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Insights from the Dutch built environment

Ahmed, Istiaque; van Esch, M.M.E.; van der Hoeven, F.D.

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Heatwave vulnerability across different spatial scales: Insights from the Dutch built environment

Istiaque Ahmed *, Marjolein van Esch, Frank van der Hoeven

Delft University of Technology, Netherlands

A R T I C L E I N F O

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A B S T R A C T

Heatwaves in urbanized areas, even in temperate regions like the Netherlands, are getting serious attention. The Royal Netherlands Meteorological Institute predicts more frequent and intense heat events in the future. Studies have explored how Dutch cities contribute to heatwaves and suggested design and planning responses to mitigate their effects. However, a review of heatwave research in the Netherlands specifically focusing on the built environment has hardly been reported in the literature. This study aims to provide such a review utilizing the vulnerability framework. Following the PRISMA protocol, 57 articles are analysed based on the components of exposure, sensitivity, and adaptive capacity within the vulnerability framework. Subsequently, findings have been classified into five built environment scales - block, neighbourhood, district, city, and region - to critically reflect upon the extent to which the studies address various vulnerability components and the specific scales they primarily focus on. Results demonstrate that most of the studies concentrate on the hazard itself and its spatial distribution from a macro perspective on a city and regional scale. The review underlines the necessity of micro-level research on the phenomena, incorporating people's everyday experiences and resilience during heat events to find context-specific adaptation and mitigation strategies.

1. Introduction

Heatwaves are a serious threat in the Netherlands, as well as many other countries throughout the world. It is basically a prolonged period of extremely warm days surpassing an absolute or relative temperature threshold (Perkins-Kirkpatrick and Lewis, 2020; Founda and Santamouris, 2017; Schär et al., 2004). The hazard has severe consequences for natural and human systems. High temperatures during a heat event can produce heat stress, which can lead to health issues such as heat exhaustion, heat stroke, and dehydration (Amengual et al., 2014). It may also worsen air pollution, resulting in higher levels of smog and ground-level ozone, both of which can have serious health repercussions (Wang et al., 2022; Kalisa et al., 2018). Furthermore, heatwaves have economic implications, such as reduced productivity and higher energy consumption (Kjellstrom et al., 2016; García-León et al., 2021). Nevertheless, substantial studies indicate cities are more vulnerable to heatwaves because of factors like the urban heat island effect, fewer green spaces, population density, poor air quality, limited access to cooling, and a high concentration of buildings (Carbon Disclosure Project (CDP), 2021). The fatal consequences of the hazard are already visible in some of the major incidents that have occurred in the Netherlands in recent decades. The 2003 European heatwave caused an additional 70,000 deaths (Robine et al., 2008). July 2006 was recorded as the

* Corresponding author at: Department of Urbanism, Faculty of Architecture and the Built Environment, Delft University of Technology (TU Delft), Netherlands.

E-mail address: A.Ahmed-1@tudelft.nl (I. Ahmed).

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warmest month in the history of the Netherlands, resulting in 1000 fatalities (CBS (Dutch Centraal Bureau voor de Statistiek), 2006). That year, the Netherlands ranked fifth on the list of deadliest disasters by the number of deaths (Centre for Research on the Epidemiology of Disasters (CRED), 2007). In the more recent 2019 heatwave, the maximum air temperature reached 38 °C in several areas in the Netherlands (Painter et al., 2021). In 2020, it reached even higher, with air temperatures exceeding 40 °C recorded in multiple regions (AMS Institute, 2020). During the summer of 2022, a maximum temperature of 39.5 °C was reported, and surface temperatures (asphalt) in several areas surpassed 50 °C (Huiskamp, 2022; ANP and NL Times, 2022). Due to the frequency, intensity, duration, and related mortality of the events, the phenomenon of heatwaves is receiving more attention than ever before. In a cooler northern European country like the Netherlands, the climate crisis is accelerating faster than anticipated.

Several studies have been conducted in the Netherlands to investigate how Dutch cities and other urban areas contribute to heatwaves and how design and planning may be employed to solve such crises. Despite an increasing number of studies on the phenomenon, there is a scarcity of systematic reviews in the literature, notably on heatwave vulnerability in the Dutch built environment. Using a vulnerability framework, this study, therefore, aims to provide a systematic and comprehensive review of built environment research conducted on heatwaves in the Netherlands. The objective is to understand the evolution of this field of study over time and identify potential research agendas for the future.

1.1. Review rationale and contribution

Within the field of urban climate, knowledge is being produced at a phenomenal rate, yet it remains fragmented and monodisciplinary at the same time. Hence, it is challenging to keep pace with cutting-edge research as well as to evaluate the body of evidence in a broader field of study. In this regard, a literature review is a useful tool for evaluating and understanding the existing body of research on a given topic. It can be defined as a systematic procedure to collect and synthesise previous research (Tranfield et al., 2003). Moreover, a thorough and well-executed literature review can provide a solid foundation for advancing knowledge and expanding theoretical understanding (Webster and Watson, 2002).

The core objective of this review is to evaluate prior built environment research on heatwaves in the Dutch context based on the three components of vulnerability: exposure, sensitivity, and adaptive capacity. Firstly, the review identifies the vulnerability components that have received more attention, and those that have received less attention in the literature. Then it classifies previous studies into five different scales of the built environment in order to find out which scales have been prioritized and where inadequacies exist. Finally, consolidating the findings, the paper concludes by indicating the knowledge gap that needs to be addressed to confront future urban heat challenges in the Netherlands.

As a case, the Netherlands is significant because it is one of the densest countries in Europe where heatwaves still need to be taken seriously. Investigating which vulnerability components receive priority and which are overlooked in such contexts can shed light on effective strategies for tackling heatwaves in colder climate regions where they are not traditionally considered a primary concern. Besides, the approach followed in this study holds broader relevance beyond this specific case, as it can work as a reflective framework for understanding how vulnerability components manifest in different spatial scales.

2. Conceptual framework: Heatwave vulnerability in urban areas across various spatial scales

2.1. Heatwave

Finding a universal definition of heatwave has yet to be possible due to the vast range of climatic conditions on earth, as well as the diverse socio-demographic backgrounds and acclimatization patterns of various communities throughout the world. At the country level, heatwaves are classified based on both natural and anthropogenic factors (Jyoteeshkumar Reddy et al., 2021; Marx et al., 2021; Hintz et al., 2018; Tong et al., 2015). In the Netherlands, according to the Royal Netherlands Meteorological Institute (KNMI), a “heatwave” is defined as a period of at least 05 (five) days with a maximum air temperature of 25 °C or higher, with at least 03 (three) of those days having a tropical temperature of 30 °C or above at their measuring station in De Bilt (KNMI, 2021). The summer heatwave of 2006 lasted 16 days and was one of the most prolonged and severe in at least 100 years. The hottest occurred in July 2019, with a maximum temperature of 37.5 °C, although the duration was only six days. The KNMI publishes new climate scenarios every seven years; the next one is scheduled for mid-2023. For an interim overview of their work, they also publish a report named Climate Signal. The 2021 Climate Signal reports that the highest maximum temperature per year has increased by 2.4 °C since 1960, more than twice as much as the increase in the annual average temperature (KNMI, 2021). Besides, along with the issue of rising temperature, the report explicitly highlights urban climate, noting that as cities tend to be warmer than their surroundings, also known as the Urban Heat Island (UHI) effect, they are more susceptible to the changing climate. The UHI effect is typically defined as the urban-rural difference in air temperature and is brought about by radiative trapping between buildings, increased heat storage in (a large surface area of) high heat capacity building and paving materials, decreased turbulent heat transport caused by a reduction of wind speed, anthropogenic heat releases, and decreased evaporative cooling as a consequence of limited vegetational cover (Oke, 1987). Interactions between UHI and heatwaves increase the difference between urban and rural temperatures (Li and Bou-Zeid, 2013; Zhao et al., 2018), leaving the urban population at even greater risk.

2.2. Vulnerability

Vulnerability can be defined as the exposure and susceptibility of individuals, families, communities, and countries coping with shocks, risks, and other contingencies. Generally, for a specific context, scholars distinguish exposure, sensitivity, and adaptive

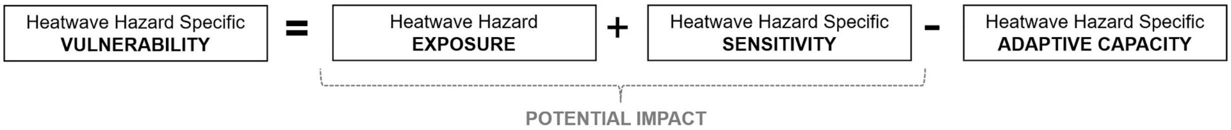

Fig. 1. Vulnerability framework used in this study.

capacity as the three main components for determining the level of vulnerability (Buzási, 2022; Bhattacharjee et al., 2019; Wilhelmi and Hayden, 2010; Cutter et al., 2008; Acosta-Michlik and Rounsevell, 2008). According to the Intergovernmental Panel on Climate Change (IPCC) approach, exposure and sensitivity share a positive functional relationship with vulnerability, whereas adaptive capacity has a negative functional relationship with vulnerability (IPCC, 2007). In the 2007 IPCC report, exposure is viewed from a driver's perspective- considered as an external stress that makes a system vulnerable. However, the 2014 IPCC report defines exposure as the presence of life, livelihoods, ecosystems, infrastructure, resources, services, or any economic, social, or cultural assets in geographic locations and settings that could be adversely impacted. Exposure and vulnerability are therefore separated in the 2014 IPCC report, emphasizing that vulnerability is independent of exposure (and hazard). Nonetheless, it is essential to assess vulnerability in relation to a hazard, particularly when it comes to heatwaves since recent studies on urban heat island effect included several exposure indicators such as land surface temperature (LST) (Logan et al., 2020; Bhattacharjee et al., 2019), daily maximum surface air temperature and relative humidity (Mora et al., 2017; Inostroza et al., 2016). To avoid ambiguity, in this review, vulnerability to heatwave hazard is discussed including the exposure component (See Fig. 1).

\`Sensitivity\` or \`susceptibility\` is the second component that contributes to vulnerability. The IPCC 2014 report defined sensitivity as the degree to which a particular system is directly or indirectly affected by any climate variability or change, either adversely or beneficially. Sensitivity comprises modifying factors that may increase or decrease an individual's vulnerability to heat hazards. Consequently, sensitivity depends on various parameters such as demographic profile (age, gender, body composition), socioeconomic status, heat acclimatization level, pre-existing health conditions, and medications (Mac and McCauley, 2017; Inostroza et al., 2016; Aubrecht and Ozceylan, 2013).

The third and final vulnerability component is \`adaptive capacity\`, also known as coping capacity. The adaptive capacities of individuals and groups are the economic, sociocultural, and technical skills and strategies directed towards responding to a certain crisis. While adaptation and mitigation may sound similar, mitigation entails proactive measures taken to minimize the potential impact of a hazard, focusing on reducing the adversities before an event occurs. In the context of a heatwave, adaptive capacity refers to an individual's, group's, community's or even a city's capability to cope with the adversities posed by heatwave hazards (Mac and McCauley, 2017; Inostroza et al., 2016).

2.3. Spatial scales in the built environment

While discussing the built environment, multiple scales and hierarchies within the system must be understood since they are strongly related to vulnerability. In the same way, it is crucial to understand that environmental issues can be interconnected and can have effects at various scales. For instance, local air pollution adds to regional and global air pollution, and global climate change may have local effects such as rising sea levels and extreme weather events like heatwaves. Moreover, environmental problems are often linked with the varied spatial scale of the built environment. The urban heat island effect, air pollution, and lack of urban greenery all can be considered urban built environment specific environmental concerns (Piracha and Chaudhary, 2022).

Erickson and Lloyd-Jones (2001) attempted to classify the scales in the built environment based on the related design activities. Although they acknowledge there is no distinct border between the design activities, Erickson and Lloyd-Jones (2001) provide a somewhat detailed idea about different scales in the built environment (Fig. 2). The built environment comprises different levels of scales ranging from interiors, building units, and blocks at the micro-scale of the spectrum to neighbourhoods and districts at the mesoscale and cities and regions at the macro-scale. Environmental issues, such as heatwaves, can manifest differently at different spatial scales. To fully comprehend how the hazard interacts with the built environment, studying it from various spatial perspectives is essential.

3. Methodology of the review

This paper aims to map prior research on heatwaves in the context of the Netherlands with the notion of identifying less prioritized areas and existing knowledge gaps. Even within the realm of the built environment, the topic of heatwaves is vast. For example, from meteorology to public health, there are multiple orientations for researching heatwaves in the urban context. Therefore, a semi-systematic or narrative review approach is best suited for this study. A semi-systematic or narrative review is designed for topics that have been conceptualized by various research disciplines and also aims to look at how research within a specific field, heatwaves in this case, progressed over time (Wong et al., 2013). So, a narrative review was conducted following a systematic searchto find answers to the research question. The review followed the guidelines of the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol to systematically identify, select, and report literature sources.

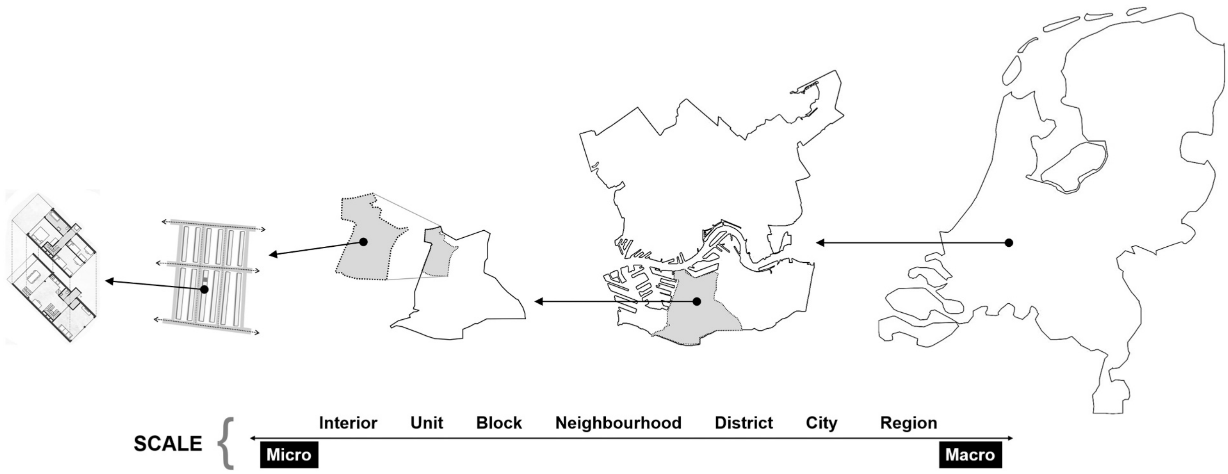

Fig. 2. Different territories (or scales) of design, adopted from Erickson and Lloyd-Jones (2001).

3.1. Search strategy and screening process

This study focuses on articles published in peer-reviewed journals from 01 January 2010 to 31 July 2022. Before 2010, limited research on heatwaves in the Netherlands was available. Two major online databases, Scopus and Web of Science, were used for searching articles. In those two databases, Boolean operators ("OR" and "AND") were employed to merge correlated terms into a single search query. In order to obtain relevant sources within the research context, the search incorporated terms pertaining to the built environment. An identical search string was used in both databases to perform the search.

As this study specifically focused on the Dutch context, a total of 165 articles were initially identified, with 135 articles found in the Scopus database and 30 articles in the Web of Science database. After removing 27 duplicates, a total of 138 unique articles were found. Subsequently, a rigorous two-stage screening process was implemented, starting with the title and abstract evaluation, which resulted in 61 articles. Four additional articles were eliminated in the second stage based on the inclusion-exclusion criteria, leaving a final set of 57 papers for analysis.

The inclusion criteria encompassed empirical and theoretical studies, scientific reports, focusing specifically on urbanized areas in the Netherlands. Variables related to the field of study included built environment, architecture, urban design, urban planning, and landscape architecture. Similarly, for studies related to heatwaves, variables such as urban heat, extreme heat, heatwave hazard, and urban heat island were considered. The exclusion criteria involved articles that were beyond the scope of the review, studies emphasizing non-human factors or aspects, studies not focusing on the Dutch context, and studies unrelated to the built environment fields. Fig. 3 provides the search, inclusion and exclusion criteria, as well as the logic behind the searches performed and the entire process sequence followed.

4. Findings

4.1. General overview of the literature

In general, research on heatwaves from a built environment perspective has been increasing with time, particularly since 2012. Articles reviewed for this study were published between 2010 and 2022. Only in the year 2016, the number of articles decreased substantially, but after that, the trend is mostly upward, and the issue of heatwaves is getting more attention than ever before.

Considering the subject area, most of the articles belong to the broader subject fields of Environmental Science (30.2%), Social Science (16.1%), and Engineering (13.3%) (See Fig. 4). Reviewed articles were obtained from 35 journals. The annexes include a thorough list of papers, together with the names of the corresponding journals and their DOIs.

Among the three main elements of the vulnerability framework, studies on exposure to heatwaves and adaptive capacity are the most discussed topics. A total of 25 articles addressed exposure to the hazard, 21 focused on heatwave adaptation, and 10 covered sensitivity factors associated with heatwaves in urban areas. The sensitivity element may not have received as much attention as the other two components for a number of reasons. Several authors, including Hansen et al. (2014) and Hatvani-Kovacs et al. (2016), noted the difficulties in comprehending the effect of heat events on various socio-demographic population groups as one of the reasons for limited sensitivity-related studies on heatwaves in cities. Additionally, the need for more available data on the health impact of heatwaves on various age groups (Xu et al., 2017) and challenges associated with quantifying the effects and experiences during heat events may result in fewer research articles on heatwave sensitivity.

A bibliometric analysis was conducted using VOSviewer (version 1.6.18) to identify the core and peripheral topics in the field of heatwave research in the Netherlands. The results, as depicted in Fig. 5, indicate that the nature of the hazard (climate, temperature, air temperature), its impact (modelling), and spatial implications (buildings, urban areas, urban heat island effect) received dominant

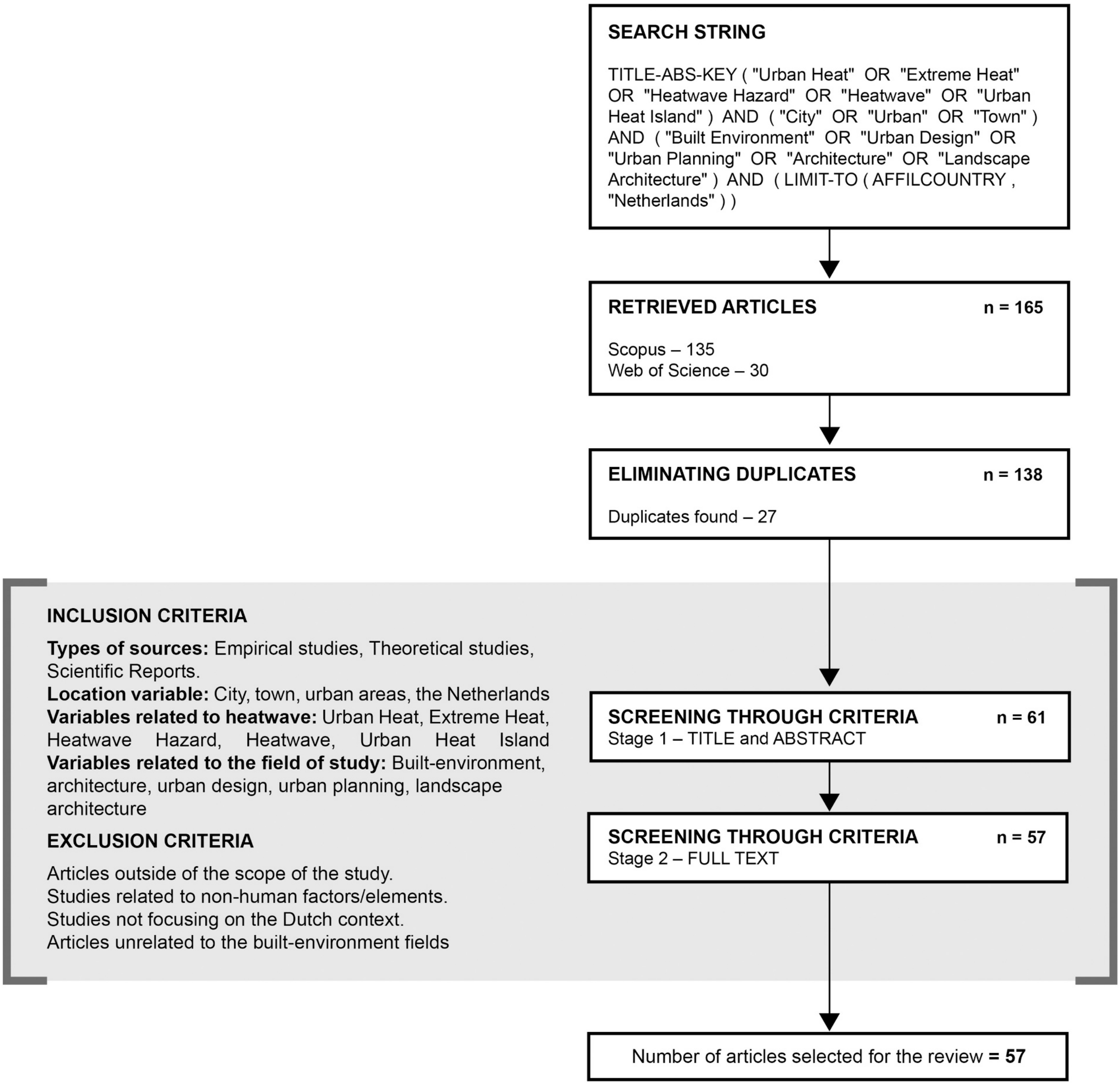

Fig. 3. The search process and selection criteria followed in the review.

attention. Besides, as evidenced by the number of citations, a strong inclination towards those core topics (research related to heatwave risk and its impacts) can be found.

4.2. Vulnerability to heatwaves in the Dutch context

4.2.1. Exposure

In the context of Dutch cities, scientific studies predict more warm days and an increase in the frequency of heatwaves (KNMI, 2014). The Amsterdam Institute for Metropolitan Solutions (AMS Institute) looked at the trajectory of summer temperatures in the Netherlands over 100 years, from 1920 to 2020, and discovered that the average number of summer days (+25 °C) in the country doubled compared to the previous 10-year average (AMS Institute, 2020). In KNMI's report called Climate Signal'21, it was found that between 1961 and 1990 and 1991–2020, the annual mean temperature in the Netherlands increased by 1.1 °C. That's more than twice as much as the increase in the global mean temperature in the same period. The highest maximum temperature per year increased by 2.4 °C, more than twice as much as the increase in the annual mean temperature (KNMI, 2021). So, scenarios are worsening faster than predicted; therefore, there is an urgency to quantify the nature, behavior, and impact of heatwave hazards. Consequently, heatwaves have drawn more attention in the scientific community since 2010 and are being studied by various disciplines to better understand the

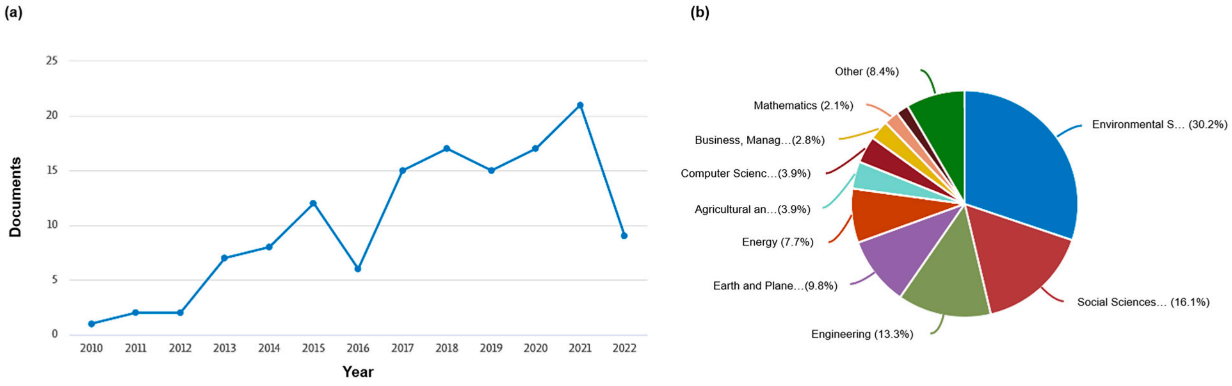

Fig. 4. Overall scenario in SCOPUS database (a) documents by year; (b) documents by subject area.

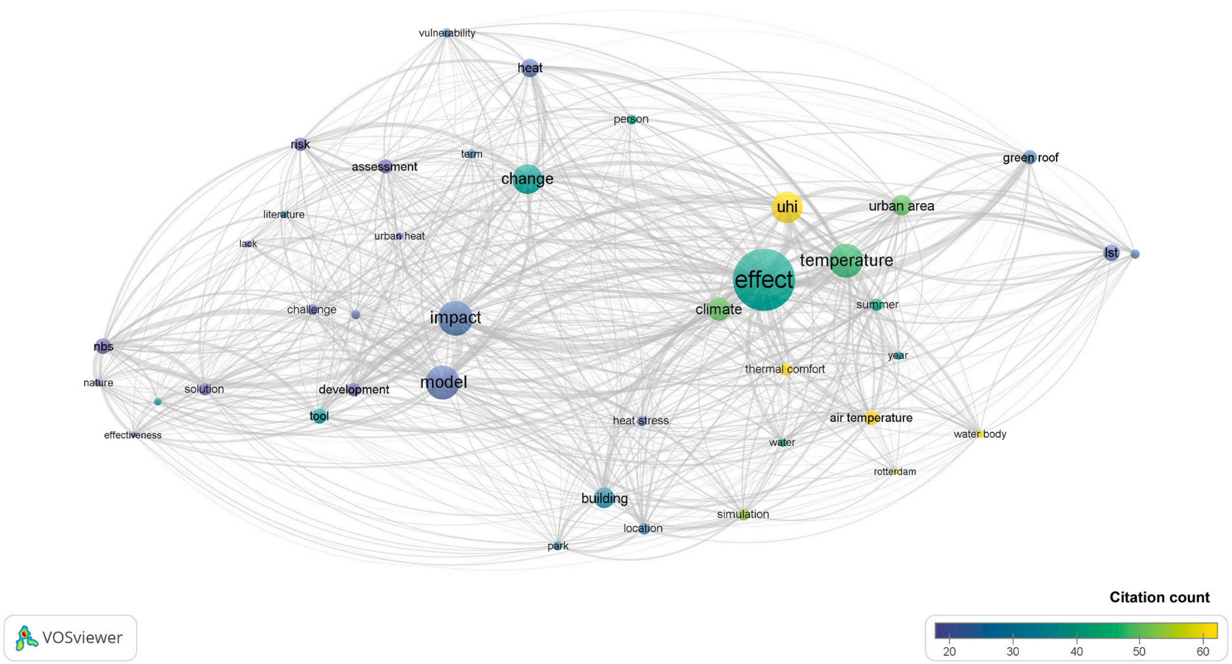

Fig. 5. Bibliometric analysis based on the Scopus database, showing the core and peripheral research topics on heatwaves in the Netherlands.

risk and how it might affect society. As a whole, in terms of exposure, earlier research focused primarily on air temperature observation data to develop indices (Steeneveld et al., 2018; Steeneveld et al., 2011). Long-term changes in temperature within a specific area can be explained using these data. Later researchers utilized satellite-derived estimates of land surface temperature (LST) (Mashhoodi, 2021a).

A substantial amount of studies attempted to either quantify the effects of the hazard (i.e increased temperature, heat stress and heat-related health issues, energy consumption) or map its spatial implications and visualize the impacts. Studies that explored ways to measure the hazard's impacts in the built environment mostly considered the urban heat island (UHI) effect as a primary driver that exacerbates the phenomenon of heatwave hazards in urban areas. Therefore, a dominant focus on investigating the current and future UHI impacts is noticeable. The UHI is measured based on the air temperature at the urban boundary layer, urban canopy layer, or near surface layer temperature (the temperature of the air closest to the surface of the earth) (Mashhoodi, 2021a; Echevarría Icaza et al., 2016; Toparlar et al., 2015; Essa et al., 2013; Klok et al., 2012; Steeneveld et al., 2011). Along with traditional approaches of measuring urban climate, usually from the data of meteorological monitoring stations, the potential and accuracy of non-traditional approaches, methods, and technologies are also being explored by researchers in the Netherlands (Cabrera et al., 2021). The use of smartphone sensors and citizens' personal amateur weather stations (PWS) to sense air temperature and other meteorological parameters are a few of those approaches (Golroudbary et al., 2018). Although new ways of measuring are coming along, researchers also highlight the importance of long-term meteorological observations for Dutch cities. At the same time, Theeuwes et al. (2017) mentioned that small and tertiary cities are not having an extensive measurement network. Hence, enabling both large and small-scale cities with proper measurement networks can provide a more realistic image of the hazard itself.

Several studies also investigated heat stress, outdoor human thermal comfort, including urban landscape parameters, and relationships between urban morphology, land coverage and surface temperature. Maiullari et al. (2021) applied a typo morphology approach for examining the urban microclimate in Rotterdam and found that spatial conditions influence indoor and outdoor temperature. The finding resonates with what Zinzi and Santamouris (2019) stated: that urban form and its configurations influence overheating, either positively or negatively. Accurate prediction of urban microclimates has the potential to precisely identify problem areas in the built environment (Toparlar et al., 2015). Therefore, location-specific urban microclimate studies are becoming increasingly important to trace specific factors and conditions that contribute to the UHI effect and heat stress.

In parallel with studies concerned with quantifying the effects of heatwaves, a body of research also attempted to make those impacts and their potential consequences/associations more visual using a variety of mapping methodologies. These approaches range from mapping the UHI effect itself and its maximum hourly distribution, to mapping health, land use and energy consumption in relation to urban heat (Koopmans et al., 2020; Golroudbary et al., 2018; de Groot-Reichwein et al., 2018; Klok and Kluck, 2018; Echevarría Icaza et al., 2016; van der Hoeven and Wandl, 2015; Essa et al., 2013; Klok et al., 2012). A recent study by Mashhoodi (2021b) found that certain gender groups are overexposed to land surface temperature and such overexposure differs across socio-economic groups and locations. The research also highlights the urgency of investigating the phenomenon of heatwave hazard from an environmental justice standpoint. According to that study, anthropogenic factors, like pre-existing socio-economic disparities and demographic conditions, are crucial in determining which particular group of society would be impacted more adversely by a heatwave hazard than others. Although such investigations exist in other contexts, the number of studies on the socio-political dimensions of heatwaves in the Netherlands is significantly limited. Table 1 offers an overview with a classification of how exposure to heatwaves has been addressed in the studies reviewed.

Table 1
Overview of how heatwave hazard exposure has been investigated in the Netherlands.

Themes	Topics Addressed	Description	Sources
Quantifying Effects			
	1. Urban Heat Island (UHI) impacts and modelling: *i. Determining the impacts of UHI* *ii. Developing a supporting equation for UHI modelling* *iii. Predicting urban temperature and potential future UHI patterns* 2. Urban heat impacts on human comfort and health: *i. Impact of urban heat on outdoor human thermal comfort* *ii. Canopy layer UHI and human comfort* *iii. Quantifying the local impact of tree volume on nocturnal UHI* 3. Measuring and modelling urban heat: *i. Impact of sky view factor on UHI.* *ii. Measuring urban air temperatures through crowdsourcing.* *iii. Hazard assessment and modelling for UHI and related hazards.* 4. Seasonal variations in UHI impacts: *i. Impact of UHI on the street canyon in different seasons*	Studies on the distribution of the impact of urban heat and urban heat island effect. These include the development of tools and deterministic, measurable methods of analysing the existing climate situation and predicting potential future scenarios.	Cabrera et al., 2021; Dirksen et al., 2019; Rafiee et al., 2016; Theeuwes et al., 2017; Theeuwes et al., 2014; Toparlar et al., 2015; Overeem et al., 2013; Steeneveld et al., 2011; Pena Acosta et al., 2020; Koomen and Diogo, 2017; Steeneveld et al., 2018
Urban Microclimate	Morphological classification of urban microclimate; Deterministic microclimate analyses; Urban design concerning microclimate;	Studies examining the relationship between temperature, urban form, morphology and the urban microclimate.	Maiullari et al., 2021; van Hove et al., 2015
Hazard Mapping	Mapping urban climate; Mapping maximum hourly urban heat island distribution; Visualising urban heat; Mapping health, land use, and energy consumption of the urban heat; Thermal image sharpening; Quantify the surface heat island (SHI);	Studies that aim to visualize the impact of urban heat using various mapping methodologies. This also helps to quantify the consequences of the hazard.	Koopmans et al., 2020; Golroudbary et al., 2018; de Groot-Reichwein et al., 2018; Klok and Kluck, 2018;Echevarría Icaza et al., 2016; van der Hoeven and Wandl, 2015; Essa et al., 2013; Klok et al., 2012
Anthropogenic Factors	Urban Inequality; Environmental justice;	Studies aimed to link heatwave hazards to various socioeconomic constitutions in order to determine how the hazard affects different groups differently based on the social construct.	Mashhoodi, 2021a; Mashhoodi, 2021b

4.2.2. Sensitivity

In the context of the Netherlands, the least explored vulnerability component is sensitivity. Simply put, sensitivity is the degree to which exposure to a hazard might affect people and the things they value. Sensitivity to heatwave hazards, particularly in urban settings, is complex. On a larger scale, the sensitivity and coping capacity of the city influence how the hazard will impact in the first place (IPCC, 2014); yet, sensitivity varies on a micro-scale due to geographic, socioeconomic, and demographic differences.

Based on the articles reviewed, three particular factors can be outlined with regard to sensitivity to heatwaves in the Netherlands comprises socioeconomic and demographic aspects, including age, gender, ethnicity, and financial capability; and the third is prior knowledge and level of awareness. Out of these three factors, the physical-spatial factor is quantifiable, therefore, easier to measure, whereas the socioeconomic factors are always challenging to quantify.

4.2.2.1. Socioeconomic and demographic aspects. Research has revealed that certain groups in the society, particularly senior citizens, bear a disproportionate share of the burden of heatwave hazards (Van Der Hoeven and Wandl, 2018). Using the mortality records due to heatwaves in Europe, Mees et al. (2015) found that the elderly, people with disabilities, and socially deprived populations are the most vulnerable groups in cities. They further highlighted that heatwave research gave little attention to the governance side, which particularly supports vulnerable citizens in society. Moreover, using a geographically weighted regression model (Mashhoodi, 2021b) found that exposure to urban heat in the Netherlands is gender sensitive. According to that study, women (over 65) are more exposed to high LST than men. It also highlighted some societal and spatial issues, such as gender imbalance in the workplace, over-representation of a particular gender in urban areas, unequal access to green etc., which can all significantly contribute to urban heat vulnerability. In general, the study found that regardless of socioeconomic characteristics, women are more exposed to higher LST than men, which applies in most Dutch residential zones. Similarly, Reckien et al. (2017) emphasized that socioeconomic status and gender are two fundamental underlying sensitivity factors that play a significant role in the urban equality concern to climate crises.

4.2.2.2. Prior knowledge and experience. Along with age, income, and gender issues, awareness about the phenomenon of a hazard is regarded as highly important. It has been found that citizens and other stakeholders have lower awareness regarding urban climate crises such as heatwaves (Lenzholzer et al., 2020b). Although there has been historical research on urban climate, literature on climate awareness is limited. From their international study, Lenzholzer et al. (2020a) also identified education as a critical parameter in exploring the awareness level of urban climate phenomena. It is also consistent with what Howe et al. (2019) found in US cities. In addition to education, they mapped people's perceptions of heat risk on a national and state-wide scale in the United States and revealed that perceptions influenced by ethnicity, income, and gender are key factors in heat sensitivity.

4.2.2.3. Physical and spatial configuration. Physical and spatial configuration includes aspects such as the concentration of heat-absorbing surfaces like pavement and buildings, the availability of green spaces or shade, and the availability of cooling infrastructure. In their research in Rotterdam, Van Der Hoeven and Wandl (2018) identified that not all parts of the city are equally affected by the UHI effect. For example, Rotterdam's northern, southern, and western districts are more exposed than other parts of the city. The research further highlighted morphological and land use factors, such as building envelope, greenery, shade, the amount of impervious surfaces, and surface water, as important determinants of the accumulation of urban heat in a district.

Higher surface temperatures raise the surrounding ambient air temperature resulting in higher household energy consumption

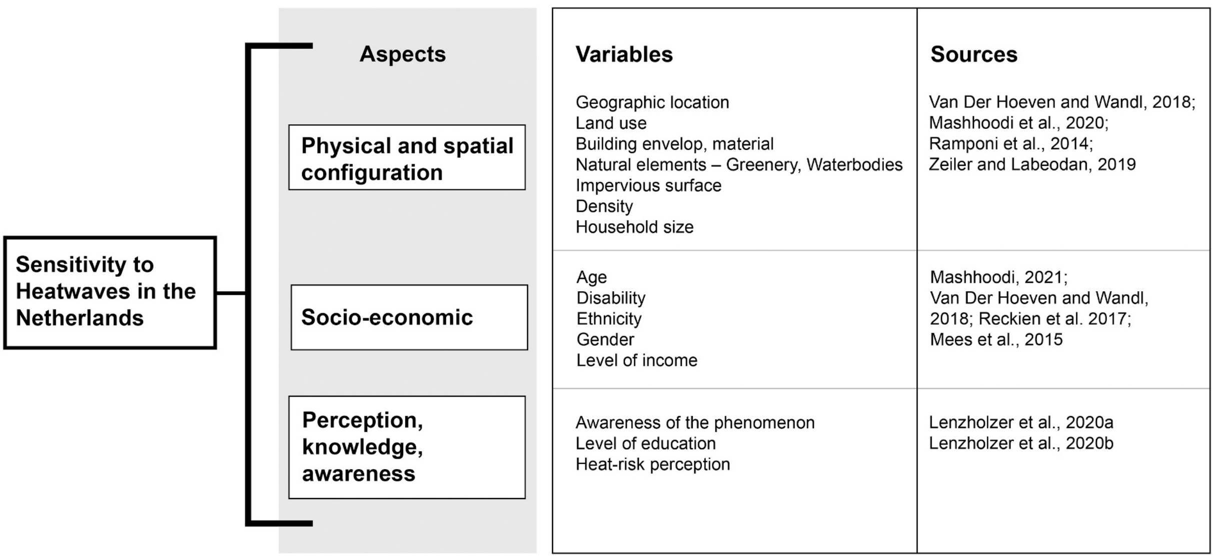

Fig. 6. Overall aspects and variables of heatwave sensitivity in the Dutch context.

(Santamouris et al., 2015). This phenomenon is spatially variant and cannot be generalized. In the Netherlands, larger households face significant household energy consumption, for which the geometry and shape of the building play the most crucial role (Mashhoodi et al., 2020). Studies also mentioned that solar shading in highly dense urban areas could reduce energy demand (Ramponi et al., 2014). Overall, the sensitivity factors related to urban heat in the Netherlands are outlined in Fig. 6.

4.2.3. Adaptive capacity

Throughout the last decade, heat adaptation and mitigation strategies available for the Dutch context are primarily related to Ecosystem Services (ES), Nature Based Solutions (NBS), and Green Infrastructure (GI). Some studies also evaluate alternative urban forms to analyze microclimate design as a means for heatwave adaptation. Within various scales in the built environment, the highest number of studies are based on the city scale, whereas the neighborhood scale has the fewest studies. House, Block, and Region received a somewhat similar number of studies in general.

Augusto et al. (2020) examined the short, medium, and long-term impacts of NBS in the city of Eindhoven using their meteorological and urban energy balance model. Their research indicated that increasing green and blue spaces has a short-term cooling effect on the surrounding area. On the other hand, van Oorschot et al. (2021) assessed urban ecosystem services by examining the mean land surface temperature (LST) for various land cover types, including trees, grass and shrubs, sand, and sealed surfaces, in the city of Den Haag. Findings say trees reduce approximately 35% of the urban heat island effect compared to other land cover types. Klok et al. (2019) conducted a Physiological Equivalent Temperature (PET) assessment in 21 public spaces in Amsterdam, including both shaded and sunny areas. In terms of PET or heat stress, both natural shading (by trees) and artificial shading (by buildings) were perceived as being cooler and more pleasant. Study findings urged incorporating either natural or artificial shading in urban spaces to enhance thermal comfort. Additionally, the research highlighted that such meteorological measures could be efficient for quantifying spatial features for setting or meeting targeted values and guidelines to reduce urban heat.

In the reviewed studies on GI, green roofs are regarded as an effective solution to tackle increasing temperatures. In their study, Solcerova et al. (2017) monitored extensive green roofs (sedum) and their effect on air temperature 15 and 30 cm above and substrate. The findings were consistent with previous research suggesting that, in a well-watered condition, a green sedum roof can help reduce air temperature (Hop and Hiemstra, 2013). In addition, Zardo et al. (2017) evaluated the cooling capacity of green urban infrastructures (GUI). The results identified that tree canopy coverage, soil cover, and size play determining roles in GUI's cooling capacity. Addressing rising temperatures, planning interventions such as converting soil cover, increasing the amount of GI, and expanding tree canopy cover were recommended by the researchers. However, since various design alternatives are available when selecting GI for an area or region, socio-cultural validation of those options is essential before applying them in practice. Derkzen et al. (2017) discovered that while individuals favoured the most efficient choices, socio-cultural factors significantly influenced their willingness to pay.

Among a range of nature-based solutions and ecosystem services, transpirational cooling was found to be effective in reducing outdoor air temperature during hot summer days (Gromke et al., 2015). Evaporation from urban open water surfaces may also lower the temperature (Theeuwes et al., 2013), and efficient use of soil ecosystems and greenery can help cool down cities (Claessens et al., 2014).

Table 2
Heatwave adaptation and mitigation approaches in the Netherlands.

Themes	Topics Addressed	Description	Sources
Nature-Based Solution and Ecological Services	Quantifying ecosystem services in relation to green infrastructure; Subsurface space in cities; Vegetation and horticulture interventions as sustainable heat mitigation method; Contribution of soil making cities climate proof; Open surface water in heat mitigation;	Studies on employing ecosystem- and nature-based approaches to lessen the effects of urban heat.	van Oorschot et al., 2021; Finesso and Van Ree, 2022; Stache et al., 2022; Timmermans et al., 2017; Claessens et al., 2014; Theeuwes et al., 2013
Green Infrastructure	Thermal performance of green roof; the Cooling potential of green infrastructure; Socio-cultural valuation of green infrastructure; Use of green roof and walls in heat mitigation; Cooling potential of urban water bodies	Studies that are more focused towards exploring various implementation strategies and actions drawn from the NBS and ES.	Solcerova et al., 2017; Zardo et al., 2017; Derkzen et al., 2017; Hop and Hiemstra, 2013; Steeneveld et al., 2014
Microclimate	Effective urban typologies for cooling at the neighbourhood scale; Quantifying thermal comfort in various urban forms; Urban courtyard blocks to alter microclimate for heat adaptation	Studies that investigated microclimate design as a means of heatwave adaptation by evaluating various urban forms.	Kleerekoper et al., 2015; Taleghani et al., 2015; Taleghani et al., 2014
Planning and Design Strategies	Regionalist concepts in UHI mitigation; Urban planning strategy consisting of certain building types and greeneries; Urban climate adaptation policy; Institutional setting for implementing climate adaptation policy; Urban design tools and strategies; Governance between public and private sector to tackle extreme heat	Studies related to governance, planning, policy, and design interventions for making cities climate-resilient.	Echevarría Icaza and Van der Hoeven, 2017; Koopmans et al., 2018; Boezeman, 2016; Tennekes et al., 2014; Kleerekoper et al., 2012; Mees et al., 2015

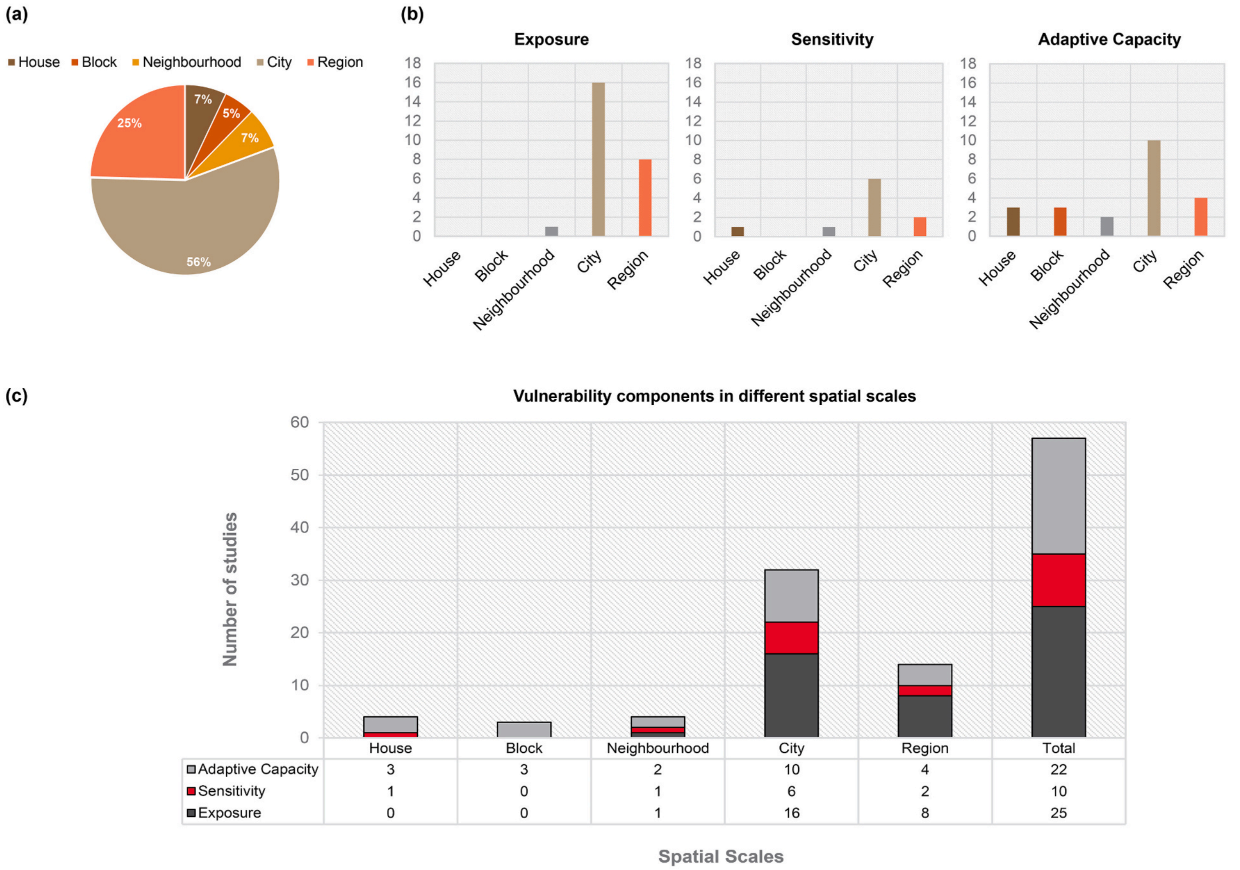

Fig. 7. (a) Share of studies per spatial scales ($n = 57$); (b) Studies related to each vulnerability components across spatial scales; (c) Overall distribution of studies in different spatial scales incorporating all three vulnerability components reveals an emphasis on macro-level (city, region) investigations while micro-level (house, block, neighbourhood) studies are limited.

Some studies also highlighted the importance of microclimate design in coping with climate change. Taleghani et al. (2014) conducted a parametric study into different geometries and orientations of urban courtyard blocks in the Netherlands on the hottest day in the Dutch reference year (19th June 2000, maximum 33 °C air temperature). The research showed that placing a water pool in the middle of a courtyard or covering it with plants may dramatically lower both the mean radiant and ambient temperature. In another study, Taleghani et al. (2015) found that the courtyard building type provides the most comfortable microclimate in the Netherlands in June compared to the other studied urban forms. The urban typology in the Netherlands is diverse, and the characteristics of the built environment contributing most to increasing temperatures may differ by neighborhood. At the neighborhood scale, heat storage can be reduced by casting more shadow, increasing the use of high albedo roofs and surfaces, and adding vegetation (Kleerekoper et al., 2015). Koopmans et al. (2018), forecasting the 2050 scenario of urban heat for The Hague, suggest densification strategies consisting of tall buildings and preserved green areas as potentially the best way to respond to urban heat. Similarly, Kleerekoper et al. (2012) emphasize the potentiality of using design principles to tackle heat accumulation in cities. Table 2 provides a summary of the approaches adopted for heatwave adaptation and mitigation in the Netherlands.

Two key findings emerge from the existing studies on adaptation. Firstly, although approaches such as ES, NBS, GI got widely investigated, there is a lack of discussion on the interplay among blue, green, and grey infrastructures, despite their strong interconnectedness and complementarity, as highlighted by Graça et al. (2022). Besides, in humid contexts, such as the Netherlands due to the influence of the North-Sea, nature based solutions, particularly increasing blue spaces may lead to thermal discomfort over time. According to Fung and Jim's (2020) research in Hong Kong, green space (lawns) adjacent to water bodies (pond) contributed to harsh thermal comfort conditions and prolonged periods of heat stress on sunny summer days. Therefore, adaptation strategies without considering their long-term implications may not be advisable.

And secondly, it is important to recognize that adaptation approaches explored in the Dutch context hardy addressed people's individual heat adaptation practices or behavioural adaptation practices such as using (electronic) devices, reducing physical activities, wearing different clothing, remaining indoors etc. In their research, Zander et al. (2021), surveying over 350 participants in Australia, found that almost 40% of the respondents deliberately changed their way of living due to extreme heat. Practices like passively cooling the house, making cultural changes, increasing water intake and taking cold showers are some of the most common forms of individual adaptation practices. Moreover, it has been found that one's level of knowledge regarding the heatwave hazard influences the adaptation measures one undertake (Beckmann et al., 2021). Therefore, in the context of Dutch cities, existing behavioural adaptation techniques are necessary to investigate as they can provide a fresh perspective on recognizing vulnerable populations and opportunities for increasing their agency. Hence, further studies are required in this area.

4.3. Netherlands' vulnerability to heatwaves in Urban areas according to varied spatial scales

Following the scales in the built environment as defined by Erickson and Lloyd-Jones (2001) the review findings are classified under five scales - block, neighbourhood, district, city, and region –to facilitate the identification of less prioritized scales in order to develop a future agenda for research. Fig. 7 provides a comprehensive overview of the number of papers addressing the three vulnerability components at the different spatial scales.

Overall, sensitivity received the least attention of the three vulnerability components. The majority of the studies focused on the hazard itself, the level of exposure and its behavior in the built environment. Adaptive capacity received a similar amount of attention. However, when the spatial scales are considered, it is evident that the city scale is dominating. Although some research on a national or regional scale exists, studies on a micro-scale, i.e., a house, block, or neighbourhood, are relatively few. Evaluating the hazards phenomenon from a broader, macro perspective yields standardized results that are primarily applicable to the overall context. Nonetheless, those findings can be inadequate while designing or planning small-scale interventions in cities or other urbanized areas, as physical-spatial as well as socioeconomic and demographic characteristics can vary widely and are highly contextual. Microscale studies are thus necessary, as they can contribute to comprehending how sensitive cities and their population are to urban heat. Furthermore, as cities are growing diverse and becoming more and more heterogeneous, small-scale investigations may also help to validate whether the broader, generalized findings are applicable to the whole city or just certain parts. These local studies may offer a more precise picture of how urban heat interacts with different neighbourhoods and how it impacts various demographic groups within cities. This data may then be utilized to develop more focused and effective measures for reducing the impacts of heatwaves in Dutch contexts.

The review also revealed a lack of studies addressing the phenomenon of heatwave combining two or multiple vulnerability components. Approaching the hazard based on multiple vulnerability components like exposure and sensitivity, or sensitivity and adaptive capacity may provide some new angles in the field of urban heat research. Moreover, the behaviour of heatwave hazard in urban areas is extremely complex. Aside from the interdisciplinary approaches of investigating the phenomenon, which has largely been the case so far, more wider multi-disciplinary or even trans-disciplinary approaches are needed. It has already been revealed that exposure to a hazard is influenced by pre-existing social, economic, and cultural disparities in society; thus, a more holistic research strategy including all stakeholders is the key.

5. Conclusion

The objective of this review was to explore built environment research on heatwaves in the Dutch context in order to identify the current state of the knowledge field, which vulnerability components have received more or less attention, and at which spatial scale those studies can be classified. Through a systematic approach, this review identifies the following limitations and key agendas for further research:

5.1. Mono to multidisciplinary approach

Research in different fields related to urban heat is currently being conducted with a disciplinary approach without significant collaboration between different fields. The complexity of heatwave vulnerability necessitates the integration of knowledge from various disciplines such as climatology, urban planning, health, and sociology in order to have a holistic understanding of the dynamics of heatwaves in Dutch cities as well as to develop effective adaptation strategies to mitigate the negative impacts of the hazard.

5.2. Generalized to context-specific investigation

A significant number of studies conducted at the macro scale in the Netherlands indicate a prevalent inclination towards the production of generalizable findings, despite the acknowledged fact that heatwave vulnerability is highly context-specific. Besides, the built environment is not homogenous, and specific features, physical conditions, and spatial characteristics can contribute to discriminatory experiences during a heat event. Looking at different scales can help comprehend the underlying factors and their interrelationships that contribute to heatwave vulnerability.

5.3. Integrating anthropogenic and socio-cultural variables

In the Netherlands, the physical factors of the built environment attained much importance in heatwave studies, but the social and cultural factors which shape people's experiences and responses to heat events in urban areas are yet to be explored. Although some recent studies are bringing anthropogenic factors such as inequality and, socioeconomic differences to the table, much remains to be investigated in this arena. Although the Netherlands is a developed and wealthy nation, there are significant socio-demographic differences, and therefore the impact of heat on minorities and people with different backgrounds, ethnicities, and cultural beliefs needs further study. Several studies have shown that death caused by heatwaves disproportionately impact socially disadvantaged groups throughout the world (Mitchell and Chakraborty, 2015). In the US, urban heat disproportionately affects certain communities and people of colour, and similarly, in Australia, ethnic minority groups are more susceptible to extreme heat due to their socio-economic status, linguistic barriers, and living conditions (Hansen et al., 2014).

5.4. Exigency of bottom-up knowledge production

So far, most of the studies in the Netherlands have approached the phenomenon of heatwaves from a more expert driven, top-down perspective, and there is a visible bottom-up knowledge deficit. While several studies used socio-demographic indicators to understand vulnerability to heatwaves, very few of them engaged directly with vulnerable communities or individuals. It is critical to actively involve local communities in the process of investigating heatwave vulnerability. This includes gathering peoples experience during heat events, how they cope, and their perceived strengths and weaknesses. Understanding the demographic group, allowing them to participate in the process, and developing their own agency is arguably more important than providing external intellectual or technical support in addressing urban heat.

Heatwaves in urbanized areas have become a vital research topic in the Netherlands. This review has portrayed the overall state of the built environment related research carried out in the Dutch context. The findings of this study may assist in setting research agendas and reinforce existing adaptation and mitigation measures.

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.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.uclim.2023.101614.

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