperatures, indoor exposure to air pollutants originating outside, and mould growth. - Increasing home air tightness to improve energy efficiency can increase indoor air pollution and biological contamination, causing adverse health impacts.
Reports			

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Table 3 (*continued*)

First author, year	Aims	Methods	Main conclusions
Romanello et al., 2022	To independently monitor climate change health impacts.	A global initiative to track progress on health and climate change research and responses.	- Heatwaves cause the highest number of deaths out of all natural disasters and at-risk groups include isolated people in low-cost housing. - Air conditioning provides effective protection but also produces waste heat and causes air pollution associated with 24 000 deaths in 2020. - Improving insulation, reflective roofing, window blinds, and using indoor fans while running air conditioners can reduce indoor heat. Electric fans are effective at certain temperatures but can worsen heat-health impacts in very hot and dry conditions.
Romanello et al., 2021	To independently monitor climate change health impacts.	A global initiative to track progress on health and climate change research and responses.	- In 2020, there were new records for temperatures and exposure to heatwaves for vulnerable groups, such as people aged over 65 years infants younger than 1 year, compared to the 1986–2005 average. - Air conditioning use avoided 195 000 heat-related deaths in people aged over 65 in 2019 but also produces waste heat and air pollution from energy used was associated with 21 000 deaths.

et al., 2021; Vardoulakis et al., 2015), fans (Romanello et al., 2022; Sy et al., 2022; Adegebo, 2022; Swain et al., 2019; Ahrentzen et al., 2016; Ehsan et al., 2021), insulation (Romanello et al., 2022; Ahrentzen et al., 2016; Hatvani-Kovacs et al., 2016; Taylor et al., 2018; Eisenman et al., 2016; Fisk, 2015), specific housing materials such as roof or wall material (Romanello et al., 2022; Adegebo, 2022; Bhatta and Pahari, 2021; Swain et al., 2019; Wright et al., 2019), window shutters, blinds, or shading (Romanello et al., 2022; Taylor et al., 2018; Kownacki et al., 2019; Fisk, 2015), and type of window (Ahrentzen et al., 2016; Hatvani-Kovacs et al., 2016; Taylor et al., 2018; Fisk, 2015). Articles also considered general housing type, age, or condition (Standen et al., 2022; Sy et al., 2022; Adegebo, 2022; Hu et al., 2022; López-Bueno et al., 2022b; Klein et al., 2014; Phung et al., 2016; Gronlund et al., 2015), general home energy efficiency (Hu et al., 2022; Taylor et al., 2018; Vardoulakis et al., 2015), and general retrofits to reduce heat (Ahrentzen et al., 2016; Hatvani-Kovacs et al., 2016; Howden-Chapman et al., 2023). Most of the original studies measured these variables using self-reported data (Sy et al., 2022; Adegebo, 2022; Teyton et al., 2022; Bhatta and Pahari, 2021; Swain et al., 2019; Wright et al., 2019; Hatvani-Kovacs et al., 2016; Williams et al., 2019; Ehsan et al., 2021), second-hand statistical data (Hu et al., 2022; López-Bueno et al., 2022b; Klein et al., 2014; Eisenman et al., 2016; Gronlund et al., 2015), membership of a cohort or intervention group (Ahrentzen et al., 2016; Williams et al., 2019), or modelling (Sailor et al., 2021; Taylor et al., 2018). Two studies did not clearly state how the housing conditions related to heat were measured (Standen et al., 2022; Phung et al., 2016).

Among the articles that considered hazards other than, or in addition to, heat, three studies considered general housing quality (Standen et al., 2022; Li et al., 2023; López-Bueno et al., 2022a), which was measured using self-reported indicators (e.g., dissatisfaction with the home) (Li et al., 2023) or government data (López-Bueno et al., 2022a), or did not state the measurement approach (Standen et al., 2022). Other studies used self-reported data to measure a range of housing indicators, including housing conditions related to flooding (Larson et al., 2021), housing conditions related to sick building syndrome (e.g., mould, dampness, and ventilation) (Lu et al., 2016), floor type (Bradatan et al., 2020), and floor level (Hernández et al., 2018). Two reviews considered evidence concerning a range of housing conditions such as, building design, ventilation, air filtration, insulation, and air tightness (Vardoulakis et al., 2015; Fisk, 2015). One review considered indoor mould and dampness (Barnes, 2018), and another review compared evidence for single fix and systemic housing retrofits (Howden-Chapman et al., 2023).

3.4. Indicators and measurements of health impacts

Heat-related health issues were the most common health outcomes among the original studies. The majority of these studies explicitly measured heat-health impacts such as heat-related illness or symptoms (e.g., dehydration, headache, heat rash, dizziness, nausea, and muscle cramps) (Adegebo, 2022; Teyton et al., 2022; Bhatta and Pahari, 2021; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Hatvani-Kovacs et al., 2016; Ehsan et al., 2021), heat-related mortality (López-Bueno et al., 2022b; Klein et al., 2014; Sailor et al., 2021; Taylor et al., 2018; Eisenman et al., 2016; Gronlund et al., 2015), both heat-related mortality and illness (Sy et al., 2022; Hu et al., 2022), and premature rupture of membranes during pregnancy (Jiao et al., 2023). Other studies considered general health impacts such as health symptoms (Standen et al., 2022; Lane et al., 2023; Chen and Qin, 2022; Teyton et al., 2022; Ahrentzen et al., 2016; Williams et al., 2019), mortality (Ma et al., 2014), child health symptoms and mortality (Bradatan et al., 2020), and risk of hospitalisations (Phung et al., 2016). Five reviews (Gronlund et al., 2018; Howden-Chapman et al., 2023; Kownacki et al., 2019; Vardoulakis et al., 2015; Fisk, 2015) and two reports (Romanello et al., 2021, 2022) considered heat-health issues including heat mortality (Romanello et al., 2021, 2022; Fisk, 2015), heat stress (Kownacki et al., 2019), and population groups more susceptible to heat-health impacts (Gronlund et al., 2018; Howden-Chapman et al., 2023; Vardoulakis et al., 2015).

The original studies used a range of approaches to measure heat-health indicators. Most of the studies that considered mortality used government records (Sy et al., 2022; Hu et al., 2022; López-Bueno et al., 2022b; Klein et al., 2014; Sailor et al., 2021; Eisenman et al., 2016; Gronlund et al., 2015; Ma et al., 2014), while one study relied on published temperature-mortality relationships (Taylor et al., 2018), and another study used birth histories to record infant mortality and self-reported data on other child health outcomes (Taylor et al., 2018). Two studies measured hospitalisations, with one study using linked hospital admission data (Phung et al., 2016) and the other study using government public health tracking data (Hu et al., 2022). Most of the studies that focused on heat-related illness or symptoms relied on self-reported health data (Adegebo, 2022; Teyton et al., 2022; Bhatta and Pahari, 2021; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Hatvani-Kovacs et al., 2016; Ehsan et al., 2021), as did three studies considering general health impacts (Lane et al., 2023; Chen and Qin, 2022; Ahrentzen et al., 2016). One study combined self-reported symptoms with data from wearable devices (Williams et al., 2019) and another study measured the heat morbidity variables using self-reported data and health facility records (Sy et al., 2022). Electronic health records were used in a study measuring premature rupture of membranes during pregnancy (Jiao et al., 2023). Finally, one study did not state how the health impacts were measured (Standen et al., 2022).

The few studies reporting health impacts unrelated to heat mainly used self-reported data to measure health variables such as asthma diagnosis in relation to home flooding (Larson et al., 2021), sick building syndrome symptoms (Lu et al., 2016), a range of physical and mental health symptoms in relation to disaster damage to homes (Li et al., 2023), and health impacts associated with a hurricane (Hernández et al., 2018). One study used available data to measure mortality attributable to extreme cold (López-Bueno et al., 2022a). Two reviews considered various health impacts linked to climate change and housing (in addition to heat-health impacts) (Vardoulakis et al., 2015; Fisk, 2015), while one review focused solely on respiratory and allergic disease associated with climate change, including mould allergies (Barnes, 2018).

3.5. Housing relationship to climate health impacts

Several included studies found the presence of home air conditioning was associated with improved heat-health outcomes (Chen and Qin, 2022; Sy et al., 2022; Swain et al., 2019; Hatvani-Kovacs et al., 2016) or the absence of air conditioning was associated with poorer heat-health outcomes (Lane et al., 2023; Teyton et al., 2022; Cardoza et al., 2020; Jiao et al., 2023; Klein et al., 2014; Sailor et al., 2021; Ma et al., 2014). Two studies found the type of air conditioning contributed to health impacts or heat exposure, with one study finding only people with air conditioning throughout the home experienced reduced health problems during heat waves (Hatvani-Kovacs et al., 2016) and the other study finding central air conditioning more effectively reduced heat exposure than window air conditioning (Williams et al., 2019). Additionally, one study found air conditioning alone was not significantly associated with heat-related illness (Hu et al., 2022) and another study found social vulnerability factors moderated the protective benefits of air conditioning in multivariate models analysing contributors to heat mortality (Eisenman et al., 2016). A number of studies and reviews raised concerns around widespread reliance on air conditioning, such as cost (Vardoulakis et al., 2015; Fisk, 2015), generation of waste heat (Romanello et al., 2021, 2022; Gronlund et al., 2018; Chen and Qin, 2022), production of greenhouse gas emissions (Chen and Qin, 2022; Kownacki et al., 2019), air pollution from electricity generation (Romanello et al., 2021, 2022; Gronlund et al., 2018), and lack of adaptation to heat (Hatvani-Kovacs et al., 2016; Williams et al., 2019).

Studies considering housing conditions other than air conditioning found varying results in mitigating heat-health impacts. Ventilation was found to reduce heat-health impacts, with cross ventilation associated with reduced frequency of heat-related illness (Bhatta and Pahari, 2021) and lack of ventilation associated with increased heat discomfort levels (Ehsan et al., 2021). Use of fans was associated with lower morbidity and mortality risks (Sy et al., 2022) and a 60% reduction in heat illness risk (Swain et al., 2019). Energy efficiency adaptation was found to increase mortality risk because increasing air tightness, along with solid wall insulation, can increase indoor temperatures (Taylor et al., 2018). Two reviews found greater air tightness can increase indoor airborne hazards (Gronlund et al., 2018; Vardoulakis et al., 2015), with one recognising an increased risk during extreme weather conditions when people spend more time indoors (Gronlund et al., 2018).

A simulation study found external window shutters were a highly effective measure, reducing heat-related mortality risk by between 30 and 60% (Taylor et al., 2018). Two reviews recognised the effectiveness of window shading and emphasised external shading over internal shading (Kownacki et al., 2019; Fisk, 2015). One review concluded solar radiation through windows has the greatest influence on cooling needs and shading devices such as blinds were effective in reducing indoor heat stress (Kownacki et al., 2019), while the other review recognised external shading among housing improvements measures to reduce health damage from heatwaves (Fisk, 2015).

Three studies reported associations between roof and wall materials and heat-health impacts (Adegebo, 2022; Bhatta and Pahari, 2021; Wright et al., 2019), with one study finding heat stress was more common in homes with concrete or cement roof types than other roof construction types (Bhatta and Pahari, 2021) and another study finding heat-health impacts were more common among people living in homes with asbestos roofs than other roof materials (Wright et al., 2019). The third study found both roof and wall materials were among the characteristics that jointly had a significant impact on heat-health symptoms (Adegebo, 2022). Additionally, one study found poorer roof condition was significantly associated with heat-related emergency department visits but exterior wall condition was not associated with any heat-health outcomes (Hu et al., 2022).

The few studies that considered health impacts relating to extreme cold found consistent associations between indoor cold and adverse health impacts, with increased self-reported health impacts (Chen and Qin, 2022) and mortality risk (López-Bueno et al., 2022a; Ma et al., 2014). Lack of home heating (Chen and Qin, 2022) and poor thermal inertia (López-Bueno et al., 2022a) were found to contribute to these adverse health outcomes. One review found home weatherisation interventions and heating improvements increased thermal comfort and decreased cardiovascular risks linked to cold temperatures and that the cold weather mortality burden could be partially attributable to exposure to indoor hazards from increased time spent indoors, including mortality from respiratory illness (Gronlund et al., 2018). It concluded long- and short-term strategies (e.g., roof repairs and insulation) to improve housing quality could reduce both heat- and cold-related health problems (Gronlund et al., 2018).

Two studies (Larson et al., 2021; Lu et al., 2016) and three reviews (Barnes, 2018; Vardoulakis et al., 2015; Fisk, 2015) considered indoor environmental quality issues, with all the articles including indoor air quality issues, and two of the reviews additionally including indoor temperature (Vardoulakis et al., 2015; Fisk, 2015). One study found asthma cases were associated with recurrent home flooding due to heavy rainfall and housing conditions linked to flooding, including mould (Larson et al., 2021). The other study found indoor factors associated with climate change impacts, such as mould and dampness, were significantly associated with reported symptoms of sick building syndrome (Lu et al., 2016), while one review concluded mould allergies were likely to increase due to damp housing resulting from climate change impacts such as changed seasonal rainfall patterns and sea level rise (Barnes, 2018). Another review found a range of health risks in homes were related to climate change, including air pollution, mould, and heat (Vardoulakis et al., 2015). The third review found the projected effects of primarily indoor exposures included a doubling of heat-related deaths, increased respiratory and cardiovascular hospitalisations during wildfires, increased mortality and hospitalisations due to ozone, and likely significant adverse impacts of increased dampness and mould on respiratory health (Fisk, 2015).

The literature identified various housing conditions associated with improved health outcomes related to climate change impacts on indoor environmental quality including insulating attics (Fisk, 2015), improving the building envelope to reduce water entry (Larson et al., 2021; Fisk, 2015), improving ventilation through exhaust fans in bathrooms and windows (Lu et al., 2016; Vardoulakis et al., 2015), using air filtration (Vardoulakis et al., 2015; Fisk, 2015), and using charcoal filters to reduce ozone (Fisk, 2015). While there was limited support for mechanical ventilation with air filtration (Vardoulakis et al., 2015), reviews noted concerns including low use by residents (Vardoulakis et al., 2015; Fisk, 2015), poor performance (Fisk, 2015), and the need for feasibility, proper installation, and maintenance (Vardoulakis et al., 2015). Overall, Fisk (2015) concluded building features can mediate health impacts associated with indoor environmental quality, but found there was lack of evidence around the net impact of increasing air tightness on indoor air quality. Vardoulakis et al. (2015) concluded that while well designed and implemented climate change mitigation and adaptation measures in residential buildings can benefit health, increasing home air tightness to improve energy efficiency can adversely affect health by increasing indoor air pollution and biological contamination.

Finally, studies considering general housing quality and conditions found associations between poor housing conditions and heat mortality (López-Bueno et al., 2022b; Klein et al., 2014), heat-related illness (Wright et al., 2019), and cold-related mortality (López-Bueno et al., 2022a); housing age and heat-related cardiovascular mortality among older people (Gronlund et al., 2015); and living in poor housing conditions prior to a climate disaster and experiencing negative health effects following the disaster (Li et al., 2023). Two reviews concluded there was a need to improve the overall quality and resilience of homes, rather than focusing on single fixes (Howden-Chapman et al., 2023; Vardoulakis et al., 2015).

4. Discussion

The results of the scoping review support the importance of housing as an adaptation priority to reduce adverse health impacts associated with climate change conditions and extreme weather events. The results also indicate this is an emerging area of research, with consistent results around the association of some housing conditions with improved health outcomes associated with climate change, and inconsistent results concerning other housing conditions. The largest volume of evidence relates to housing conditions and heat-health impacts, reflecting the high proportion of results considering heat.

Findings from the scoping review that support consideration of housing modifications combining multiple measures to improve housing conditions rather than single fixes included that a range of housing conditions jointly influenced health outcomes (Adegebo, 2022), energy efficiency alone was not effective in reducing heat-health impacts (Hu et al., 2022; Taylor et al., 2018), nor was air conditioning alone (Hu et al., 2022), a range of housing conditions were linked to flooding and associated childhood asthma (Larson et al., 2021), and that combining a range of housing retrofits was most effective in reducing heat-health impacts (Taylor et al., 2018). The broader literature around housing and health recognises holistic approaches to housing are generally associated with positive health outcomes (Haverinen-Shaughnessy et al., 2018; Jacobs et al., 2010; Macmillan et al., 2016; Howden-Chapman et al., 2017) and can address the potential unintended consequences of energy efficiency upgrades (Macmillan et al., 2016; Levasseur et al., 2017). In the scoping review, ventilation was the only housing condition associated with improved health outcomes in relation to multiple climate change hazards, namely, indoor heat and indoor environmental quality, and increased home air tightness was conversely associated with adverse health outcomes relating to the same hazards (Gronlund et al., 2018; Bhatta and Pahari, 2021; Taylor et al., 2018; Ehsan et al., 2021; Vardoulakis et al., 2015). The paucity of results demonstrating the potential for improving specific housing conditions to address multiple climate health challenges does not reflect the recognition in the World Health Organisation's guidelines on housing and health that specific housing conditions can have co-benefits for multiple health outcomes (World Health Organization, 2018).

Heat is a widely recognised impact of climate change which can negatively impact health through acute events such as heatwaves, and smaller, long-term temperature increases (Romanello et al., 2022; Uejio et al., 2016; Neira et al., 2023). The health impacts of exposure to heat include acute and chronic kidney injury, sleep problems, heatstroke, adverse outcomes in pregnancy, exacerbation of pre-existing diabetes, cardiovascular disease, respiratory disease, mental health impacts, and increased non-accidental and injury-related mortality (Romanello et al., 2022; Teyton et al., 2022; Neira et al., 2023). However, the chronic disease impacts of heat were largely not considered by the studies included in the scoping review, which instead mainly focused on self-reported, short-term symptoms of heat-related illness (e.g., dehydration, headache, heat rash, dizziness, nausea, and muscle cramps) (Sy et al., 2022; Adegebo, 2022; Teyton et al., 2022; Bhatta and Pahari, 2021; Cardoza et al., 2020; Swain et al., 2019; Wright et al., 2019; Hatvani-Kovacs et al., 2016; Hu et al., 2022; Ehsan et al., 2021) or heat-related mortality (Sy et al., 2022; Hu et al., 2022; López-Bueno et al., 2022b; Klein et al., 2014; Sailor et al., 2021; Taylor et al., 2018; Eisenman et al., 2016; Gronlund et al., 2015). The findings support consideration of the following housing modifications to reduce adverse heat-health impacts: improving ventilation, installing fans, installing window shading (particularly external shutters), and improving roof and wall materials. The broader literature provides some support for these findings (Alidoust and Huang, 2021; Loughnan et al., 2015) but also recognises a lack of evidence around indoor heat and health (Howden-Chapman et al., 2017). The over-representation of air conditioning as a mitigation resource in the literature may partly stem from the high number of studies from the United States, where indoor air conditioning is the norm rather than the exception in most communities (Nazaroff, 2013). This also draws attention to the need for greater geographic representation in the literature. While the scoping review's finding that air conditioning is largely effective in reducing indoor heat and preventing adverse heat-health impacts is consistent with broader literature (Neira et al., 2023; Schmeltz et al., 2015; Kondo et al., 2013), the included articles also recognised the adverse consequences of air conditioning, such as cost, air pollution, waste heat, and greenhouse gas emissions (Romanello et al., 2021, 2022; Gronlund et al., 2018; Chen and Qin, 2022; Kownacki et al., 2019; Vardoulakis et al., 2015; Fisk, 2015). According to Chen and Qin (2022), air conditioners were responsible for 8.5% of global electricity consumption in 2018, and Romanello et al. (2022) found air conditioning was responsible for 24 000 deaths attributable to fine particular matter exposure in 2020. Housing adaptations to reduce heat should therefore consider targeting air conditioning to populations with greater susceptibility to heat-health impacts and combining its use with additional measures to reduce indoor temperatures.

The scoping review's articles focusing on indoor environmental quality issues linked to climate change considered indoor airborne hazards (Larson et al., 2021; Lu et al., 2016; Barnes, 2018; Vardoulakis et al., 2015; Fisk, 2015), which can be produced by indoor sources or infiltrate homes from outdoor sources (Zhang et al., 2021; Nazaroff, 2013). Air pollution is associated with a wide range of health risks, including respiratory infection, cardiovascular and allergic diseases, increased hospitalisations, and all-cause mortality (Zhang et al., 2021; Vardoulakis et al., 2020). Indoor temperature is another aspect of indoor environmental quality and Gronlund et al. (2018) found temperature extremes may increase exposure to indoor airborne hazards if people spend more time indoors. Dampness and mould, which increase the risk of asthma, allergic disease, and respiratory infections (Larson et al., 2021; Howden-Chapman et al., 2023; Vardoulakis et al., 2015), were also highlighted in the scoping review. The combination of climate change impacts, such as heavy rainfall and flooding (Eguiluz-Gracia et al., 2020), and inadequate housing conditions, such as poor ventilation (Vardoulakis et al., 2020), can intensify dampness and mould issues. While there was some support in the findings for sealing gaps in homes to prevent the entry of outdoor pollution (Vardoulakis et al., 2015; Fisk, 2015), there was also recognition that home energy efficiency measures such as air tightening and insulation can worsen indoor environmental quality (Gronlund et al., 2018; Taylor et al., 2018; Kownacki et al., 2019; Vardoulakis et al., 2015). The results support consideration of improving ventilation when undertaking energy efficiency improvements, reducing indoor pollution sources, and using air filtration to maintain healthy indoor air quality (Vardoulakis et al., 2015; Fisk, 2015). Broader literature has considered the effectiveness of different types of air purifiers in removing specific pollutants found in homes (Schraufnagel et al., 2019) and compared particulate matter infiltration in homes which used heating, ventilation, and air conditioning systems to homes without these systems (Liang et al., 2021). Despite the need for integrated approaches to managing indoor air quality in response to changing in outdoor conditions due to climate change (Levasseur et al., 2017), there is a lack of data around the direct impacts of climate change on indoor environmental quality and health (Fisk, 2015), indicating the need for further research to inform housing adaptations in response to climate change impacts on the indoor environment and health.

4.1. Research gaps

Indoor heat in homes is an important area for future climate adaptation research given the rise in temperatures and increasing frequency of heatwaves (McMichael and Lindgren, 2011; Romanello et al., 2022; Uejio et al., 2016; Neira et al., 2023), and the amount of time spent inside homes (McKinnon et al., 2020; Institute of Medicine, 2011; Klepeis et al., 2001; Zhang et al., 2021; Liang et al., 2021). Despite the high proportion of articles in the scoping review which focused on heat, research gaps were evident, including a lack of understanding of the health impacts of indoor heat compared with indoor cold (Howden-Chapman et al., 2023; Kownacki et al., 2019; Riva et al., 2023). Further, there is a lack of empirical research into the relationship between indoor and outdoor heat, meaning current guidelines for heat are based on modelling, in contrast to guidelines for cold (Howden-Chapman et al., 2023). More research is needed into effective housing modifications to minimise heat-health damage, particularly around developing, implementing, and evaluating policy responses (Williams et al., 2019). Qualitative studies would assist with understanding vulnerability, while co-designed intervention studies could help meet the needs of specific communities or population groups. The scoping review revealed a significant research gap concerning housing adaptations to climate change hazards other than heat, such as bushfires, storms, flooding, and airborne hazards. Research into the ways housing conditions can mitigate the health impacts of these hazards could inform targeted policy responses or contribute to more holistic climate adaptation strategies if housing adaptations demonstrate health benefits across multiple hazards. Any future research should seek to understand both the risks and benefits of housing adaptations, and health impact assessment has been suggested as a useful methodology (Vardoulakis et al., 2015).

There are methodological limitations in the studies included in the scoping review, which largely relied on population level health outcomes in ecological studies and self-reported health outcomes in cross-sectional studies. Ecological and cross-sectional designs can suggest associations but are not able to confirm causal relationships between housing conditions, climate change hazards and health outcomes (Lash et al., 2021), which highlights the need for well-designed prospective cohort studies with repeated measurements, including objectively measured health outcomes. In addition, the scoping review results highlight the need for more original studies on outcomes related to chronic diseases, such as asthma, with only one study focusing on asthma in relation to flooding (Larson et al., 2021) and another considering asthma related to heat (Sy et al., 2022). This gap is noteworthy given the extensive research on asthma and housing conditions (Quansah et al., 2012; Richardson et al., 2005), and the large number of climate change impacts that can influence asthma (Fisk, 2015; D'Amato et al., 2014).

4.2. Limitations

As a scoping review, this research did not assess the quality of the included studies. Further, heterogeneity in study designs, variables, and measurements made it difficult to compare or synthesise findings from the included studies. There was a lack of detail around certain variables in some studies, particularly the housing variables. We did not include homelessness and housing precarity because our inclusion criteria focused on housing conditions, however, we note people experiencing homelessness and housing precarity are highly vulnerable to climate health impacts (Bezgrebelna et al., 2021). To scope research from the previous decade, we excluded results published earlier than 2013, meaning some relevant studies may have been missed. The scoping review only included articles in English, which means relevant studies in other languages, including studies from developing countries, are likely to have been left out. Grey literature was not included, meaning government policies around housing conditions that may have mentioned connections to climate change and health may have been left out, but it is likely the impact of this was small, based on the limited number of studies connecting these areas.

5. Conclusion

This scoping review considered an emerging area of research around the contribution of housing conditions to the health impacts of climate change. Despite a lack of experimental studies, the review demonstrates the importance of housing as a climate change adaptation priority. While it is not possible to draw recommendations from the findings of this scoping review as the methodology does not include assessment of the quality of included results, the literature supports consideration of housing improvements in future climate change adaptation policy and interventions. Where appropriate, holistic approaches to housing adaptation should be prioritised over single fixes, such as combining air conditioning with measures to reduce indoor heat such as window shading, and considering cooling, ventilation, and air filtration needs alongside energy efficiency improvements such as air tightening and insulation. The scoping review also revealed research gaps, particularly around climate change hazards other than heat, and the need for future research to prioritise empirical and qualitative research into indoor heat in homes and intervention studies to inform climate adaptation responses.

CRediT authorship contribution statement

Angela Cartwright: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Saman Khalatbari-Soltani:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Ying Zhang:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Angela Cartwright reports a relationship with Asthma Australia Ltd that includes: employment. Angela Cartwright reports a relationship with Climate and Health Alliance that includes: board membership. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2025.120846.

Appendix A
Detailed search strategy

1) Housing conditions
hous*
AND 2) Climate change
"climate change" OR warming OR bushfire* OR wildfire* OR flood* OR "heavy rain*" OR drought* OR heatwave* OR heat OR cold OR "temperature extreme*" OR "extreme* temperature" OR hurricane* OR cyclone* OR thunderstorm*
AND 3) Health outcomes
health* OR wellbeing OR morbidity OR mortality OR hospitali?ation* OR illness OR disease OR emergency OR injury OR death OR accident)

Data availability

All data are available in the main text and Supplementary File.

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