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Climate-related healthy housing risk factors: a scoping review of citizen science approaches

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ABSTRACT

The profound effects of climate change jeopardise the ability of housing to protect human health and wellbeing. Citizen science, with its potential for generating data and engaging individuals and communities in action, is an important addition to the suite of tools needed to prepare our housing for this reality. Our scoping review assessed how citizen science approaches have been used to identify and address climate-related housing risk factors that impact upon health. We searched five electronic databases and conducted forwards and backwards citation searching to identify studies for inclusion. We synthesised data on key study characteristics, as well as their focus, methods, and reported impacts. Fifty-six studies were included. Most studies focused on water quality (53.6 %), followed by toxic substances (35.7 %), air quality (19.6 %), noise (7.1 %), and indoor temperature (1.8 %). Studies utilised quantitative (100 %) and, to a much lesser extent, qualitative data collection methods (8.9 %). Over one-third of studies reported impacts, ranging from benefits to citizen scientists through to influencing government action. Citizen science holds great potential for collecting large amounts of data, incorporating diverse perspectives, generating awareness of issues, and catalysing action to improve housing in the face of climate change. By focusing on a broad set of risk factors and methods, integrating mechanisms to improve data quality, and articulating impacts, citizen science approaches could better meet the needs of research that seeks to involve communities and create change.

1. Introduction

Housing is a key social determinant of health (World Health Organization, 2025). Critically, the ability of housing to protect human health is connected to the climate and environmental conditions of its location, (Rajagopal, 2022) for example, the need for insulated houses in cold climates or raised homes in flood prone areas. Slow-onset and extreme weather events are increasing in intensity and frequency: geographic patterns of temperature and humidity are changing and wildfires and floods are projected to worsen, leading to widespread and catastrophic impacts (IPCC, 2023). These climatic changes have amplified the importance of housing that is affordable, secure, and in good condition to protect human health and reduce health inequalities (Mansour et al., 2022).

Housing that is in poor condition exposes its occupants to a myriad of health risks which are and will continue to be amplified by a changing climate (World Health Organization, 2018). In particular, the increased occurrence and intensity of heat waves, as well as more frequent and persistent cold snaps, give rise to dangerously low and/or high indoor temperatures (Howden-Chapman et al., 2023); heavier rainfall and major flooding events are instigators of mould growth (Coulburn and Miller, 2022); and exposure to toxic substances such as asbestos, lead and radon may be amplified due to remobilisation after climate-related disasters (Crawford et al., 2022). Moreover, hazards that cause significant property damage, such as wildfires and devastating winds, can compel individuals to vacate their homes entirely and occupy housing with limited space in the absence of suitable alternatives, leading to overcrowding (Mason et al., 2021). These and other *climate-related housing risk factors* have implications for health, specifically cardiovascular disease, (Janssen et al., 2023) respiratory illnesses, (Janssen et al., 2023; Caillaud et al., 2018) infectious disease, (Kvalsvig et al.) and poor mental health and wellbeing, (Ruiz-Tagle and Urria, 2022) and combine

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with underlying social and health risks (e.g., age, pre-existing health conditions, healthcare access) and environmental hazards (e.g., fires, storms, temperature extremes) to exacerbate inequalities (Cissé et al., 2022).

Radical social and policy reform is required to transform systems of governance of housing to adapt to and counter the impacts of climate change (Howden-Chapman et al., 2023; McPhearson et al., 2021). Citizens, the ultimate beneficiaries of such reform, play a critical role in mobilising action for change (Friel et al., 2023). The Sendai Framework for Disaster Risk Reduction 2015–2030, for instance, emphasises the role of civil society in promoting and implementing the Framework (UNISDR, 2015). The 2030 Agenda for Sustainable Development goes beyond this by recognising citizens as primary agents in advancing efforts and monitoring progress towards the achievement of the Sustainable Development Goals (SDGs) (UN, 2015). Relatedly, the New Urban Agenda advocates for widening mechanisms that promote meaningful citizen participation to ensure sustainable urban development and accelerate progress towards achieving the SDGs (UN, 2017).

The benefits of citizen participation in scientific research are also increasingly recognised. Indeed, evidence suggests that participatory research approaches that feature the *active* involvement of citizens in the research process are more likely to prompt action (Cook, 2008) and, notably, structural change (Davis and Ramírez-Andreotta, 2021). Citizen science is a participatory research approach that is acknowledged for its potential to yield data that is both timely and expansive, (Fritz et al., 2019) mobilise support for a particular issue, and bridge the gap between evidence generation and its uptake in policy (van Noordwijk et al., 2021). It is characterised by the active involvement of the general public ('citizen scientists') in the research process – this can include defining the research problem, designing study methods, data collection, analysis, and/or interpreting and disseminating findings (English et al., 2018). Originating in the natural sciences, citizen science has been applied across research disciplines – from disaster risk reduction (Hicks et al., 2019) to enhancing agricultural practices (van de Gevel et al., 2020) and strengthening policies concerning health-harming environmental hazards such as air and noise pollution (Froeling et al., 2021). These advantages and its extant applications confer on citizen science the potential to contribute to achieving healthy housing in the face of current and future climatic adversity. Importantly, citizen engagement in research can give voice to those most affected by climate-related issues, increasing the likelihood of evidence-informed strategies and policy responses achieving equitable housing-focussed solutions.

Despite the potential benefits of citizen science as a research approach and catalyst for social change, there is currently no review of citizen science studies that has featured its application to the home or immediate neighbourhood environment. Instead, prior research has narrowly sought to map how citizen science has been applied to examine select environmental exposures, such as air and water pollution, (English et al., 2018; Commodore et al., 2017) and toxic substances (Cori et al., 2022). For this reason, there is a need to better understand the potential of citizen science in this space. To fill this gap, our scoping review synthesises how citizen science approaches have been applied to identify and address climate-related housing risk factors that have consequences for health. Drawing on the WHO Housing and Health Guidelines (HHGL) (World Health Organization, 2018) as our conceptual framework, our review details the current state of citizen science's application to studies examining climate-related housing risk factors that impact upon health. In doing so, it aims to contribute to the evolution of citizen science as a research approach that aids the development of healthy, climate-resilient housing, by generating high quality evidence and actively engaging citizens in achieving structural change.

2. Methods

This review was guided by Arksey and O'Malley's (2005) framework for conducting a scoping review and guidance provided by Levac et al. (2010). It is reported in line with the Preferred Reporting Items for Systematic Reviews and Meta-Analysis Protocols extension for scoping reviews (PRISMA-ScR) (Tricco et al., 2018) (Appendix A) and covered the following steps: (1) identifying the research questions, (2) identifying relevant studies, (3) study selection, (4) charting the data, (5) critical appraisal of studies and (6) collating, summarising, and reporting the results. The review was registered via Open Science Framework prior to execution of the finalised search strategy (protocol URL: https://osf.io/j6n48/?view_only=0c46f3dfae65407181314601dfd8a699).

2.1. Identifying the research question

Three questions guided this review:

(1) *Which climate-related housing risk factors have been the focus of research that incorporates citizen science approaches?*
(2) *What methods have been employed to identify and measure climate-related housing risk factors within studies that incorporate citizen science approaches, and how has data quality been managed?*
(3) *What have been the impacts of studies that incorporate citizen science approaches in addressing climate-related housing risk factors?*

2.2. Identifying relevant studies

A search of the peer-reviewed literature contained within five scientific databases (Scopus (1970–), Web of Science (1900–), Medline (1946–), CAB Direct (1973–), and Embase (1947–)) was executed on 5 May 2023.

The search string combined the breadth of terms related to citizen science (including "citizen sensing", "participatory science", "crowd science", "popular epidemiology"), housing (including "home", "dwelling", "residential") and climate-related housing risk factors detailed in the WHO HHGL (including, "indoor temperature", "potable water", "air quality", "mould", "pollution", "environmental noise") (Appendix B). To enhance the search strategy, forwards and backwards citation searching of all full-text papers included in this review was conducted by one reviewer (AM) and checked by a second reviewer (MRG).

2.3. Study selection

Table 1 summarises the inclusion and exclusion criteria for this review (see Appendix C for a detailed description of approach, setting and objective).

2.3.1. Article screening

The records returned by each database were imported into Covidence for de-duplication and screening (Veritas Health Innovation, 2023). Title and abstract and full-text screening was carried out independently by two reviewers (AM, MRG). Discrepancies were resolved by consulting a third reviewer (SR). Publications that did not meet the inclusion criteria were excluded from the review.

2.4. Charting the data

Data extraction was conducted by one reviewer (AM) and checked by a second reviewer (MRG) (Buscemi et al., 2006). A template was created by AM in Covidence to facilitate the data extraction process (Appendix D). An iterative process was employed whereby the data extraction form was reviewed by the research team, piloted, and updated prior to extraction of data from included studies.

2.5. Critical appraisal of included studies

Recent reviews have highlighted the need for greater appraisal of

Table 1
Inclusion and exclusion criteria.

Inclusion criteria	Exclusion criteria
Document type:	
Peer-reviewed research papers published in English	Editorials, commentaries, reviews, study protocols, dissertations, conference papers and conference proceedings, books, book chapters and book reviews
Approach:	
Research that is consistent with a citizen science approach: the *active* participation of citizen scientists in one or more stages of the research (it needn't explicitly use the term 'citizen science')	Research methods that are not consistent with a citizen science approach (e.g., traditional methods such as large-scale surveys administered by trained researchers)
Citizen scientists (i.e., people who are not trained researchers) may include members of the public, students, grassroots organisations comprised of community representatives	Research involving trained researchers, members of government or private organisations
Setting:	
Projects conducted in the home and/or the immediate environment in which the housing is situated, anywhere in the world	Residential aged care, hostels, other types of non-private dwellings, schools, community settings, workplaces
Objective:	
Studies that investigate climate-related housing risk factors (drawn from those outlined in the WHO HHGL)	Housing conditions that are not climate-related or set out in the WHO HHGL

citizen science activities, their outcomes, and engagement of the public (Marks et al., 2022; Wehn et al., 2021a; Rosas et al., 2022). Our review employed the newly created Citizen Science Appraisal Tool (CSAT), (Wood et al., 2022) which considers "scientific standards, participation, data quality, and dissemination, which are elements of good quality" citizen science (Wood et al., n.d.). Overall quality is assessed via 16 questions across four domains: 1) science and research; 2) leadership and participation; 3) delivery and data; and 4) outcome, evaluation and open data. The final score indicates a study's standing from Low to High quality (see Appendix E for more detail on the CSAT and how it is scored). Studies in this review were evaluated against the CSAT independently by two reviewers (AM, MRG). Discrepancies were resolved through consultation with a third reviewer (SR). Where a study consisted of multiple reports, critical appraisal was performed on the one that was identified as the primary report.

2.6. Collating, summarising, and reporting the results

Reports pertaining to the same study were grouped together for analysis. To address RQ1, a descriptive summary of included studies was undertaken. It includes an assessment of the level of citizen scientist engagement within each study against the four common models of citizen science approaches (Fig. 1), according to the highest level of citizen scientist involvement described. To respond to RQ2 and RQ3, key information was narratively synthesised. 'Data quality' is a multi-faceted concept consisting of several metrics such as timeliness, validity, consistency, accuracy, and bias (Balázs et al., 2021; Kosmala et al., 2016). Therefore, in responding to RQ2, we assessed how the studies managed data quality by considering whether and how they had incorporated any of the five mechanisms to account for inaccuracies and minimise bias that we had identified in the literature (Balázs et al., 2021; Freitag et al., 2016). In responding to RQ3, we synthesised reported impacts – irrespective of whether they were identified through formal or informal processes – as opposed to conducting a separate assessment. These approaches were deemed appropriate to identify and articulate the focus, methods, and impacts of the studies selected for inclusion, given the discrepancies in reporting among them. Synthesis was performed by the lead author (AM) and refined through consultation with the wider research team.

3. Results

Fig. 2 depicts the process of screening and selecting publications for inclusion in this review.

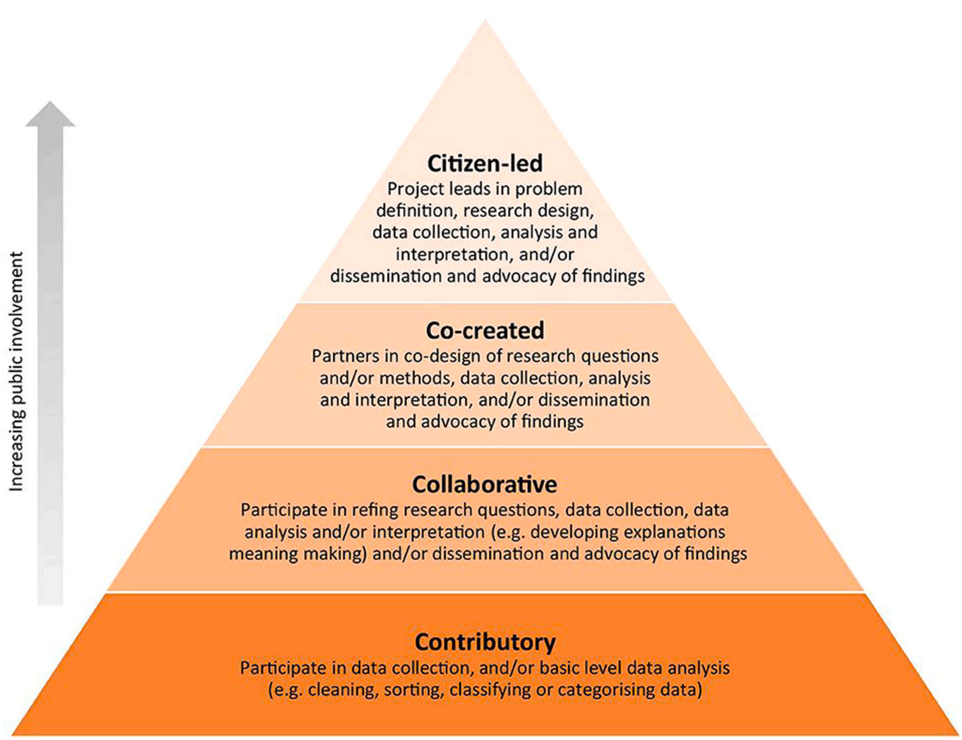

Fig. 1. Four common categorisations of citizen science projects ordered by increasing public involvement. From '*A Scoping Review of Citizen Science Approaches in Chronic Disease Prevention*,' by Marks et al. (2022).

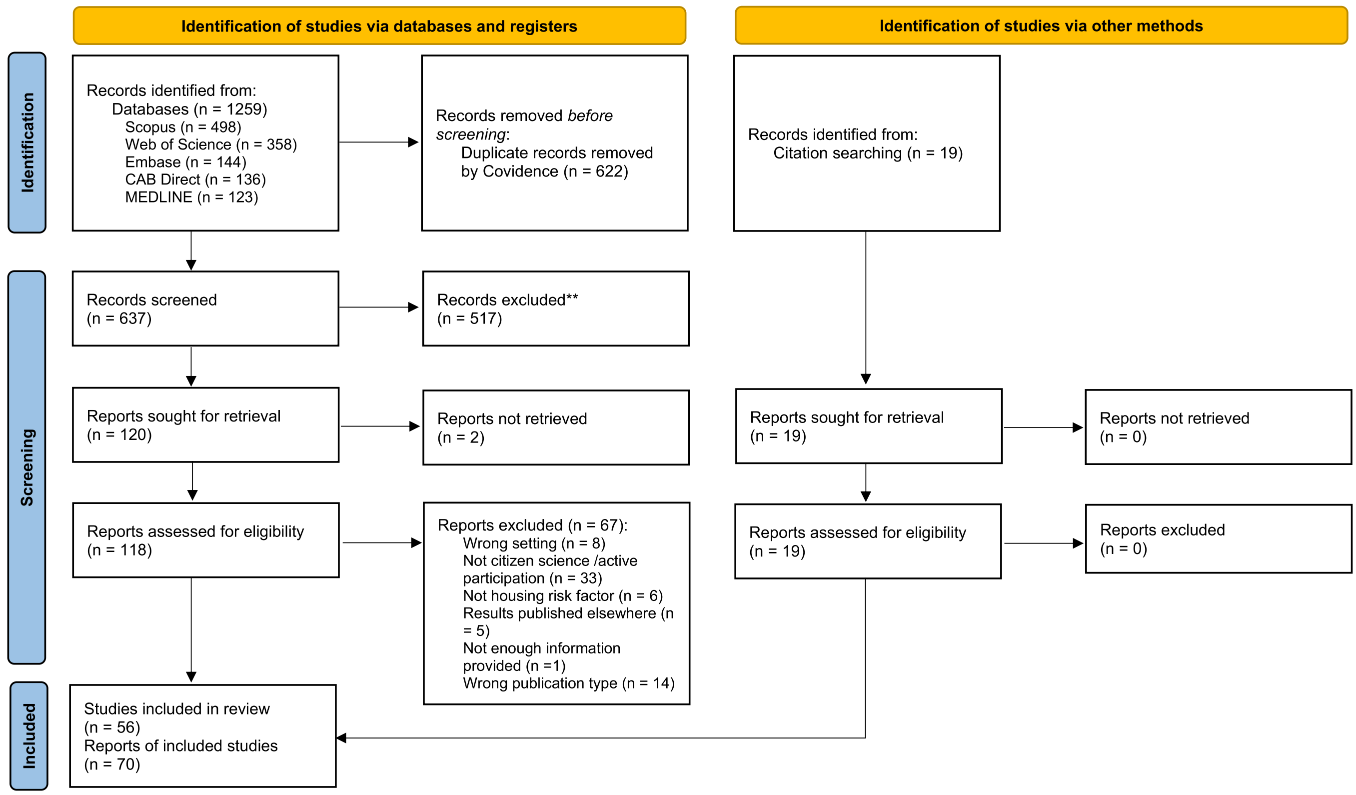

Fig. 2. PRISMA flow diagram. The database search yielded 1259 results. Following removal of duplicates, the titles and abstracts of 637 records were independently screened. Of these, 118 full texts were reviewed and 67 were excluded. After conducting forwards and backwards citation searching of the 51 included records, 19 additional reports were identified. This resulted in 70 reports associated with 56 distinct studies selected for inclusion in this review.

3.1. Overview of included studies

Seventy reports associated with 56 studies were selected for inclusion (see Appendix F for a summary of the key characteristics of each study). The reports were published between 2002 and 2023, with most reports (94.3 %, $n = 66/70$) published in the past 10 years.

The studies predominantly took place in North America (71.4 %, $n = 40/56$), (Odetola et al., 2021; Dietrich et al., 2023a, 2023b; Jakositz et al., 2020; Fawkes et al., 2022; Hoponick Redmon et al., 2022; Sefchick et al., 2021; Eiffert et al., 2016; Hahn et al., 2020; Hauser et al., 2015; Tighe et al., 2020; Filippelli et al., 2018; Masri et al., 2023; Keeler et al., 2002; Heaney et al., 2011; Pieper et al., 2018; Ringwald et al., 2021; Heaney et al., 2013; Stewart et al., 2014; Abe et al., 2016; Chan et al., 2021; Newman et al., 2020; Mandigo et al., 2016; Wilson et al., 2017; Stanifer et al., 2022; Huerta et al., 2023; D'Alessio et al., 2021; Palawat et al., 2023; Quach et al., 2015; Segev et al., 2021; Willett et al., 2021; O'Shea et al., 2021; Hung et al., 2023; Mulhern et al., 2022; Shang et al., 2023; Brickle and Evans-Agnew, 2017; Pieper et al., 2015, 2017; Swistock et al., 2013; Downs et al., 2009) followed by Australia (5.4 %, $n = 3/56$), (Taylor et al., 2021; Rajagopalan et al., 2020; Harvey et al., 2016) Southeast Asia (5.4 %, $n = 3/56$), (Jaleel et al., 2020; Loo et al., 2019; Lee et al., 2020) Europe (5.4 %, $n = 3/56$), (Woutersen et al., 2022; Martin-Sanchez et al., 2021; Rozzi et al., 2022) South America (5.4 %, $n = 3/56$), (Rivas et al., 2020; García and Brown, 2009; Velastegui-Montoya et al., 2023) Southwest Asia (3.6 %, $n = 2/56$), (Tsapalov et al., 2020; Baalbaki et al., 2019) and East Africa (1.8 %, $n = 1/56$) (Corburn et al., 2022). One study had an international focus, spanning over 30 countries (Isley et al., 2022).

The studies analysed a range of climate-related housing risk factors, with the majority concentrated on water quality (53.6 %, $n = 30/56$) (Odetola et al., 2021; Dietrich et al., 2023a; Jakositz et al., 2020; Fawkes et al., 2022; Hoponick Redmon et al., 2022; Sefchick et al., 2021; Heaney et al., 2011; Pieper et al., 2018; Heaney et al., 2013; Abe et al., 2016; Chan et al., 2021; Newman et al., 2020; Huerta et al., 2023; D'Alessio et al., 2021; Palawat et al., 2023; Segev et al., 2021; Willett et al., 2021; Mulhern et al., 2022; Shang et al., 2023; Pieper et al., 2015, 2017; Swistock et al., 2013; Downs et al., 2009; Harvey et al., 2016; Jaleel et al., 2020; Loo et al., 2019; Rivas et al., 2020; García and Brown, 2009; Baalbaki et al., 2019; Corburn et al., 2022). Other housing risk factors examined include toxic substances (35.7 %, $n = 20/56$; namely lead [excluding those concerned with lead in water which have been grouped with water quality] and radon), (Dietrich et al., 2023a, 2023b; Sefchick et al., 2021; Hahn et al., 2020; Tighe et al., 2020; Filippelli et al., 2018; Ringwald et al., 2021; Stewart et al., 2014; Newman et al., 2020; Mandigo et al., 2016; Wilson et al., 2017; Stanifer et al., 2022; Huerta et al., 2023; O'Shea et al., 2021; Hung et al., 2023; Downs et al., 2009; Taylor et al., 2021; Tsapalov et al., 2020; Corburn et al., 2022; Isley et al., 2022) air quality (19.6 %, $n = 11/56$; including mould), (Eiffert et al., 2016; Hauser et al., 2015; Masri et al., 2023; Keeler et al., 2002; Newman et al., 2020; Quach et al., 2015; Brickle and Evans-Agnew, 2017; Downs et al., 2009; Woutersen et al., 2022; Martin-Sanchez et al., 2021; Corburn et al., 2022) noise (7.1 %, $n = 4/56$) (Quach et al., 2015; Lee et al., 2020; Rozzi et al., 2022; Velastegui-Montoya et al., 2023) and indoor temperature (1.8 %, $n = 1/56$) (Rajagopalan et al., 2020). Most studies (87.5 %, $n = 49/56$) focused solely on one of the predefined housing risk factors, while seven (Dietrich et al., 2023a; Sefchick et al., 2021; Newman et al., 2020; Huerta et al., 2023; Quach et al., 2015; Downs et al., 2009; Corburn et al., 2022) aimed to measure several exposures (e.g., water quality, air quality *and* toxic substances). Few studies (17.9 %, $n = 10/56$) (Hoponick Redmon et al., 2022; Chan et al., 2021; Newman et al., 2020; Mandigo et al., 2016; Palawat et al., 2023; Shang et al., 2023; Rajagopalan et al., 2020; Jaleel et al., 2020; Rivas et al., 2020; Corburn et al., 2022) conducted their analysis in the context of, or make explicit mention to, the link to climate change or associated extreme/slow-onset weather events (e.g., exposure to microbial contaminants following damaging flood events).

Across the studies, reporting on the number of citizen scientists engaged in activities, as well as their socio-demographic characteristics, was mixed. Very few studies detailed citizen scientists' gender, level of education, income or other information pertinent to understanding the distribution of those involved. Selected studies did however explicitly engage population groups disproportionately burdened by environmental exposures (e.g., Heaney et al., 2011; Chan et al., 2021; Downs et al., 2009; Corburn et al., 2022). Nonetheless, most studies were undertaken in the general community, often with a group of citizen scientists from a specified geographic area (e.g., residents of a local neighbourhood), while almost one third (32.1 %, $n = 18/56$) (Hoponick Redmon et al., 2022; Sefchick et al., 2021; Eiffert et al., 2016; Hahn et al., 2020; Stewart et al., 2014; Abe et al., 2016; Newman et al., 2020; D'Alessio et al., 2021; O'Shea et al., 2021; Hung et al., 2023; Shang et al., 2023; Downs et al., 2009; Loo et al., 2019; Lee et al., 2020; Rozzi et al., 2022; Rivas et al., 2020; Velastegui-Montoya et al., 2023; Tsapalov et al., 2020) were conducted with students across elementary, secondary, or tertiary education settings and several others engaged young people in their activities. Among studies that had identified the number of citizen scientists involved, the highest recorded number was over 3500 households, (Taylor et al., 2021) while the lowest number was one individual (Pieper et al., 2017).

3.1.1. *Models of citizen scientist engagement*

Studies engaged citizen scientists to varying degrees. The most common model of citizen scientist engagement was contributory (57.1 %, $n = 32/56$), (Odetola et al., 2021; Dietrich et al., 2023a, 2023b; Jakositz et al., 2020; Hoponick Redmon et al., 2022; Sefchick et al., 2021; Hauser et al., 2015; Tighe et al., 2020; Filippelli et al., 2018; Stewart et al., 2014; Mandigo et al., 2016; Stanifer et al., 2022; Huerta et al., 2023; D'Alessio et al., 2021; Segev et al., 2021; Willett et al., 2021; O'Shea et al., 2021; Hung et al., 2023; Mulhern et al., 2022; Shang et al., 2023; Pieper et al., 2015; Swistock et al., 2013; Taylor et al., 2021; Rajagopalan et al., 2020; Harvey et al., 2016; Jaleel et al., 2020; Loo et al., 2019; Martin-Sanchez et al., 2021; Rozzi et al., 2022; Velastegui-Montoya et al., 2023; Tsapalov et al., 2020; Isley et al., 2022) followed by co-created (26.8 %, $n = 15/56$), (Fawkes et al., 2022; Eiffert et al., 2016; Masri et al., 2023; Keeler et al., 2002; Ringwald et al., 2021; Heaney et al., 2013; Chan et al., 2021; Wilson et al., 2017; Palawat et al., 2023; Quach et al., 2015; Pieper et al., 2017; Downs et al., 2009; Woutersen et al., 2022; García and Brown, 2009; Corburn et al., 2022) collaborative (14.3 %, $n = 8/56$), (Hahn et al., 2020; Pieper et al., 2018; Abe et al., 2016; Newman et al., 2020; Brickle and Evans-Agnew, 2017; Lee et al., 2020; Rivas et al., 2020; Baalbaki et al., 2019) and citizen-led (1.8 %, $n = 1/56$) (Heaney et al., 2011). Contributory studies saw citizen scientists participate in data collection activities, such as collecting samples (e.g., dust, soil), conducting measurements (e.g., evaluating noise via a phone application) or administering surveys. Where these studies involved citizen scientists in data analysis, it was primarily to perform basic analyses such as mapping results. Studies that set out to 'crowdsource' information are prevalent among those employing a contributory approach, with participation generally limited to one-off activities performed by a large group (e.g., over 100 citizen scientists). Conversely, co-created and citizen-led studies exhibited clear partnerships between researchers and citizen scientists and featured the latter's active involvement in various stages, ranging from the study's design and implementation to data collection, data analysis, interpretation and/or dissemination of findings. Owing to the degree of citizen scientist engagement in the research process, co-created and citizen-led studies were implemented over long periods of time, often several years. Table 2 provides examples of studies that fall within each model of citizen scientist engagement.

3.1.2. *Critical appraisal of studies*

Three studies (5.4 %) were classified as High, (Hahn et al., 2020; Chan et al., 2021; Baalbaki et al., 2019) 26 studies (46.4 %) were classified as Medium-High, (Dietrich et al., 2023a; Fawkes et al., 2022; Eiffert et al., 2016; Hauser et al., 2015; Filippelli et al., 2018; Masri et al., 2023; Keeler et al., 2002; Pieper et al., 2018; Ringwald et al., 2021; Abe et al., 2016; Stanifer et al., 2022; D'Alessio et al., 2021; Palawat et al., 2023; Quach et al., 2015; Mulhern et al., 2022; Pieper et al., 2015, 2017; Swistock et al., 2013; Downs et al., 2009; Taylor et al., 2021; Loo et al., 2019; Woutersen et al., 2022; Rozzi et al., 2022; García and Brown, 2009; Corburn et al., 2022; Isley et al., 2022) 26 studies (46.4 %) were classified as Medium, (Odetola et al., 2021; Jakositz et al., 2020; Hoponick Redmon et al., 2022; Sefchick et al., 2021; Tighe et al., 2020; Dietrich et al., 2023b; Heaney et al., 2011, 2013; Stewart et al., 2014; Newman et al., 2020; Mandigo et al., 2016; Wilson et al., 2017; Huerta et al., 2023; Segev et al., 2021; Willett et al., 2021; O'Shea et al., 2021; Hung et al., 2023; Shang et al., 2023; Brickle and Evans-Agnew, 2017; Rajagopalan et al., 2020; Harvey et al., 2016; Jaleel et al., 2020; Lee et al., 2020; Martin-Sanchez et al., 2021; Velastegui-Montoya et al., 2023; Tsapalov et al., 2020) and one study (1.8 %) was classified as Low-Medium (Rivas et al., 2020). Appendix G provides an overview of the CSAT outcome of each study and Appendix H provides examples of studies that fall within each CSAT category. For the most part, studies categorised as High/Medium-High ranked favourably across the first three domains of the CSAT (i.e., science and research, leadership and participation, delivery, and data). These studies featured delineated and transparent roles and responsibilities (e.g., agreements in place) between community stakeholders and researchers and considered data limitations and biases inherent to citizen science approaches (e.g., measurement error, sampling bias), some of which were accounted for in the projects' methodology (e.g., validation of data). However, the

Table 2
Examples of studies that fall within each model of citizen scientist engagement.

Contributory model
In their study, Rajagopalan et al. (2020) used citizen science data, consisting of outdoor environment measurements, to predict indoor temperature and thermal comfort conditions. Two hundred and ninety citizen scientists conducted outdoor microclimatic measurements (e.g., air temperature, relative humidity, wind speed) using portable handheld devices in local government areas across Australia. Citizen scientists recorded the data, along with metadata, on pre-designed data collection sheets.
Collaborative model
Hahn et al. (2020) sought to explore the feasibility of using citizen science to raise awareness of home radon testing, and to test the agreement between indoor and outdoor radon measurements in two U.S. states. Twenty-seven student citizen scientists recruited households who were interested in testing their home for radon and supported homeowners to deploy their radon detectors. With the support of the research team, student citizen scientists were also involved in interpreting the radon values upon laboratory analysis and reporting back the results to homeowners.
Co-created model
García and Brown (2009) investigated the availability and quality of water in a rural Andean watershed. Thirty citizen scientists aged nine to 17 years old were involved as co-researchers, contributing to the design of study methods (e.g., survey), field monitoring, sample collection, and laboratory analysis. Citizen scientists were also involved in disseminating the findings: citizen scientsits co-led community workshops, presenting the results of the study and discussing solutions with community members.
Citizen-led model
Heaney et al. (2011) describe a citizen-led study, which sought to assess the safety and adequacy of water and sewer services in the U.S. through a household survey and water sampling. The research was community-owned and managed. Community stakeholders initiated and led most aspects of the research – from problem definition (initiating the community-academic partnership) and research design (developing a survey tool prior to their work with researchers), to participant recruitment and data collection (collecting drinking and surface water samples).

results of the outcomes, evaluation and open data domain were mixed. This was particularly so for studies classified as Medium-High, which often did not document their 'ripple effects', assess citizen scientists' knowledge, attitudes, and behaviours, invite citizen scientists' participation in the publication process, or facilitate their critical evaluation of the study.

3.2. Methods for examining climate-related housing risk factors

Studies employed a range of data collection methods to measure climate-related housing risk factors, with quantitative approaches (100 %, $n = 56/56$) being much more common than qualitative approaches (8.9 %, $n = 5/56$) (Wilson et al., 2017; Quach et al., 2015; Brickle and Evans-Agnew, 2017; Downs et al., 2009; Corburn et al., 2022). The following section provides a summary of the data collection methods utilised for each housing risk factor of focus. Many studies measured housing risk factors as part of a suite of study components (e.g., as seen in the First Nations Food, Nutrition and Environment Study) (Chan et al., 2021). Therefore, what follows is a description of citizen science methods used to generate evidence of relevance to the climate-related housing risk factors that are the focus of this review.

3.2.1. Water quality

Among the 30 studies investigating water quality (e.g., presence of metals, per- and polyfluoroalkyl substances, coliforms), (Odetola et al., 2021; Dietrich et al., 2023a; Jakositz et al., 2020; Fawkes et al., 2022; Hoponick Redmon et al., 2022; Sefchick et al., 2021; Heaney et al., 2011; Pieper et al., 2018; Heaney et al., 2013; Abe et al., 2016; Chan et al., 2021; Newman et al., 2020; Huerta et al., 2023; D'Alessio et al., 2021; Palawat et al., 2023; Segev et al., 2021; Willett et al., 2021; Mulhern et al., 2022; Shang et al., 2023; Pieper et al., 2015, 2017; Swistock et al., 2013; Downs et al., 2009; Harvey et al., 2016; Jaleel et al., 2020; Loo et al., 2019; Rivas et al., 2020; García and Brown, 2009; Baalbaki et al., 2019; Corburn et al., 2022) a common technique involved the collection of 'first draw' and/or 'flushed' residential tap water samples for testing. Testing was either performed *in situ* by citizen scientists themselves, subsequently by the research team, or both. The CrowdWaterSens study, for example, saw citizen scientists test their own water samples by submerging the provided test strip in a tap water sample before comparing it with a colorimetric chart, followed by submission of samples to the lab for *post-hoc* testing to validate (Shang et al., 2023). Conversely, water samples collected by citizen scientists via the Virginia Household Water Quality Program were simply provided to the research team for processing and analysis in a laboratory (Pieper et al., 2015). Engaging citizen scientists to administer a survey tool to assess water quality, either as the sole method of data collection or in tandem with water sampling to augment the information collected, was observed to a lesser extent. Heaney et al. (2011), for instance, describe a process whereby citizen scientists distributed "drinking water and sewer surveys" and collected household water samples, while Jaleel et al. (2020) relied solely on the use of a questionnaire, administered with the assistance of citizen scientists, to understand groundwater quality.

3.2.2. Air quality

The 11 studies concerning air quality engaged citizen scientists in documenting, sampling and/or measuring selected pollutants, such as particulate matter (PM) and nitrogen dioxide (NO_2), and mould (Eiffert et al., 2016; Hauser et al., 2015; Masri et al., 2023; Keeler et al., 2002; Newman et al., 2020; Quach et al., 2015; Brickle and Evans-Agnew, 2017; Downs et al., 2009; Woutersen et al., 2022; Martin-Sanchez et al., 2021; Corburn et al., 2022). Studies varied as to whether they focused on indoor exposure, outdoor exposure, or both.

Devices such as sensors and sampling pumps/tubes were among the tools used to measure pollutants (e.g., $PM_{2.5}$, PM_{10}, NO2, ozone). Citizen scientists hosted devices in their homes or neighbourhoods and assisted with their deployment and retrieval during sampling windows. One study combined the use of an air sampling device with qualitative methods, employing Photovoice to document woodsmoke along with a guided analysis of the citizen scientists' own photographs (Brickle and Evans-Agnew, 2017). Another study by Corburn et al. (2022) gathered observations of air pollution journalled by citizen scientists.

The three studies that assessed mould exposure employed mixed methods, (Eiffert et al., 2016; Downs et al., 2009; Martin-Sanchez et al., 2021) whereby citizen scientists were engaged to perform sampling, administer a survey, conduct a visual inspection, or implement a combination of these methods. Eiffert et al. (2016) describe citizen scientists administering a questionnaire, conducting a home inspection, and collecting an indoor dust sample at selected residences. In comparison, Martin-Sanchez et al. (2021) only required citizen scientists to collect and submit dust samples from predefined locations around their homes.

3.2.3. Toxic substances

Among the 20 studies that documented toxic substances of interest, 17 were focussed on lead and four were concerned with radon (Dietrich et al., 2023a, 2023b; Sefchick et al., 2021; Hahn et al., 2020; Tighe et al., 2020; Filippelli et al., 2018; Ringwald et al., 2021; Stewart et al., 2014; Newman et al., 2020; Mandigo et al., 2016; Wilson et al., 2017; Stanifer et al., 2022; Huerta et al., 2023; O'Shea et al., 2021; Hung et al., 2023; Downs et al., 2009; Taylor et al., 2021; Tsapalov et al., 2020; Corburn et al., 2022; Isley et al., 2022). The studies concerning lead (excluding those related to water quality) describe citizen scientists gathering environmental media (e.g., soil, dust, paint) samples from various locations in and around the home that were then supplied to the research team for *ex situ* analysis (Dietrich et al., 2023a, 2023b; Sefchick et al., 2021; Tighe et al., 2020; Filippelli et al., 2018; Ringwald et al., 2021; Stewart et al., 2014; Newman et al., 2020; Mandigo et al., 2016; Wilson et al., 2017; Huerta et al., 2023; O'Shea et al., 2021; Hung et al., 2023; Downs et al., 2009; Taylor et al., 2021; Corburn et al., 2022; Isley et al., 2022). DustSafe (also known as '360 Dust Analysis'), for example, asked citizen scientists to dispense the contents of their vacuum cleaner into a sealable bag that is posted to a collection site (Isley et al., 2022). Similarly, the studies concerned with radon, (Hahn et al., 2020; Stanifer et al., 2022; Downs et al., 2009; Tsapalov et al., 2020) with the exception of one, only involved citizen scientists in sampling, by deploying and retrieving a radon detector (e.g., charcoal-based test kits) for analysis in a laboratory. In contrast, Stanifer et al. (2022) engaged citizen scientists to consistently report their own radon values via a daily SMS survey.

3.2.4. Noise

Of the four studies that focused on measuring exposure to noise, three did so via the use of smartphone applications (e.g., OpenNoise, Decibel X) (Lee et al., 2020; Rozzi et al., 2022; Velastegui-Montoya et al., 2023) while one study evaluated the impact of noise through an audit tool (Quach et al., 2015). Among those that relied on the use of an application, two studies required citizen scientists to record their collected data via a form (e.g., ArcGIS Survey123) separate to the application, in addition to other observations, such as their subjective acoustic comfort level and the predominant emitting source of noise (Rozzi et al., 2022; Velastegui-Montoya et al., 2023). The audit tool described by Quach et al., (Quach et al., 2015) conversely, required citizen scientists to complete a survey documenting activities that signify the presence of environmental noise (e.g., construction), and also report on perceived noise and the types of noise observed (e.g., transportation). Three of the four studies evaluated noise exposure in the residential environment; (Quach et al., 2015; Lee et al., 2020; Velastegui-Montoya et al., 2023) that is, they collected data on noise external to the home, of which two produced noise maps (Lee et al., 2020; Velastegui-Montoya et al., 2023). Only one study measured exposure to environmental noise from inside the home (Rozzi et al., 2022).

3.2.5. Indoor temperature

The sole study focused on indoor temperature engaged citizen scientists to perform outdoor measurements of local weather conditions (including air temperature, humidity, wind speed) using several different portable handheld devices (Rajagopalan et al., 2020). These data were subsequently used by researchers in analyses to simulate indoor temperature and thermal discomfort inside the home. This approach differs from all other housing risk factors, which saw citizen scientists directly sample or measure the exposure in question. Citizen scientists recorded the data, as well as associated metadata, on provided collection sheets.

3.3. Mechanisms to manage data quality

All studies, except for one, (Rivas et al., 2020) incorporated mechanisms in their study design to reduce or ameliorate inaccurate or biased data. Nonetheless, there was considerable variation among studies regarding the extent to which they incorporated certain mechanisms.

3.3.1. Iterative project design

Iterative development of methods, through piloting and refinement, ensures data collection can be performed without confusion or error, reducing mismeasurement (Bonney et al., 2009). Studies included in this review seldom reported an iterative approach in their study design. Of those that did, studies piloted methods prior to an official commencement. Rozzi et al., (Rozzi et al., 2022) for instance, first engaged a dozen schools to conduct noise measurements, enabling the authors to “fine tune” their protocols prior to the project’s national launch. Another study piloted measurements with citizen scientists and revised their data collection sheet in advance of citizen scientists conducting and recording microclimatic measurements (Rajagopalan et al., 2020).

3.3.2. Citizen scientist training

Well trained citizen scientists have been shown to produce data comparable to that of trained researchers, minimising measurement error (Kosmala et al., 2016). In their study, Baalbaki et al. (2019) found close agreement across results produced by trained citizen scientists and researchers for several of the physical and chemical water quality parameters that were tested. Studies invested in training for their citizen scientists, whether online or in person, ranging from brief tutorials lasting 10 min through to participation in several workshops. Fawkes et al. (2022), for example, describe an extensive training program whereby citizen scientists “received specialized training via Zoom… and participated in several in-person training days” in addition to just-in-time training prior to going into the field. In contrast, Stanifer et al. (2022) required citizen scientists to attend a 2-h online training session before proceeding with the study’s activities. Other studies arranged for citizen scientists to undertake standardised, third-party training programs (e.g., Human Subjects Training, Hazardous Waste Operations and Emergency Response Standard Training) (Eiffert et al., 2016; Wilson et al., 2017) prior to their participation.

3.3.3. Standardised methods and tools

Standardised methods (e.g., location, time, duration) and data collection tools (e.g., sampling vials, calibrated instruments) support the generation of consistent, unbiased information (Kosmala et al., 2016). A vast array of standardised methods and tools were observed, and collection protocols varied in complexity. The sampling of environmental media, in some instances, required citizen scientists to merely obtain a sample from a specified location. Other studies were more prescriptive, requiring citizen scientists to utilise a pre-supplied testing kit and adhere to protocols regarding quantity, timing, location, depth, and labelling, depending upon the exposure in question.

The requirement for data collection to occur within a certain timeframe was also observed among studies relating to noise and air quality exposures. Velastegui-Montoya et al. (2023) and Quach et al. (2015) – who engaged citizen scientists to conduct noise measurements and streets audits, respectively – both specified the day and/or time of day for data collection to generate comparable information.

Standardising methods included calibrating project tools. Studies concerned with conducting microclimatic, air quality, and noise measurements described calibrating their data collection devices to guarantee the accuracy and reliability of the results generated. Lee et al. (2020) outlined how citizen scientists were actively involved in this process: students were required to calibrate their smartphones via the NoiseExplorer application prior to conducting noise measurements.

3.3.4. Validation and/or verification

Validation and verification (e.g., through researchers collecting and confirming observations, recording metadata) of citizen science data are crucial for ensuring that data are accurate (Baker et al., 2021). A range of techniques to validate and/or verify the citizen scientist data were observed across studies, such as requiring citizen scientists to collect metadata (e.g., location, timing, contextual factors) alongside samples (e.g., water, dust) or measurements (e.g., noise, climatic parameters). Beyond aiding the interpretation of the information generated, the use of metadata was leveraged to identify inconsistencies, errors, and duplicate samples or measurements.

Other means of validating and verifying the data involved researchers or trained ‘experts’ collecting repeat samples or observations (in addition to citizen scientists), citizen scientists submitting an image of their test results, or *post hoc* analysis of the collected sample (to verify citizen scientists’ own interpretation), replicate measurements (e.g., duplicates, triplicates) and, owing to the large amount of projects focused on the collection of environmental media, using field blanks (i.e., clean sampling media) among other quality assurance and quality control measures. Both Woutersen et al. (2022) and Hauser et al. (2015), for example, describe the collection of duplicate air quality measurements to examine uncertainty and ensure precision. In another study, trained staff conducted repeat audits to gauge repeatability of the audit tool utilised as a method of quality assurance (Quach et al., 2015).

3.3.5. Accounting for inaccuracies and bias in analyses

Like all research, citizen science data may contain errors or bias, and techniques exist to minimise these in the analysis phase, whether that be simply via data cleaning or by utilising sophisticated statistical modelling tools (Bonney et al., 2009). Measures to reduce errors included removing erroneous entries, inconsistent records, and outliers from the dataset prior to conducting further analyses. For example, when describing their approach to analysing trace metal concentrations obtained as part of the VegeSafe program, the authors discarded measurements due “to address match error[*s*], superfluous data entry, or having no trace metal data recorded for the sample” (Taylor et al., 2021).

Stratified analyses were among the methods used to overcome potentially biased results. Swistock et al. (2013), for example, analysed the well water samples of experienced volunteers separately from those of other homeowners due to likely differences in their well management practices, while Masri et al. (2023) performed separate analyses of particulate matter for weekday and weekend measurements based on anticipated variation in firework activity. Advanced methods for handling potential uncertainty (e.g., stemming from variability in adherence to sampling protocols) were also observed. In their study, Stewart et al. (2014) integrated ‘fuzzy sets’ in their model to account for the degree of uncertainty associated with the data collection process – specifically, the potential inconsistencies in soil sampling (i.e., in terms of depth, location) among student citizen scientists due to limited oversight over whether protocols were correctly followed.

3.4. The impact of studies that use citizen science approaches

One third of studies (33.9 %, $n = 19/56$) reported impacts associated with addressing climate-related housing risk factors, ranging from providing benefits to citizen scientists through to influencing government actions.

Studies reporting impacts on citizen scientists (25.0 %, $n = 14/56$) (Odetola et al., 2021; Jakositz et al., 2020; Hahn et al., 2020; Abe et al., 2016; Stanifer et al., 2022; D'Alessio et al., 2021; Mulhern et al., 2022; Brickle and Evans-Agnew, 2017; Swistock et al., 2013; Taylor et al., 2021; Rajagopalan et al., 2020; Loo et al., 2019; Corburn et al., 2022; Isley et al., 2022) demonstrated an increase in awareness and understanding of climate-related housing risk factors, and the perceived or actual ability to take action to reduce harmful exposure (e.g., by contacting a remediation specialist). For some studies, examining this was an explicit objective of their research (e.g., Stanifer et al., 2022). Changes in citizen scientists' knowledge, attitudes, and practices (KAP), or similar, was commonly ascertained via a pre-/post- or post-participation questionnaire (Jakositz et al., 2020; Hahn et al., 2020; Stanifer et al., 2022; D'Alessio et al., 2021; Mulhern et al., 2022; Brickle and Evans-Agnew, 2017; Taylor et al., 2021; Isley et al., 2022). In one study of home radon testing, citizen scientists were surveyed at baseline, post testing, and five months after the conclusion of activities, revealing greater confidence in testing their homes for radon and contacting a mitigation professional after participating in the study's activities (Stanifer et al., 2022). The VegeSafe project, which assessed citizen scientists' motivation, impact, and engagement via a short questionnaire, similarly demonstrated that participation improved citizen scientists' understanding of trace metals, with over 40 % of citizen scientists surveyed implementing strategies to reduce exposure (e.g., removing lead paint) (Taylor et al., 2021). A single study of air quality combined questionnaires with researcher observations (Brickle and Evans-Agnew, 2017). All other studies reporting the impact of their citizen science activities in moves to address climate-related housing risk factors (e.g., taking action to reduce exposure in the home) did so via informal feedback mechanisms, such as community forums, (Loo et al., 2019) or omitted the ways in which this information was ascertained from their reporting (Odetola et al., 2021; Abe et al., 2016; Swistock et al., 2013; Rajagopalan et al., 2020; Corburn et al., 2022). Loo et al. (2019), for example, received feedback during a community follow-up meeting, from which the authors indicate that their study had a direct and immediate impact, changing citizen scientists' perceptions of their water supply. Another study reported that their use of a citizen science approach had empowered residents to contact local officials about their water quality, without indicating the manner through which this impact was established (Odetola et al., 2021).

Less than one fifth of studies (14.3 %, $n = 8/56$) (Heaney et al., 2011; Pieper et al., 2017; Downs et al., 2009; Taylor et al., 2021; Loo et al., 2019; García and Brown, 2009; Baalbaki et al., 2019; Corburn et al., 2022) reported the impacts that they had on a broader scale and no studies evaluated impact through a formal assessment. Typically, the outcomes of studies were observed at the local/municipal level (e.g., service improvements and upgrades to community water infrastructure), (Heaney et al., 2011; Downs et al., 2009; Loo et al., 2019; García and Brown, 2009; Baalbaki et al., 2019; Corburn et al., 2022) while one reported influence across jurisdictions, (Taylor et al., 2021) and another prompted significant changes at the local- through to national-levels (Pieper et al., 2017). When considering these effects, in most cases it was possible to discern that they had materialised as a result of using a citizen science approach. The impacts that ensued from the study by Pieper et al. (2017), for example, clearly relate to the citizen science activities undertaken during the Flint MI Water Crisis (FWC). Made possible through the community-academic collaboration that uncovered the city-wide problem of lead in water, findings initiated a whole-of-system water sampling effort that led to local, state, and federal emergency declarations by health officials (Pieper et al., 2017). Such outcomes were achieved with the active involvement of a citizen scientist ('Resident Zero') in an intensive water quality monitoring campaign. Similarly, albeit on a different scale, the use of a citizen science approach in Corburn et al. (2022) study was pivotal in achieving impact, including the implementation of a village sanitation project that serves 3000 households, among other upgrade proposals implemented by Nairobi's Metropolitan Service. The authors describe citizen scientists using their data to propose community upgrades and working alongside stakeholders (e.g., engineers) to achieve these outcomes.

4. Discussion

Our review sought to understand how citizen science has been used to identify and address climate-related housing risk factors that impact health. We found that water quality has been the principle focus of citizen science studies in this space; however, the approach also extends to examining several other risk factors that feature less prominently in the peer-reviewed citizen science literature (e.g., noise, temperature). Studies were predominantly conducted in the global north and, while several explicitly engaged population groups who are disproportionately burdened by environmental exposures or other disadvantages, many studies involved the general community and presented limited socio-demographic information on citizen scientists. This is a critical issue to consider from the perspective of equity and environmental justice; while citizen science has the potential to address equity issues by giving voice to disadvantaged communities, equitable engagement is critical to the realisation of the potential benefits of citizen science and ensuring that any benefits arising from these approaches do not inadvertently amplify pre-existing inequities (Rowbotham et al., 2019). Moreover, studies mostly featured a contributory level of citizen scientist engagement, with the majority achieving a quality rating between Medium and High. Studies consistently scored lowest across the outcome, evaluation and open data domains of the CSAT. Few tracked citizen KAP or their long-term impacts, and critical evaluation of study methods and limitations by citizen scientists was seldom discussed. This aligns with research that finds evaluation in citizen science remains limited (Davis et al., 2022); however, it is important to recognise that, while these details were not apparent in the included studies, this information may have been documented elsewhere. Regardless, employing tools, such as the CSAT, when designing, executing and reporting on citizen science studies is one way to enhance their quality and minimise discrepancies.

In addressing RQ1, we surmise that the considerable focus on water quality in this review may be attributed to the fact that it is a major societal challenge: global water resources are increasingly affected by worsening pollution (e.g., untreated wastewater), newly emerging contaminants (e.g., industrial chemicals) and changing climate patterns (e.g., droughts, flooding) (Schwarzenbach et al., 2010). Accelerated urbanisation and population growth further exacerbate the issue. Additionally, exposure to heavy metals such as lead via the consumption of contaminated drinking water remains a significant issue in the U.S. (e.g., FWC 2014–16, which is the focus of two studies included in this review) and across countries in Europe, Oceania, and Asia (Pieper et al., 2015; Harvey et al., 2016; Hayes and Skubala, 2009; Lee et al., 2016). Climate change may worsen this issue, with the predicted frequency and intensity of heat increasing water lead levels and, at the same time, warmer temperatures increasing water consumption (Levin et al., 2023). Water quality and citizen science garnered considerable attention during the FWC, which may have prompted further attention on the utility of citizen science and greater efforts to address water quality issues. The low cost and relative ease by which water and other environmental media (e.g., paint, soil, dust) samples can be collected lends itself to citizen science approaches and thus could also explain the focus on water quality and toxic substances among studies included in this review. This is in comparison to studies concerned with air quality, noise and indoor temperature which often entail training citizen scientists to use specialised devices.

In contrast to water quality, a single study focused on indoor temperature. While additional indoor temperature studies that state they adopt a citizen science approach exist, (Just et al., 2019; Sansom et al., 2023) they did not meet our criteria of *active* participation of citizen scientists in data collection or analysis at a minimum. Even accounting for these studies, there remain relatively few indoor temperature studies. Considering the IPCC Sixth Assessment Report, which describes the unequivocal temperature extremes society will face, (IPCC, 2023) there exists a critical gap in the literature. Additional indoor temperature studies that incorporate citizen science approaches may help to spur policy solutions, such as provision of energy efficient housing stock in the residential sector, by mobilising communities to demand change.

Turning to RQ2, this review identified a breadth of methods that are being used to assess climate-related housing risk factors, and mechanisms to manage the quality of data produced. A variety of data collection techniques were observed, ranging from gathering environmental media samples and the use of sensors and sampling pumps/tubes to conduct measurements, to the use of surveys, visual inspections, audit tools, and smartphone applications to collect pertinent information. Most studies solely employed quantitative methods of data collection, with few studies combining them with qualitative methods. While the adoption of qualitative research in related fields (e.g., environmental epidemiology) is increasing, it remains for the most part uncommon (Noël et al., 2021). The limited application of qualitative methods might be explained by research in the environmental health field, and its traditional reliance on quantitative methods and strong emphasis on accurately measuring environmental exposures to maintain validity and enhance generalisability. Yet, qualitative methods are particularly valuable for developing a nuanced understanding of *how* communities experience and act on an issue and ultimately give a voice to those impacted (Brown, 2003). For example, Photovoice, a method in which participants capture photographs and reflect upon the factors that influenced their chosen image, (Sutton-Brown, 2014) was among the qualitative methods employed by studies included in our review. Photovoice approaches are increasingly being used as part of citizen science projects and offer considerable potential in terms of providing rich contextual insights, enhanced community engagement, and eliciting a more holistic understanding of issues under investigation (Kangsen, 2010).

Regarding the quality of citizen science data, the proliferation of citizen science across research disciplines is impeded by scepticism concerning its ability to produce credible, high-quality data (Fritz et al., 2019). Although not unique to this approach, overcoming data quality issues in citizen science presents distinct challenges given the variability of projects, in terms of resourcing, purpose, and intended use, among other factors (Balázs et al., 2021). The absence of a guiding framework makes addressing this matter all the more difficult (Balázs et al., 2021). Applied across difference phases of the project (i.e., planning/design, data collection, data analysis/evaluation), some commonly accepted mechanisms include piloting procedures, training citizen scientists, standardising protocols and tools, conducting peer or expert verification, and performing statistical analyses (e.g., linked data analysis) (Balázs et al., 2021; Freitag et al., 2016). In this review we assessed how studies had incorporated commonly accepted mechanisms for minimising inaccurate or biased information (bearing in mind that this is not an exhaustive list of all possible mechanisms, but rather those which are frequently discussed in the extant literature) and found that the use of these mechanisms was mixed. Iterative project design, through piloting and refining methods was, unexpectedly, the least observed mechanism.

Pilot testing and refining protocols are a crucial component of any study. Scholars advocate for pilot-testing protocols with a variety of citizen scientist groups and across settings to ensure that they can be accurately followed with ease (Kosmala et al., 2016; Bonney et al., 2009). It is possible that other studies in our review did feature this mechanism, however, given discrepancies in reporting, these details may have been omitted from the publication. By contrast, the most widely adopted mechanism was the incorporation of standardised methods and data collection tools. Most studies were focused either on water quality or toxic substances, which likely explains this observation. Regardless, it is important to note that citizen science requires team capabilities, skills, and resourcing (Laird et al., 2023). This is noted by one study in our review when reflecting on their use of sensors which, despite being a low-cost method, can become costly due to needing expertise to perform data validation and calibration (Woutersen et al., 2022). Therefore, the decision to make use of uniform and/or calibrated equipment may be tied to available funding and the technical skills within the team. More broadly, the decision to implement certain mechanisms over others is typically driven by the scale of the project and the resourcing available (Wiggins et al., 2011). Though, irrespective of the mechanisms employed, resourcing, or scale, there is a need for projects that incorporate citizen science approaches to place greater emphasis on documenting and sharing their insights (regarding data quality) to enable the reuse of data and continual advancements in the field (Balázs et al., 2021; Wiggins et al., 2011).

Finally, to address RQ3 we synthesised the reported impacts of studies that incorporated citizen science approaches in moves to address climate-related housing risk factors. Just under two thirds of all studies included in our review did not report any impacts. Several studies were ongoing at the time of publication which might partly explain this. Other possible explanations include a lack of resources and skills required to capture the impacts of the study, as well as the time lag between the conclusion of the study and impacts materialising (especially when measuring policy impact) (Wehn et al., 2021b). Nonetheless, a tangible effect was reported by over one third of studies, with most focused on the outcomes of their activities for the citizen scientists' KAP. Through this, several studies demonstrated the benefits of citizen science for addressing climate-related housing risk factors at the household level: because of their participation citizen scientists had taken steps to reduce their exposure to certain contaminants (e.g., by making minor home modifications). This dovetails with other research that finds participation in citizen science activities can enhance individuals' knowledge and lead them to take action (King et al., 2016; Peter et al., 2019).

Housing reform requires action at the institutional level (Howden-Chapman et al., 2023); therefore, of particular interest are studies reporting the impact of their activities on housing systems (e.g., at the local-, city- or federal-levels). However, studies included in this review seldom demonstrated their influence on policy. While the method and degree to which citizen science is integrated into policy-making processes varies across geographies, (Haklay, 2015) the capacity for citizen science to inform policy is apparent. A recent analysis of policy documents revealed the relevance of citizen science for local issues, such as natural resource management and biodiversity strategies, through to global issues, such as climate change and food security (Hecker et al., 2019). It has been used, for example, to track changes in insect biomass which triggered the adoption of a federal German Insect Protection Law (von Gönner et al., 2023). While its potential to transform policy is certainly promising, evidence suggests the use of citizen science data by decision-makers remains relatively scant. To overcome this issue, some advocate for engaging with decision-makers and ensuring relevance to policy early on in the project in order to achieve genuine influence (von Gönner et al., 2023). An example of this is observed in the CurieuzeNeuzen citizen science project, where the project team engaged in dialogue with relevant governmental divisions to garner support for their air quality monitoring project (Van Brussel and Huyse, 2019). This resulted in political buy-in, including officials actively participating in the project, and informed subsequent policy discussions concerning air quality in Antwerp, Belgium (Van Brussel and Huyse, 2019).

4.1. Limitations

First, restricting our search to the peer-reviewed literature may have biased the selection of papers included. Citizen science is not solely documented in the peer-reviewed literature. Many projects are reported on in the grey literature (e.g., websites, forums), as noted by Kullenberg and Kasperowski (2016) who found that out of 490 citizen science projects reviewed, only 16 % had a scientific output/publication. Therefore, our review findings are generalisable only to studies that aim to contribute to scientific knowledge through publication in academic journals. Second, restricting our inclusion criteria to studies that demonstrated clear active involvement of citizen scientists in the research has possibly skewed the overall results of the critical appraisal (CSAT) towards higher quality studies. This meant that most studies met the criteria for questions two (*Is it clear that the study used a citizen science approach?*) and three (*Is the degree of active engagement or participation of citizens identified clearly by the study?*) of the CSAT and received full points. However, this criterion was necessary for locating studies that clearly transcend traditional research approaches. Third, while we can draw parallels between the involvement of citizen scientists and broader scale impacts materialising in these studies, it is pertinent to note that no study reported undertaking a formal impact evaluation and conducting a separate assessment was outside the scope of this review. This underscores the need to focus greater efforts on thoroughly evaluating citizen science projects in this field.

5. Conclusions

Addressing 'wicked' societal problems, such as improving housing and its systems of governance to be resilient to climate change, "require[*s*] diverse views, new processes, and new thinking" (Rowbotham et al., 2019). As countries around the world grapple simultaneously with both housing and climate crises, citizen science represents a novel approach to informing the evidence base that underpins decision-making and enacting change. Combining studies from disparate fields, our scoping review is the first to synthesise how citizen science has been applied at the intersection of climate, housing, and health – specifically, how it has been leveraged to identify and address climate-related housing risk factors that impact upon health. In discussing the three research questions above, our findings indicate that the utilisation of citizen science in this space is mostly concentrated on water quality, an immense challenge facing communities in the 21st century, though there remains scope to focus on other climate-related housing risk factors that will feature prominently as extreme weather events increase in severity and frequency. Our results also indicate that there is capacity for studies that incorporate citizen science approaches to expand their methods, making use of both quantitative *and* qualitative data, adopt a broader set of mechanisms to minimise inaccurate and/or biased data and thereby enhance the quality of information produced, and better articulate their impacts. Embedding citizen science within broader programs of work, such as those already underway in the community, could expand opportunities to focus on other housing risk factors and methodological approaches. Notwithstanding its scope for further advancement, our review also demonstrates how citizen science approaches can be used to collect wide-ranging data with relative ease (when compared to traditional methods), incorporate new and diverse perspectives, and foster buy-in among various actors – from citizens to policymakers – to create change. Thus, it presents a promising addition to the suite of tools needed to develop healthy and climate-resilient housing, whilst fostering meaningful involvement of the public in this process.

CRediT authorship contribution statement

Adelle Mansour: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Conceptualization. **Rebecca Bentley:** Writing – review & editing, Methodology, Conceptualization. **Kathryn Bowen:** Writing – review & editing, Methodology, Conceptualization. **Gatto Maria:** Writing – review & editing, Investigation. **Samantha Rowbotham:** Writing – review & editing, Methodology, Investigation, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2025.104102.

Data availability

Data will be made available on request.

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