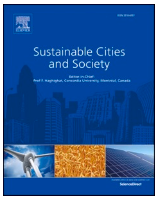
Sustainable Cities and Society 90 (2023) 104387

Contents lists available at ScienceDirect

Sustainable Cities and Society

journal homepage: www.elsevier.com/locate/scs



Co-occurrence of urban heat and the COVID-19: Impacts, drivers, methods, and implications for the post-pandemic era

Wei Wang [a,b], Bao-Jie He [a,b,c,d,e,*]

[a] Centre for Climate–Resilient and Low–Carbon Cities, School of Architecture and Urban Planning, Chongqing University, Chongqing, 400045, China
[b] Institute for Smart City of Chongqing University in Liyang, Chongqing University, Liyang, 213300, Jiangsu, China
[c] Key Laboratory of New Technology for Construction of Cities in Mountain Area, Ministry of Education, Chongqing University, Chongqing, 400045, China
[d] State Key Laboratory of Subtropical Building Science, South China University of Technology, Guangzhou, 510641, China
[e] Network for Education and Research on Peace and Sustainability (NERPS), Hiroshima University, Hiroshima, 739-8530, Japan

ARTICLE INFO

Keywords:
Urban heat
Pandemic
Co-occurrence
Urban governance
City manager

ABSTRACT

Cities, the main place of human settlements, are under various mega challenges such as climate change, population increase, economic growth, urbanization, and pandemic diseases, and such challenges are mostly interlinked. Urban heat, due to heatwaves and heat islands, is the combined effect of climate change and urbanization. The COVID-19 is found to be a critical intervention of urban heat. However, the interrelationship between COVID-19 and urban heat has not been fully understood, constraining urban planning and design actions for improving the resilience to the dual impacts of heat and the pandemic. To close this research gap, this paper conducted a review on the co-occurrence of urban heat and the COVID-19 pandemic for a better understanding of their synergies, conflicts or trade-offs. The research involves a systematic review of urban temperature anomalies, variations in air pollutant concentrations, unbalanced energy development, and thermal health risks during the pandemic lockdown. In addition, this paper further explored data sources and analytical methods adopted to screen and identify the interventions of COVID-19 to urban heat. Overall, this paper is of significance for understanding the impact of COVID-19 on urban heat and provides a reference for coping with urban heat and the pandemic simultaneously. The world is witnessing the co-existence of heat and the pandemic, even in the post-pandemic era. This study can enlighten city managers, planners, the public, and researchers to collaborate for constructing a robust and resilient urban system for dealing with more than one challenges.

1. Introduction

Urban heat has been widely recognized as a climate-related challenge at both global and local scales, along with climate change and urbanization. The urban heat island (UHI), referring to the phenomenon that cities are warmer than their surrounding areas, is a key driver to the urban heat. The UHIs have been widely observed in almost all settlements all over the world (Santamouris, 2020). To address UHI issues, existing studies have well documented the causes in aspects of the modification of physio-morphological characteristics (e.g. building materials, urban density, functional land use, green coverage), the emissions of anthropogenic heat from urban activities (e.g. air-conditioning, vehicle) (He, 2022), and their linkages with climatic and environmental factors (e.g. environmental quality, diurnal seasons, and climate) (Oke, 1982; Ren et al., 2022). The heat wave, the phenomenon that temperature remains higher for several or dozens of lasting days, is another contributor to urban heat. In recent years, the frequency, intensity, and duration of extreme heat events have increased significantly with global climate change. In general, there is an exponential increase in the number of people exposed to extreme heat, posing a significant threat to urban sustainability (GHHIN, 2021). Therefore, urban heat is one of the most urgent climate-related issues to address.

Apart from global and local climate change, cities are under many other mega challenges such as population growth, environmental deterioration, social inequality, and the pandemic. Such mega challenges are mostly interlinked. For instance, the COVID-19 pandemic outbroke in early 2020, and it generated lasting impacts on urban heat aggravation, mitigation and adaptation. For instance, the COVID-19 diverted public attention to dealing with urban heat challenges. In the early stage of the pandemic, to alleviate pandemic spread, the

---

* Corresponding author.
E-mail address: baojie.unsw@gmail.com (B.-J. He).

https://doi.org/10.1016/j.scs.2022.104387
Received 28 October 2022; Received in revised form 28 December 2022; Accepted 29 December 2022

government of many nations prioritized precautionary measures, such as home quarantines, online offices, closure of public places, and the suspension of transportation and industrial sectors. Such measures alleviated urban temperature by reducing anthropogenic heat release. In Japan, for example, COVID-19 lockdown measures resulted in a 12% reduction in anthropogenic heat and a 0.05 °C reduction in surface air temperature (Nakajima et al., 2021). These actions but resulted in indoor overheating aggravation among low-income households which cannot afford cooling systems. The pandemic-related economic losses locked them into an unexpected situation. That is to say, urban heat appears to be in a good and positive state, but heat vulnerability is significantly increased, due to the linkages with various socioeconomic factors (Wilhelmi et al., 2021).

Given that the uncertainties caused by pandemics are not well understood, it is required to conduct a review of urban heat variability during COVID-19 and the associated drivers in order to increase societal resilience to urban heat and pandemics. Therefore, this paper provides a systematic review of the literature on both the pandemic and urban heat. In particular, the review paper elucidates the changes in urban temperature, and heat-related air pollution, energy, and public health during the pandemic. Furthermore, this paper analyses the research methods adopted to uncover the impact of the pandemic on urban heat. On the one hand, this paper enhances people's understanding of the heat-related impacts of the intervention of COVID-19 pandemic. On the other hand, with the successful control of the COVID-19 virus, the world is going to enter a post-pandemic era. However, in the post-epidemic era, the dual challenges of the pandemic and extreme heat continue to hinder the normal functioning of society. This paper is therefore conducive to providing strategic recommendations for urban heat preparation, mitigation and adaptation under future large public health events. The remainder of this paper is structured into five sections. Section 2 introduces the research method of this paper. Section 3 presents the compounding effects of COVID-19 and the urban heat in aspects of urban temperature anomaly, air pollution, energy use, and public health and safety. Section 4 analyses experimental design and associated methodological variability for investigating the impacts of COVID-19 on heat-related impacts. Section 5 discusses the findings and proposes recommendations for dealing with the heat and pandemic simultaneously, and Section 6 concludes this paper.

2. Materials and methods

Fig. 1 exhibits a comprehensive framework for understanding the co-occurrence of urban heat and COVID-19. The first section of the framework briefly introduces urban heat in aspects of its definition, causes and effects. Based on this, the second section of the framework regards COVID-19 and its associated impacts as interventions to urban heat for investigating the linkage between urban heat and the pandemic.

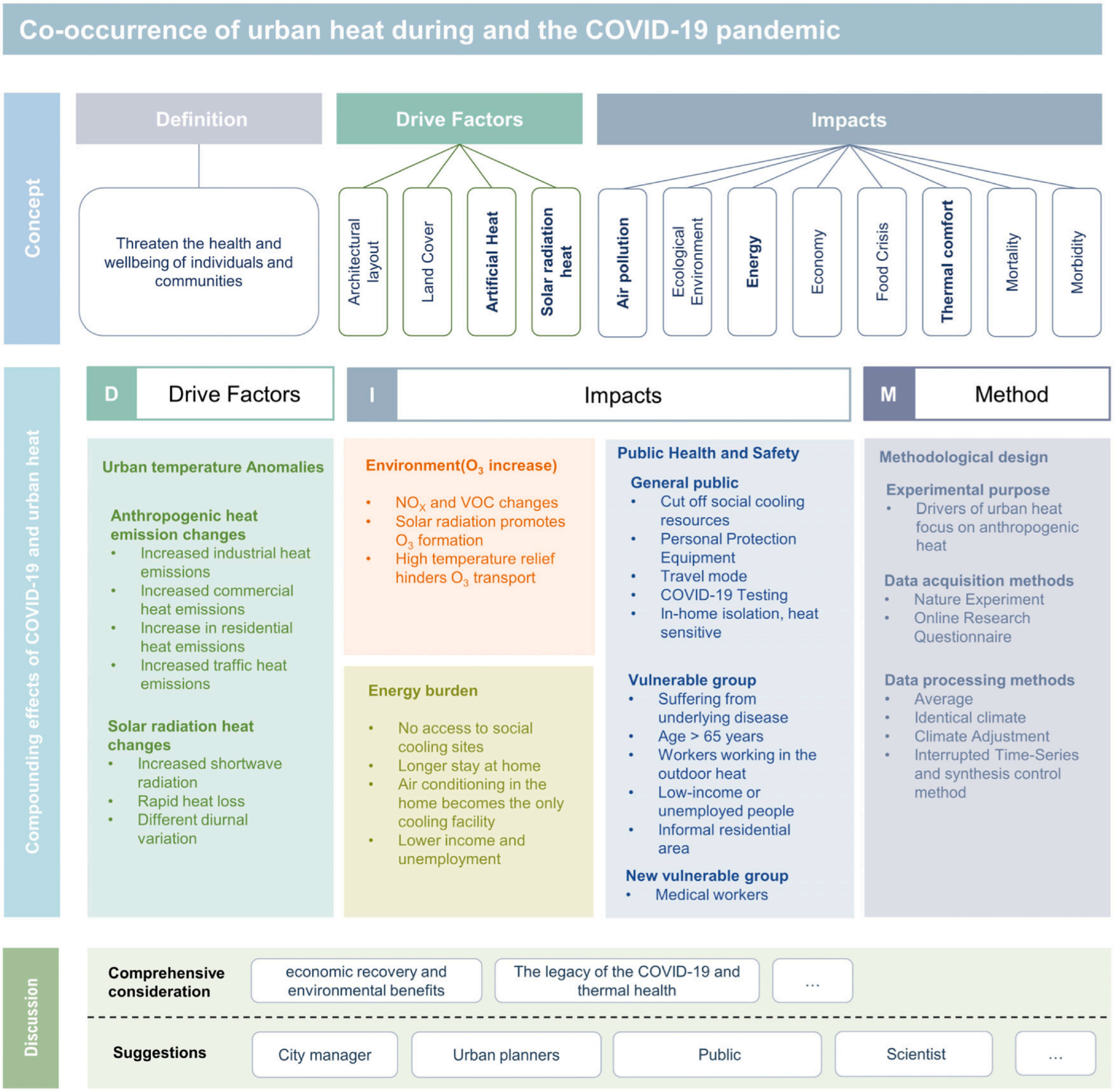


Fig. 1. The framework for urban heat concept, changes, considerations and recommendations.

In particular, their linkages are investigated in aspects of urban temperature anomaly, the environment, energy, public health safety, and research methods. Finally, the discussion section of the framework presents a more comprehensive understanding of the relationship between economic recovery and environmental benefits, as well as the legacy of the pandemic and thermal health. In addition, it proposes strategies for coping with urban heat in the post-pandemic context from various stakeholders in society.

2.1. Urban heat definition, impact and the drivers

Urban heat refers to high temperatures that can threaten the health and wellbeing of individuals and communities (NSW, 2022). Urban heat is intensifying with UHIs and extreme heat events. As a result of global climate change and ongoing urbanization, the frequency and intensity of urban heat keep rising (WHO, 2018). Urban heat causes grave repercussions to the environment, economy, health and safety. For instance, the photochemical phenomenon can lead to an ozone concentration increase as a result of rising urban temperatures. High temperatures have a significant effect on electricity demand for cooling, and every degree of temperature increase can lead to an 0.45%-4.6% increase in peak electricity demand (Santamouris et al., 2015). The morbidity and mortality increase during extreme heat periods. Heat-related physiological illnesses such as respiratory, digestive, thermal skin damage, and cardiovascular disease have been well identified. Increasing numbers of research have shown that heat is also a factor in psychological diseases such as depression, suicide, insomnia, and self-perception problems, as well as other socially undesirable consequences such as crime and domestic violence (Wong et al., 2017). The interaction between work productivity reduction and the burden of cooling utility bills brought by extreme heat can increase public thermal risks, especially among vulnerable groups.

The development of UHI is relevant to the responses of surface energy balance to the modification of urban morphology and the variation of anthropogenic activities. In the spatial dimension, urban ventilation is a significant regulator of UHI intensity (Oke et al., 2017). The closer to the urban core, the lower the wind speed and the greater the anthropogenic warming (Bueno et al., 2012). The land use/land cover has also changed greatly, with vegetated and permeable surfaces replaced by buildings, roads, and other impervious surfaces. Areas with low-albedo construction materials and less green cover generally witness higher air temperatures and greater UHI intensities. In summer, the average air temperature around lawns can be 2.1-5.5 °C lower than that around impermeable surfaces (Huang et al., 2020). Solar radiation is the most significant contributor to urban thermal environments. An increase in aerosol optical depth (AOD) concentration can lead to a decrease in incident short-wave radiation and an increase in long-wave radiation. Compared with the daytime situation, the particulate matter at night is more likely to accumulate and less likely to disperse, thereby contributing more to temperature. A study shows that air pollution can cause an increase of 0.70 ± 0.26 °C in urban nighttime temperatures (Liang et al., 2021). Anthropogenic heat is primarily comprised of emissions from domestic heat sources (especially energy consumption for cooling or heating), transportation heat sources, and industrial heat sources. The contribution of anthropogenic heat to the UHI intensity averaged around 29.6% throughout the day (He et al., 2007). Morphological indicators such as block orientation, street height-to-width ratio, and building density are the control of anthropogenic heat. Therefore, anthropogenic heat emissions and their warming effect can be potentially regulated by appropriate urban design strategies (Kimura et al., 1991).

In the temporal dimension, the nocturnal UHI is generally more intense than diurnal one. This is relevant to the use of artificial materials which have high heat capacity. Such a thermal-radiative property enables materials to store more heat during the day and release more long-wave radiation at night, causing cities to cool more slowly than rural areas (Hou et al., 2022). Moreover, many large cities remain active at night with prominent heat release, compared with their rural counterparts, enabling cities to be warmer. (Soltani et al., 2017) showed a maximum diurnal temperature difference of 4.4 °C in UHI intensity in Adelaide, and the peak of UHI intensity occurred at midnight. Furthermore, (Lee et al., 2010) investigated the diurnal UHI intensity in different seasons and demonstrated that the diurnal variations in UHI intensity were smaller in summer compared to other seasons, in part due to the more rainfall. In addition, anthropogenic heat can also reduce significantly during weekends and holidays. For instance, during the Spring Festival in China, UHI intensity reduced with urban workers migrated outwards, and UHI intensity in Beijing can be 0.3–0.6 °C below normal (Dou et al., 2017).

2.2. Changes in the urban heat challenges during COVID-19

COVID-19 is one of the largest global health crises since World War II (Morabito et al., 2020). It threatens and changes the society in numerous aspects, including the aggravation, mitigation and adaptation of urban heat. During the pandemic, many cities witnessed a reduction in the urban temperature effect. Anthropogenic heat, an important contributor to UHI, may disrupt normal atmospheric circulation and influence urban temperatures (Doan et al., 2019). For instance, government measures such as traffic control and residential segregation have significantly reduced anthropogenic activities, resulting in heat emission reduction and a subsequent change of urban climate. The anthropogenic heat could result in a 2-3 °C increase in near-surface air temperature (Singh et al., 2022). Despite a general downward trend in urban temperature, the heat vulnerability of society as a whole increased. This is because of limited access to cooling resources caused by a chain effect of economic burdens, energy poverty, and social isolation, associated with the lockdown measures across all sectors. The closure of various activities may increase secondary pollutants (e.g. ozone) in cities. The activity reduction could lead to a decrease in airborne particulate matter concentrations and an increase in solar radiation entering the city. This could be a significant factor in accelerating ozone formation and causing an increase in ozone concentrations during the pandemic (Henao et al., 2020). During the pandemic, the burden on the public energy use increased. Due to the city lockdown, the primary office location of most people shifted from companies, schools, and other public places to homes. Payment for cooling also shifted from enterprises to individuals, so that the ability of residents to withstand extreme heat became almost entirely dependent on individuals' ability to afford air-conditioning systems. The shift of office location also implies the variation of waste heat release, relevant to air-conditioning operation, from commercial and factory areas to residential areas, and thereby the UH aggravation in the residential areas. Nowadays, the initial severity of the pandemic is diminishing gradually, and the society goes into a phase of normal prevention and control. Urban temperature and UHIs tend to rebound. Moreover, it is undoubtful that in the post-pandemic era, urban temperatures continue to rise, affecting every aspect of the public's economic and social activities, health care access, and ability to escape the heat.

Apart from daily functions and production patterns, the academia is also shifted by the COVID-19. First, the pandemic has shifted the academic community's attention to the issue of urban heat. Field measurements, face-to-face questionnaire, and interviews are required to be uncontactable to avoid virus transmissions. For example, during the pandemic, a series of heat-related studies were conducted by QR code and online questionnaires in order to follow the COVID-19 restrictions (e.g. isolation) in place (Wilhelmi et al., 2021). Second, heat-related studies are conducted to gain a deeper understanding of the effects and mechanisms of the COVID-19 on urban heat. However, the effects can be intervened by multiple confounding factors. Therefore, to better visualize the challenges posed by the pandemic to urban heat, it is critical to exclude the influence of other factors. For example, to re-analyze the variation of urban heat variables caused by the pandemic-related factor, many innovative data processing techniques

Fig. 2. Distribution of academic research related to urban heat and COVID-19 in countries worldwide.

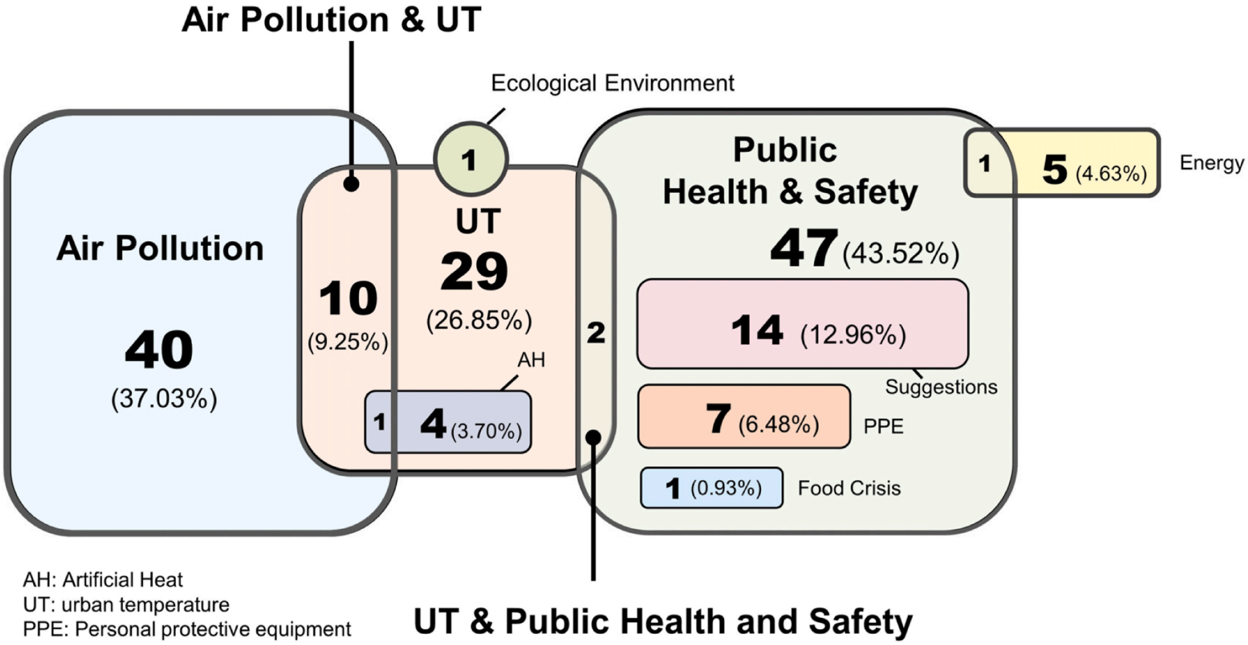


Fig. 3. Depicting the thematic classifications and percentages in the reviewed COVID-19 and urban heat literatures.

(e.g. interrupted time series method, synthetic control method) were proposed and implemented (Burns et al., 2021). Third, personal protective clothing, masks, and the small and confined huts of COVID-19 testing medical personnel have a negative impact on human thermal comfort. In addition to meteorological variables, there is a need to examine the influence of behavioral properties on thermal comfort which is imperative to secure the heat health of medical staff and volunteers. Fourth, the pandemic presents an opportunity to enhance understanding of urban heat causes and effects. Urban activities are well regulated by the COVID-19 restrictions (e.g. lockdown), which can provide a good context to understand activity-related heat variations and to generate implications for heat mitigation. The connection between UHI mitigation and air pollution has also prompted to reconsider the trade-offs and co-benefits between the two.

2.3. Data sources

To comprehend the impact of the COVID-19 on urban heat, this

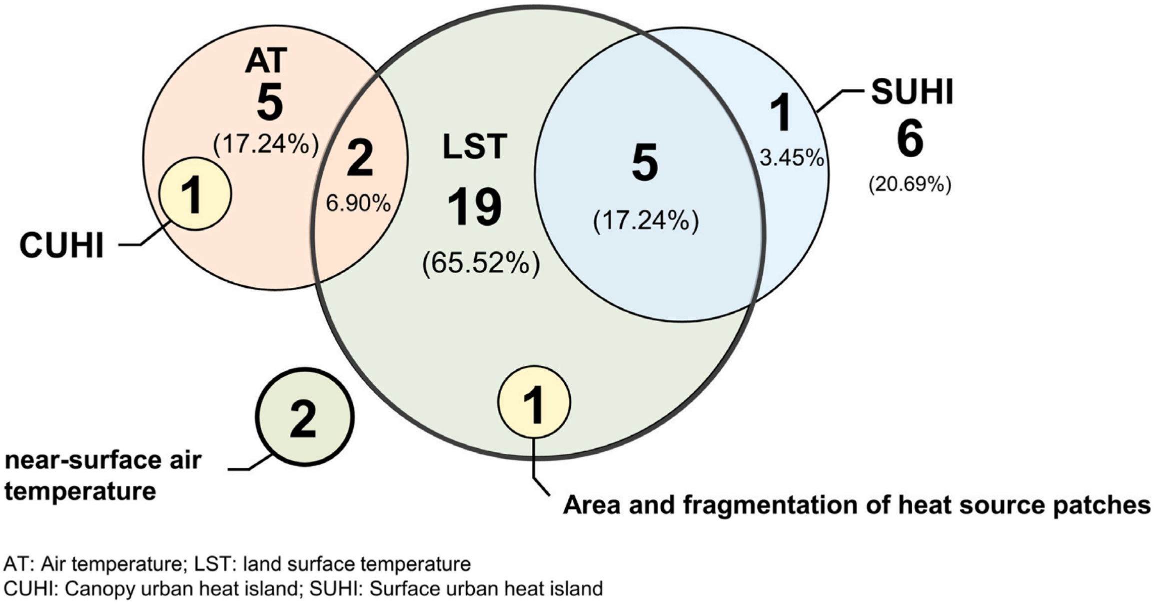


Fig. 4. Assessment indicators for analyzing temperature-related anomalies during the COVID-19 pandemic.

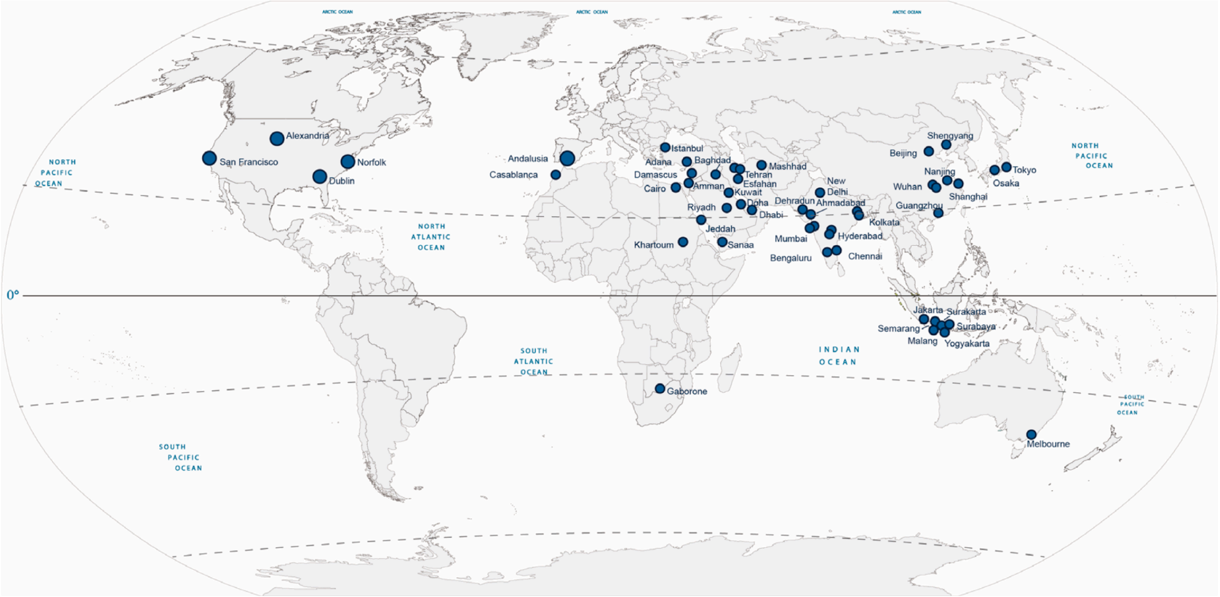


Fig. 5. Distribution of cities as the study context of urban temperature anomalies during the COVID-19. (Cai et al., 2021; Taoufik et al., 2021; Nanda et al., 2021; Nakajima et al., 2021) Parida et al., 2021; Nanda et al., 2021; Potter et al., 2021; Maithani et al., 2020; Wai et al., 2022; Das et al., 2021; Lele et al., 2021; Chakraborty et al., 2021; Sai et al., 2021; Shikwambana et al., 2021; Roshan et al., 2021; El Kenawy et al., 2021; Agni et al., 2021; Roshan et al., 2022; Liu et al., 2022b).

paper presents a systematic review of the existing literature. A systematic search of all possible peer-reviewed literature on COVID-19 and urban heat was conducted on May 20, 2022, via the Scopus database. To make the search as exhaustive and reasonable as possible, the terms such as “urban heat island,” “extreme heat,” “urban warming,” “urban high temperature,” “heatwave,” “COVID-19,” “pandemic,” and “coronavirus disease” were identified. The search was limited to articles published from the time of the pandemic to the present (2020-2022) and containing search terms in their titles, abstracts, and keywords. A total of 554 publications were found after the initial search, after which 316 papers were eliminated for duplication. Finally, 238 papers were subjected to a secondary screening using the following criteria and a thorough reading of the abstracts and full texts (Appendix 1).

(1) Exclude papers that did not provide a substantial analysis of heat-related issues on urban heat occurrence, aggravation, causes, effects, mitigation and adaptation.
(2) Exclude papers that did not provide an understanding of the co-occurrence of the pandemic and the urban heat.

3. Impact of the COVID-19 on urban heat and associated drivers

A total of 108 publications have considered both the pandemic and urban heat. Fig. 2 depicts the origins of the 108 publications. Relevant studies were widely found in the East Asia, South Asia Middle East, Mediterranean area, West Europe, and the North America. The majority of papers are originated in the United States (20), China (16), India (14), and Australia (9). Moreover, the 108 publications mainly cover four subjects including public health and safety (43.52%), air pollution

Table 1
Global urban temperature heat anomalies during the COVID-19.

Region	Lockdown period	Variations	References
Wuhan, China	Lockdown period (2020.02.09) compared to the normal weekday (2019.12.07)	SUHI: -9.41%	(Cai et al., 2021)
Casablanca, Morocco	Lockdown period (2020.03.21 – 2020.05.23) compared to the same period in 2016–2019	LST: -10.96 °C	(Taoufik et al., 2021)
Delhi, India	Lockdown period (2020.04) compared to the same period in 2018–2019	LST: -16.4%	(Nanda et al., 2021)
Ahmedabad, India		LST: -0.64%	
Hyderabad, India		LST: -6.39 %	
Kolkata, India		LST: +12.05%	
Mumbai, India		LST: -4.73%	
Bengaluru, India		LST: -8.19 %;	
Chennai, India		LST: -13.61%	
Osaka, Japan	Lockdown period (2020.6.28) compared to 2019.06.11–2019.06.30	AT: -0.1 – -0.2 °C	(Nakajima et al., 2021)
Europe	Lockdown period (2020.03.10 –2020.05.10) compared to the same period in 2015–2019	LST: -0.11– -2.6 °C	Parida et al., 2021)
North America		LST: -0.70 °C	
Andalusia, Spain	Lockdown period (2020.03–05) compared to the same period in 2019	LST: -4.6 °C (-19.3%) SUHI: -1.02 °C (-59.8%)	(Nanda et al., 2021)
San Francisco, US	Lockdown period (mid-March to late May 2020) compared to the same period of 2017–2019	LST: -5 – -8 °C	(Potter and Alexander, 2021)
Dehradun, India	Lockdown period (2020.04.14) compared to 2019.04.28, 2018.04.25 and 2017.05.08	LST: -8.23 °C	(Maithani et al., 2020)
Melbourne, Australia	Lockdown period (2020.01–2020.08) compared to the same period of 2017–2019	SUHI: -0.1125 °C	(Wai et al., 2022)
Tokyo, Japan		SUHI: -0.165 °C	
New York, US		SUHI: -0.315 °C	
Dublin, UK		SUHI: +0.085 °C	
Oslo, Norway		SUHI: -0.0425 °C	
Kolkata, India	Lockdown period (2020.04) compared to the same period in 2019	LST: -0.64 °C	(Das et al., 2021)
Mainland India	Lockdown period (2020.03.25–2020.04.15) compared to the same period in 2019	LST: -2 to -6 °C	(Lele et al., 2021)
India	Lockdown period (2020.04.01–2020.05.15) compared with the same period of 2015–2019	SUHI: -0.56 to -0.97 °C	(Chakraborty et al., 2021)
Hyderabad, India	Lockdown period (2020.03.23–2020.06.30) compared with the same period in 2019	LST:3 – 5 °C	(Sai and Singh, 2021)
Gauteng, South Africa	Lockdown period (2020.03.27–2020.04.30) compared with the same period in 2019	LST: -3 °C	(Shikwambana et al., 2021)
Tehran, Iran	Lockdown period (2020.03.20–2020.04.20) compared to the same period of 1950–2019	AT: -5 – -10 °C	(Roshan et al., 2021)
21 major cities in the Middle East	Lockdown period (2020.03–06) compared to the same period 2003-2019	SUHI: -1.16 °C – +2.7°C	(El Kenawy et al., 2021)
Bandung, Indonesia	Lockdown period (2020.04–06) compared to the same period in 2019	LST: -1.58 °C	(Agni et al., 2021)
Semarang, Indonesia		LST: -3.68 °C	
Surakarta, Indonesia		LST: -2.68 °C	
Yogyakarta, Indonesia		LST: -3.32 °C	
Surabaya, Indonesia		LST: +1.92 °C	
Malang, Indonesia		LST: +1.01 °C	
Esfahan, Iran	Lockdown period (2020.03.20~04.20) compared to the same period 2000~2019	LST max: -9.42 °C; LST min: -2.94 °C	(Roshan et al., 2022)
China	Lockdown period (2020.01~04) compared with the same period 2017–2019	SUHI: Southern: -0.65 – -0.41 °C; Northern cities: -0.23 – -0.29 °C	(Liu et al., 2022)
Shenyang, China		CUHII: -0.53 °C (27%)	
Beijing, China		CUHII: -0.47 °C (21%)	
Wuhan, China		CUHII: -0.52 °C (33%);	
Shanghai, China		CUHII: -0.51 °C (27%)	
Nanjing, China		CUHII: -0.40 °C (35%);	
Guangzhou, China		CUHII: -0.45 °C (29%)	

(37.03%), urban temperature (26.85%) and energy (4.63%) (Fig. 3). The public health and safety received the most attention, and it had multiple sub-categories, such as recommendations on the heat and pandemics (12.96%), personal protective equipment (PPE) (6.48%), food crisis (0.93%), urban temperature (1.85%), and energy (0.93%). Despite their divergent topics, these publications were linked with social vulnerability. On the urban temperature, there were 10 papers simultaneously addressing air pollution, in addition to five and one papers focusing on energy and ecological issues, respectively.

3.1. Urban temperature anomalies

There were 29 papers on urban temperature anomalies. The determination of urban temperature indicators gives people a uniform standard and a more scientific measure to compare the temperature changes in various cities. Air temperature (AT) and land surface temperature (LST) can be adopted to directly show urban temperature. The surface UHI intensity (SUHII) and canopy UHI intensity (CUHII) are also prevalent to show the urban-rural temperature difference implying the disparity of urban surface energy balance. Fig. 4 presents an overview of the assessment indicators of urban temperature anomalies, in which 19 of the papers adopted LST to measure urban temperature. The LST could account for the highest proportion (65.52%) as it is retrieved from remote sensing inversion, a large measurement range method which can interpret large-scale urban heat variability and vulnerability (He et al., 2022). The remote sensing is also a non-contact method is always, allowing people to keep urban temperature studies during the pandemic. Moreover, six papers (20.69%) adopted SUHI as the measurement indicator, and five papers (17.24%) adopted AT to investigate temperature-related anomalies during the COVID-19 pandemic.

Fig. 5 reveals distribution of 46 cities which were adopted as the context of for urban temperature variability investigation. The 46 cities

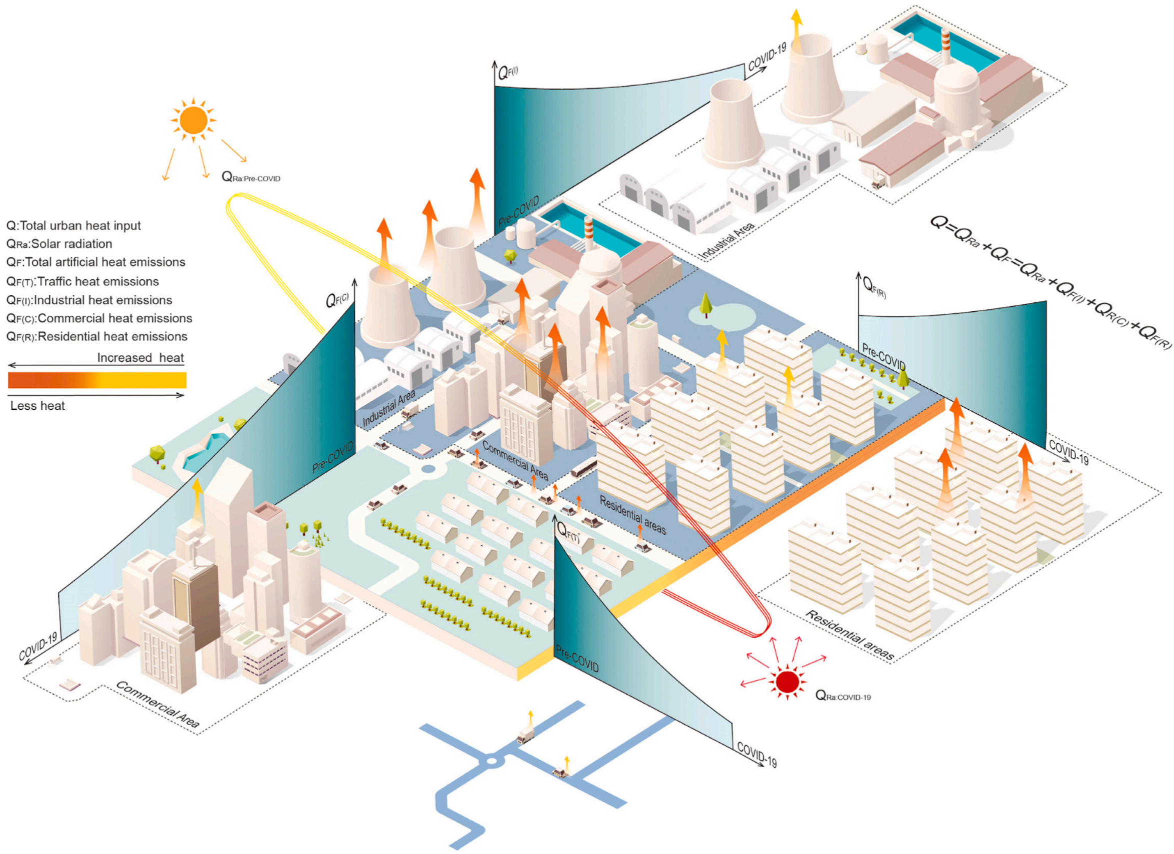


Fig. 6. Trends in urban heat input during the COVID-19 pandemic lockdown.

consisted of 37 from developing regions (e.g. East Asia, Middle East, Southeast Asia) and nine from developed regions (e.g. North America, Japan, Mediterranean Area). All 46 cities underwent negative temperature anomalies, where Table 1 documents specific variations. Five major conclusions were obtained: (1) The majority of regions experienced a substantial decrease in urban temperature during the pandemic, whereas a few regions experienced an increase. (2) The nighttime cooling of urban temperature was prominent, whereas the daytime cooling was minimal or even higher than urban temperature before the pandemic. (3) The average LST decrease in developed cities was smaller than that in developing countries. (4) The CUHI was more sensitive to anthropogenic heat than SUHI. (5) The UHI decrease weakened with latitude increase during the lockdown in China.

Urban temperature anomalies were associated with heat source variability during the pandemic, especially anthropogenic heat and solar radiation, which intervened the normal urban surface energy balance. The anthropogenic heats varied in four aspects including industrial heat, commercial heat, residential heat, and transportation heat. In comparison, the impact of solar radiation on the urban temperature is relevant to the air pollution. For example, the attenuation rate of solar radiation due to air pollution ranges from 1.32% to 6.03%, and in a haze condition in the North China (Yang et al., 2022), and the AOD-induced radiation reduction could cool surface temperature by about 3 °C (Miller et al., 2021). Specific pandemic-related changes of heat sources are shown in Fig. 6. On the anthropogenic heat, industrial heat emissions showed different trends, causing cooling effect differences in industrial and non-industrial areas. In peninsular India, the LST of intensive industries decreased by 5 °C, while non-industrial sites decreased by only 1 °C (Pal et al., 2021). Some cities implemented relatively lax lockdown measures or no industrial economic activity restrictions, and the urban temperature decreased less significantly and, even increased in some cases. In two major Indonesian cities, the LST rose 1.92 °C in Surabaya and 1.01 °C in Malang (Agni et al., 2021), respectively. Kolkata, an Indian city primarily engaged in agricultural and industrial activities, experienced a 12% increase in LST during the pandemic compared to the same period in 2019 (Nanda et al., 2021). This indicates that physical modifications towards built environment and meteorological factors dominated if the lockdown policy was not stringent.

Commercial heat emissions decreased significantly as a result of antiviral regulations by reducing public activities, and encouraging household work and self-isolation. In Osaka, Japan, for example, the daytime population in commercial areas reduced by 75%, resulting in a 90.2% reduction in heat emissions associated with air-conditioning cooling and a 0.13 °C drop in LST (Nakajima et al., 2021). The same phenomenon was found in Semarang, Indonesia, where state restrictions on social and economic activities resulted in the greatest LST drop of 3.68 °C (Agni et al., 2021). During the pandemic, there was also a significant decrease in traffic and travel distance. For instance, traffic volumes in Tehran decreased by 50-85% (Roshan et al., 2021), and the average travel distance in the Montreal metropolitan area decreased by 76% (Teufel et al., 2021). Accordingly, the traffic heat emissions decreased significantly. In Osaka, traffic heat emission in commercial areas decreased by 9.8% and that in residential areas by nearly 4.9% (Nakajima et al., 2021). Studies also confirmed that an 80% decrease in traffic heat emission could result in a 1 °C decrease in near-surface AT (Teufel et al., 2021). During the pandemic, the population living in residential areas may increase compared with the pre-pandemic period. In Osaka, the population in residential areas increased by 30%, and the anthropogenic heat emission increased by 2.5 W/m^2, resulting in a LST increase by about 0.1 °C (Nakajima et al., 2021).

Solar radiation is another important intervention of urban temperature during the COVID-19 pandemic, while this process can be affected by the AOD concentrations. In general, AOD particles reflect solar radiation back into space, thereby decreasing the amount of solar radiation that

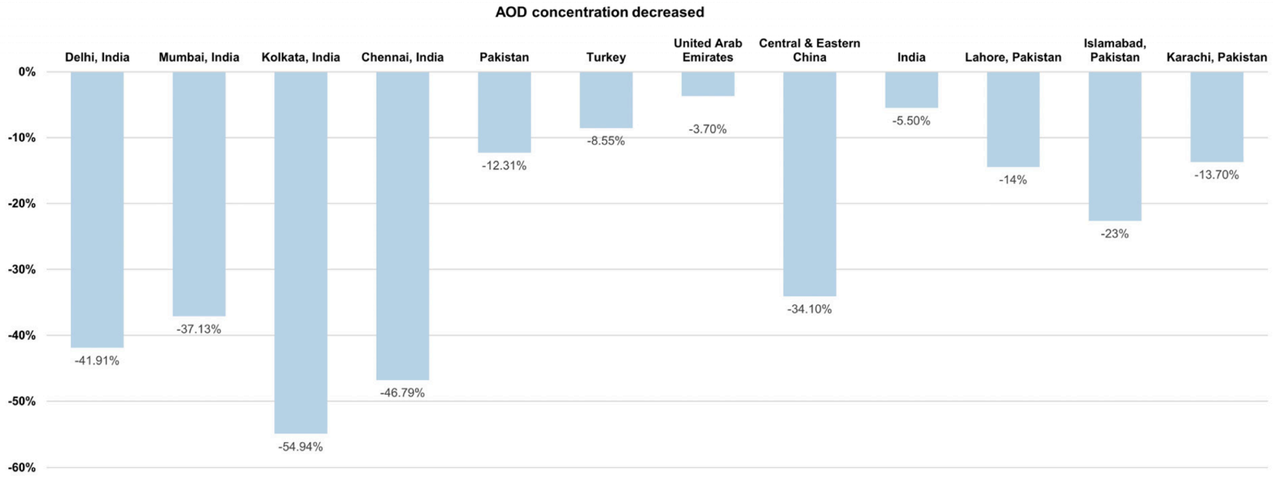


Fig. 7. The AOD variations in lockdown period in 2020 compared to 2019. (Pal et al., 2022; Ali et al., 2021; Ghasempour et al., 2021; Alqasemi et al., 2021; Miller et al., 2021; Chakraborty et al., 2021; Syed et al., 2021).

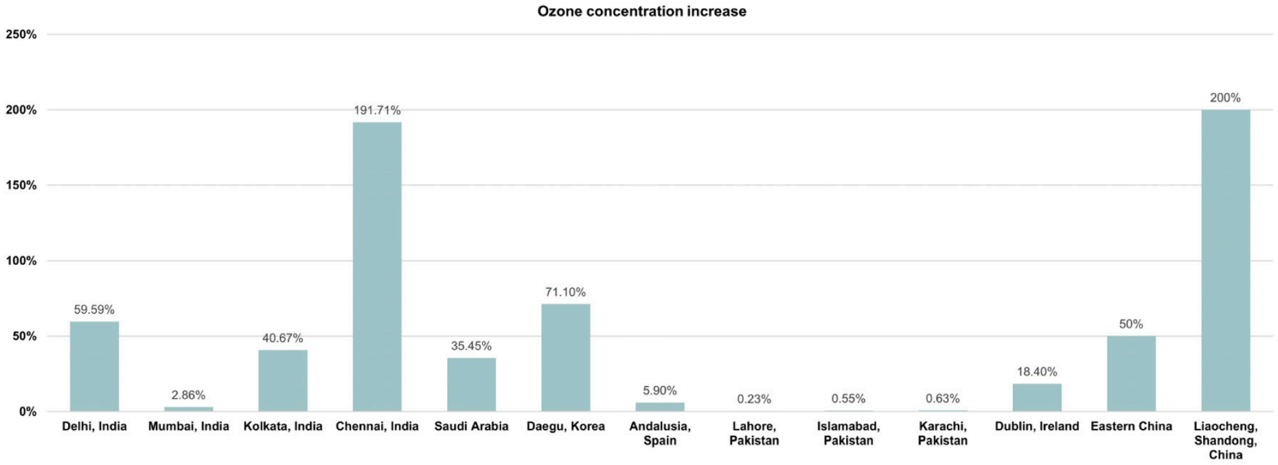


Fig. 8. The ozone variations in lockdown period in 2020 compared to 2019. (Pal et al., 2022; Keshtkar et al., 2022; Vuong et al., 2020; Hidalgo Garcia et al., 2022; Syed et al., 2021; Perillo et al., 2022; Fan et al., 2021; Li et al., 2021).

reaches the surface. AOD particles can also absorb long-wave radiation from the earth surface, contributing to ground warming. Overall, the incidence of solar radiation, especially the shortwave radiation, generally increased with the decrease in AOD concentration (Fig. 7) (Cao et al., 2016). In Mumbai, for instance, the solar radiation intensity increased from 827 W/m^2 prior to the lockdown to 948 W/m^2 during the lockdown (Gupta et al., 2020). The decrease in AOD concentration in the atmosphere permits the heat to dissipate as rapidly as possible. During the pandemic, therefore, both radiant heat input and heat dissipation increased. Nevertheless, the decrease in daytime urban temperature was not significant. In comparison, heat loss at night was enhanced due to the absence of AOD insulating shield, and many cities experienced a greater reduction in nocturnal temperature than diurnal temperature. For instance, Pierre (United States) experienced a 1.65 °C drop in LST at night and a 0.44 °C drop during the day (Parida et al., 2021).

3.2. Ozone pollution with urban temperature anomalies

There were 40 papers on air pollution, covering trends in pollutants such as NO_x, SO_2, O_3, $PM_{2.5}$, PM_{10}, and CO during the pandemic, with the consideration of control measures during the pandemic. Nevertheless, this section is not to reveal changes in the concentrations of individual pollutants during the pandemic, but to analyze changes in the concentrations of pollutants closely associated with high temperatures and the reasons for their changes. For example, NO_x concentration declined by 20%-80% worldwide during the outbreak (Burns et al., 2021; Lin et al., 2021; Perillo et al., 2022; Pal et al., 2022), primarily due to a reduction of motor vehicles rather than temperature anomalies, so that it is not the focus for consideration. In comparison, ozone cumulation is highly relevant to the temperature-related photochemical effects, and it will be mainly analyzed in this section.

Overall, ozone levels increased significantly during the pandemic period (Fig. 8). The primary causes are threefold. First, the precursors of ozone formation, such as NO_x and VOC, did not change proportionally during the pandemic period. One of the largest contributors to NO_x is the "traffic" sector. In Europe, traffic contributed 39% while non-road traffic contributed 8% (Sicard et al., 2020). Given different levels of sector closure, traffic activity decreased more than industrial activity (Zhao, 2020), resulting in a greater decrease in NOx than VOCs. Ozone production was highly dependent on the relative concentrations of VOC and NOx, with a VOC/ NO_x ratio between 4:1 and 10:1 being optimal for ozone formation (Oke et al., 2017). Higher VOC concentrations accelerated the chemical reaction rate, whereas lower NO_x concentrations decelerated the titration rate of ozone ($NO+O_3 \rightarrow NO_2+O_3$). Therefore, the dramatic decrease in NO_x during the pandemic might be a significant contributor to the enhancement of ozone pollution. Second, the dramatic decrease in AOD, during the pandemic period, enhanced the incidence of solar shortwave radiation. The photochemical reactions for ozone formation could be accelerated by the high intensity of shortwave radiation (Fallmann et al., 2016). Third, as a result of the pandemic-related UHII reduction, which improved atmospheric stability and altered the vertical transport of ozone in cities (Henao et al., 2020), allowing the pollutants to concentrate near emission sources and preventing its dispersion to surrounding areas. Ozone concentrations in the lower atmosphere would endanger human health and intensify the greenhouse effect. Additionally, elevated ozone levels inhibited plant growth, resulting in lower crop yields (Zhang et al., 2019).

3.3. Energy

Implementation of COVID-19 restrictions such as the reduction of all unnecessary economic activities limited total urban energy demand (Nundy et al., 2021). It is found that China's electricity demand in February 2020, when the nation was lockdown, was 11% less than that in February 2019 (IEA, 2021). Despite this, the electricity burden increased during the pandemic depending on the socioeconomic features. During the outbreak in Illinois, for example, the energy burden on low-income consumers rose from 2.31 % to 2.44 % (Lou et al., 2021), and heat threats to the public increased as well. It should be noted that the reduction of urban temperature did not necessarily lead to the decrease in urban electricity demand. Instead, it resulted in a change in energy use patterns of buildings characterized by different types. The majority of public buildings, particularly office and educational structures, had a significant reduction in energy consumption, whereas residential structures saw energy use increase. The electricity consumption of public buildings in Korea decreased by 2.70-21.56% in 2020, compared with 2019, while that of multifamily residences increased by 3.17 % (Kang et al., 2021). In the United Kingdom, during its strictest lockdown in 2020, electricity use of a residential project increased by approximately 7 % compared with the same period in 2019 (Tubelo et al., 2022).

Anti-pandemic policy adoption also reduced access to public spaces and increased time indoors, forcing people to change the way to adapt to the heat. Typically, the public adapt to the summertime heat by frequenting air-conditioned indoor spaces such as libraries, shopping malls, and workplaces, or by venturing outdoors to green spaces, water bodies, and parks. However, the arrival of the pandemic disrupted this adaptation pattern. Restrictions of closing public places or limiting people to enter could decrease the availability and accessibility of public cooling resources. The self-preservation and the panic further caused people to stay at home over venturing out. Air conditioning was the only means by which family residences obtained continuous cooling when hot weather happened. The transition from the public access to electricity which was paid by government, enterprises, or communities to individuals unquestionably increased individuals' electricity burden. Due to electricity price increase and unemployment caused by the pandemic, people were less able to use air-conditioning systems. The empirical studies demonstrated a strong correlation between heat-related symptoms during the pandemic and the inability to change one's behavior for air-conditioned areas (Wilhelmi et al., 2021). Overall, the pandemic and the heat, synergistically exacerbated energy insecurity among individuals, especially for the economically vulnerable groups, and in turn increased the public's heat stress.

3.4. Public health and safety

Although urban temperature generally decreased during the pandemic, the slight UHII relief did not place cities in a full cool temperature range. Cities are still under the threats of extreme heat, given the increasingly frequent, intense, and severe extreme heat events. The pandemic lockdown period (in March–May 2020) saw the coldest spring of North America since 2014 (NOAA, 2020), but the temperatures were still above the average. To prioritize anti-pandemic measures, social cooling adaptation and mitigation strategies were limited, and people were forced to change their daily heat prevention behaviors. The imbalance between the two, where heatwaves persisted and cooling measures could not be accessed as before, increased the number of vulnerable groups and their heat susceptibility.

3.4.1. Heat impacts onto the general public

The general public refers to the people who were able to escape the heat impacts prior to the onset of the pandemic, but the arrival of the pandemic increased their difficulty in coping with the heat and their likelihood of heat illnesses. Access to social cooling resources was more difficult than ever before due to the restrictions such as home isolation, traffic control, and the reduction of unnecessary social gatherings. First, public spaces such as shopping malls, subway stations, city parks, and libraries were closed, preventing people to access to public cooling spaces in these areas. The majority of large naturally cooling places discouraged people to enter, exposing people to additional heat risks. Second, the top-down focus on the pandemic diverted early heat warning information, preventing people from being prepared prior to the onset of heatwaves. In particular, the heat warning plan implementation could reduce mortality by at least two-thirds (Fouillet et al., 2008). Therefore, reducing access to heat-related social information could increase public heat insecurity. Third, masks, gloves, and protective clothes could help prevent virus spread, but they could also prevent the body from heat exchange with surroundings through breathing or skin. As suggested by the ISO 7933 (2004), if the body's core temperature exceeds 38 °C, the heat will cause excessive and abnormal physiological changes among the majority of people (Broede et al., 2018). A study of PPE and heat stress found that 72.3% of the respondents felt "hot", 89.7% felt "very uncomfortable" or "uncomfortable", and 98.7% felt "uncomfortable" when wearing PPE (Davey et al., 2021). Fourth, people's travel preferences also changed, with people less likely to choose public transportation and carpooling services (Loa et al., 2021). Public transportation dropped by 80% during the pandemic (Wai et al., 2022), while the walking or bicycling modes increased the risk of heat exposure. Moreover, public transportation required the use of a mask, and the uncomfortable nature of heat was amplified in the confined and cramped subway or bus space. Fifth, the anti-pandemic policy fostered the routine mass COVID-19 testing in high-risk areas, increasing the heat threats to the public when standing in line. Sixth, people stayed at home between 10%-40% longer since the outbreak than they did prior to the outbreak (Data, 2020). Being socially marginalized and overly concerned about the pandemic for an extended period of time also made the public more sensitive to heat perception, increasing people's psychological burden and subsequently contributing to psychological and social illnesses such as depression, insomnia, domestic violence, and crime (Fuse-Nagase, 2022).

3.4.2. Vulnerable groups

Vulnerable groups are those susceptible to heat shock before the pandemic, and the onset of the pandemic exposes them to additional heat impacts. First, both the COVID-19 and the heat were more likely to affect individuals with underlying medical conditions and those older than 65 (Shumake-Guillemot et al., 2020). This was partly due to the low immunity of this group. However, during the pandemic, medical resources were overburdened, making it impossible for the public to receive timely medical care for heat-related illnesses. Second, outdoor workers were also vulnerable. They might not be required to wear tight protective clothing, but the masks they wore could increase their skin temperature and heart rate, ultimately resulting in diminished health and comfort (Liu et al., 2020). The third was the population with low or no income. It is estimated that the global economy shrank by 3% in 2020 (IMF, 2020), and losing a job or having a lower income decreased people's ability to use household air-conditioning facilities. The inhabitants of informal settlements were the fourth group. Informal settlements were distinguished by high building density, low green space coverage, poor thermal performance of building maintenance structures, and lack of effective domestic cooling facilities. Their outdoor temperatures were generally

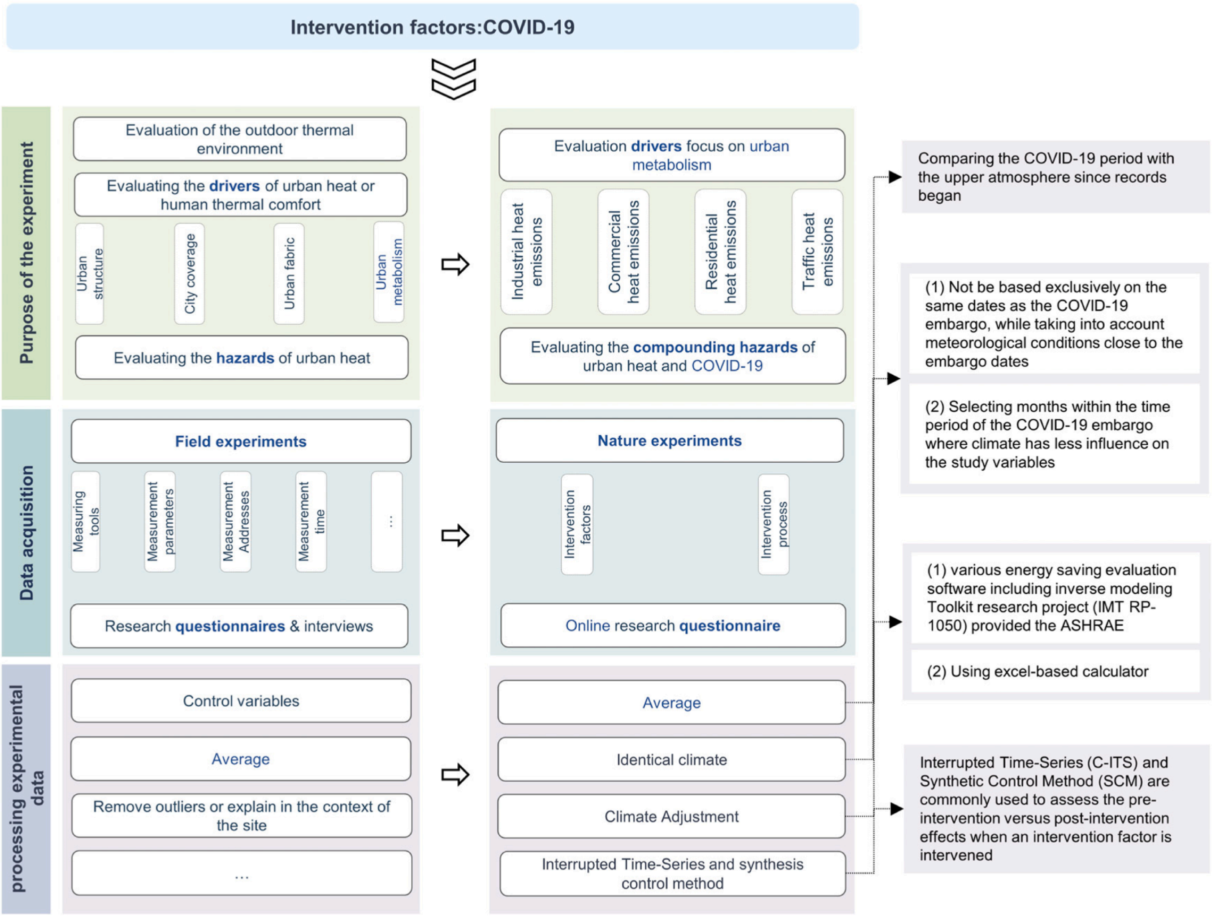


Fig. 9. Comparison of the main research methods on the urban heat before and after the COVID-19 intervention.

higher than formal settlements, and thermal discomfort indoors was significantly worse. In Ahmedabad, India, informal settlements were typically 2–3 °C warmer than formal areas, whereas houses in informal areas of Johannesburg were typically 4-5 °C hotter than the outdoor temperature (GHHIN, 2020d). In addition, the adoption of cooling strategies such as the installation of public faucets and temporary water points, for heat adaptation might increase the risk of the virus spreading throughout the community (e.g. public water supply). Consequently, the general public in informal settlements was exposed to a more dangerous situation than those in formal urban areas.

3.4.3. *New vulnerable groups*

The new vulnerable group refers to a new generation of individuals who were able to escape the heat prior to the outbreak, but the outbreak exposed them to stronger heat threats among the public. Co-occurrence of the pandemic and the heat widened the reach of vulnerable groups (GHHIN, 2020c), and more social groups faced heat health and heat safety difficulties. The first were medical personnel. Healthcare staff were overburdened during both peak and normal pandemic periods. They were also often faced with excessive working hours, harsh working conditions (e.g. heat, sun, cold), closed and impermeable protective clothing, etc. Particularly in the context of summer outbreaks, workers in tight protective clothing performed single, repetitive nucleic acid tests for extended periods of time outdoors, increasing the thermal burden on healthcare workers and making their bodies enter a state of disorder and dysregulation (Lee et al., 2021). In addition, the virus was highly contagious and the resemblance of the initial symptoms of fever-related disorders to those of COVID-19 discouraged hospitalization (GHHIN, 2020a). Overall, their occurrence could wreak havoc on people's physical and emotional health.

4. Methodological design

4.1. *An overview of urban heat research methodology*

The research methodology of urban heat consists of three components of establishing research objectives, collecting experimental data, and analyzing data (Fig. 9). Research objectives can be categorized into three groups, including assessment of outdoor thermal environment conditions, analysis of urban heat hazards, and assessment of human thermal comfort (Liu et al., 2022a). Identification of experiment's objectives aids in developing a thorough protocol, and determines experimental program for use. The experimental design should clarify methods and parameters for obtaining experimental data. The data collection should respect experimental site, time, and tools. In field measurements, air temperature, relative humidity, wind speed, and solar radiation are frequently regarded parameters. Sometimes, the concentration of pollutants in the atmosphere is one of the most important measuring factors for the investigation of thermal problems, and it can be detected using specialized sensors or satellite remote sensing. Potential sites should have obvious key drivers that affect the outdoor thermal environment, such as particular building layouts, surface covering materials, anthropogenic heat, etc(Oke, 2004). These experiments are typically conducted with control variables and excluding other confounding variables.

On the data analysis, given the complexity of the outdoor environment, systematic errors are inevitable, although the experimental design for field experiments has attempted to avoid the interference of numerous factors. Therefore, the abnormal data results need to be further analyzed or rejected in conjunction with the recorded logs of the field experiments. Moreover, to reduce the measurement error, typical

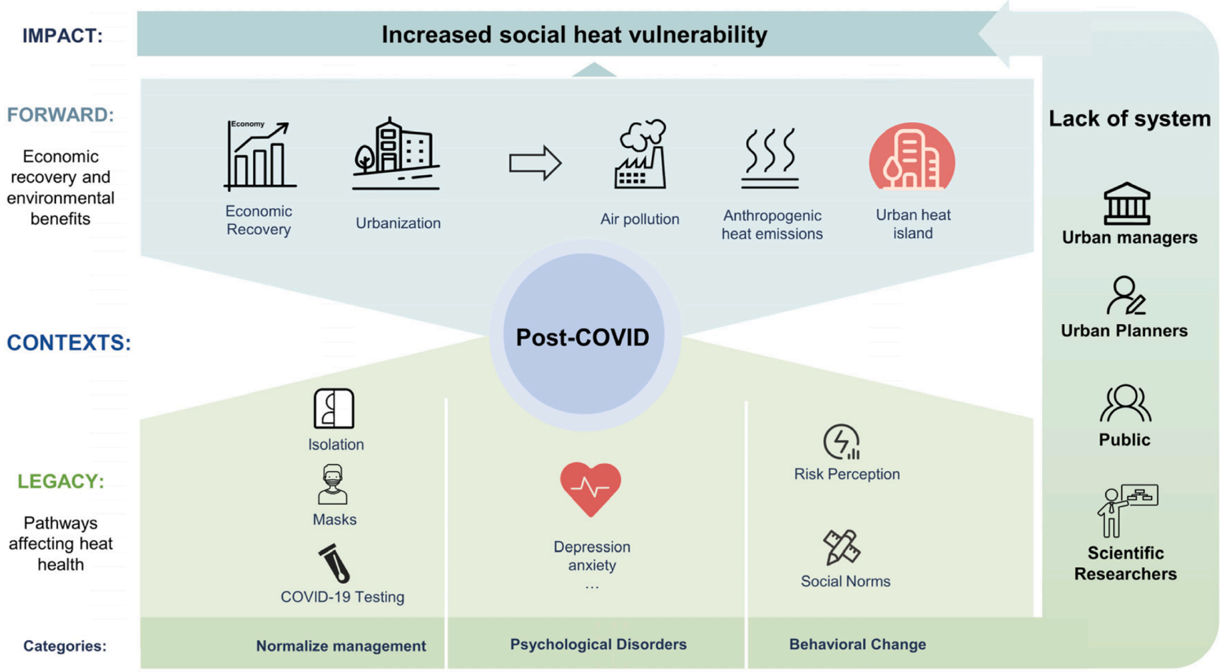


Fig. 10. The influence path of urban development and COVID-19 legacy on urban heat in the post-pandemic era.

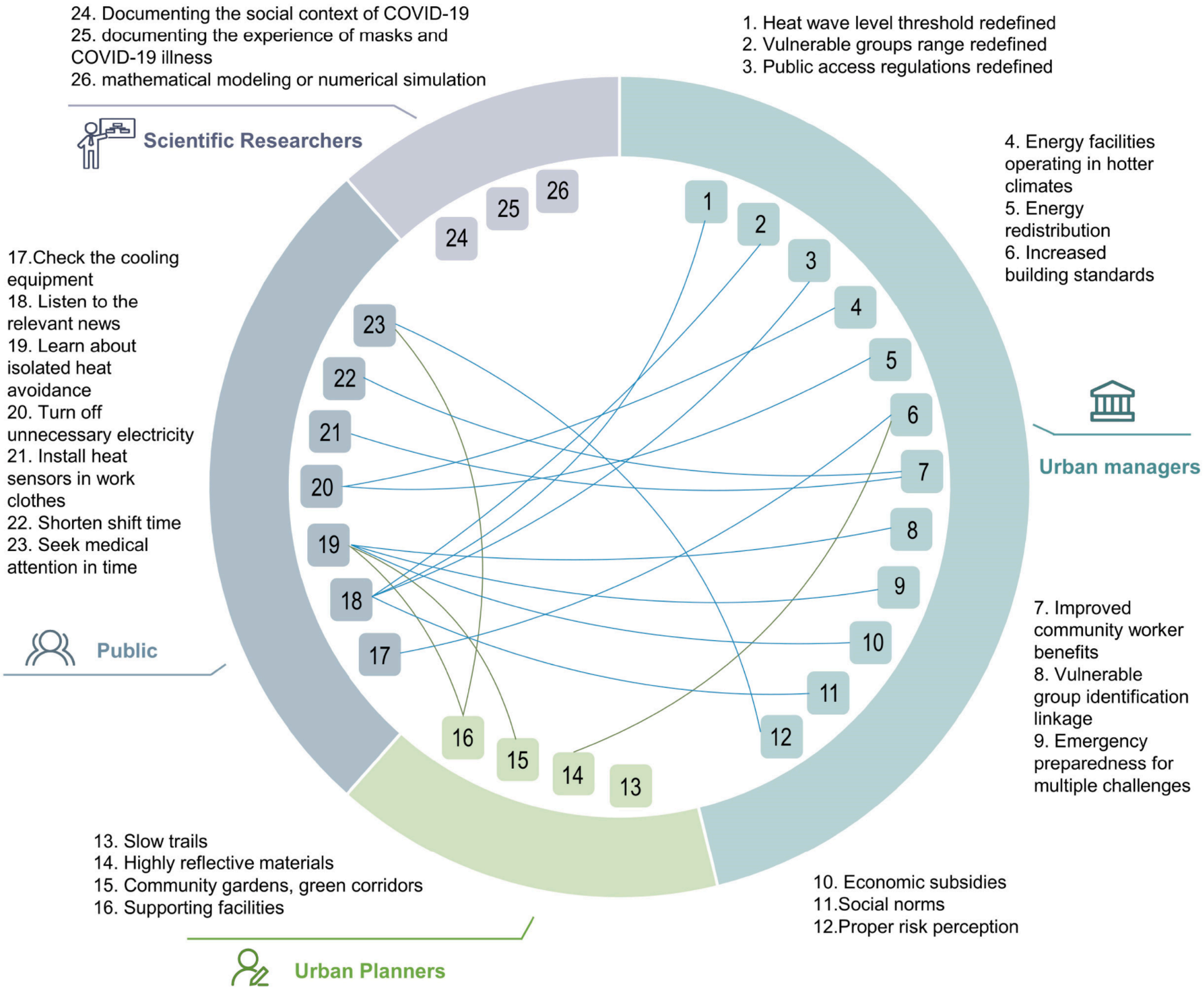


Fig. 11. Suggestions for urban heat and health action plan in the post-epidemic era.

weather conditions are generally selected for averaging over multiple days of measurements, and raw data can be averaged in 5-10min increments (Liu et al., 2022a).

4.2. COVID-19 caused changes in experimental design for investigating urban heat challenges

An examination of the research methods in 64 papers revealed distinct variations in experimental objectives, data collection, and data analysis (Fig. 9). Urban structure, cover, texture, and metabolism are ordinarily the primary variables in experiments for understanding the determinants of urban thermal environment (Oke, 2004). However, the anti-pandemic measures shifted urban metabolism to be the primary driver. There were also differences between pre- and post-pandemic experiments to examine the urban heat hazards. Pre-pandemic research focuses on a single effect of urban heat (i.e. on energy use) (Santamouris et al., 2015). After the pandemic it is essential to analyze the co-impacts of the COVID-19 and urban heat, or the relationship between the COVID-19 intervention and urban heat outcomes, such as the pandemic intervention to air pollution and energy use (Farahat et al., 2021; Wang et al., 2021b)(Fig. 9a). Remote sensing, official published data, and online questionnaire were key methods of data acquisition. Such experiments can be done as natural experiments for investigating the effects of naturally occurring variables on the outcome of interest (Craig et al., 2017), while can be traced back to John Snow's seminal mid-19th-century study of the London Cholera Pandemic (Snow, 1849). The primary distinction between a natural experiment and a field scientific experiment is whether a group or unit is randomly assigned to a control or intervention group (Craig et al., 2017). If this allocation is random, the difference in mean outcomes between the two groups can be used to estimate the causal effect of an intervention factor. However, the majority of natural experiments lack such randomization, necessitating the use of a variety of experimental methods to eliminate this systematic error (Fig. 9b).

Transformation of data analytical method is also a challenge caused by the pandemic. To achieve the experimental objectives, experimental data should be processed with intent for the presence of multiple confounding factors in natural experiments. Deliberately, the data analysis was to reduce or eliminate the impact of non-pandemic factors, particularly climatic factors. Through the literature review, this section identified four types of data analytical methods (Fig. 9c). The first is the comparison of the average background conditions over the long term in the past. The objective was to minimize the impact of non-COVID-19 intervention factors (e.g. climate fluctuations) on experimental outcomes. To avoid confusion between changes caused by atmospheric climate and those caused by anti-pandemic measures, the upper atmospheric conditions over the previous decades were compared with that in the pandemic period (Roshan et al., 2021). During the lockdown period (March-April 2020), the upper atmosphere conditions were largely comparable to the long-term average, and heat island areas in 2020 were the lowest ever recorded. This verifies the reduction in urban heat island during the pandemic was related to anti-pandemic measures rather than weather conditions. Second, when comparing the changes in parameters before and after the pandemic, determining time periods before the pandemic was essential for comparison. However, some studies did not rely solely on the same dates as the COVID-19 lockdown, while the meteorological conditions similar to the lockdown period were also considered. Overall, they selected the time range that had the least impacts on the variable of interest among the available time ranges (Taoufik et al., 2021; Perillo et al., 2022).

Third, climate adjustment by calculating correction factors was adopted to compare the changes in energy use of different building types before and after the pandemic, based on the same climatic background conditions. The Climate Adjustment Toolkit in energy efficiency software was one method, while multiple regression in Excel could be used to derive correction factors (Kang et al., 2021). Both approaches utilized two representative indicators that relate energy use to local climate, such as the heating degree day (HDD) and cooling degree day (CDD). Fourth, evaluation utilizing interrupted time-series analysis methods (TIS) and synthetic control (SC) methods(Burns et al., 2021; Bouttell et al., 2018), were frequently used to evaluate the effect of an intervention before and after its implementation. These techniques were also applicable for analyzing variations in study results before and after the pandemic. Both methods can ensure that the changes that occurred during the pandemic were caused solely by the intervention and not by other factors (Fig. 9d).

5. Discussion and implications

There have been numerous studies on the COVID-19 since its outbreak. However, these studies have only singularly described the various changes that occurred during the pandemic and lacked the analysis of the intervention processes and intervention mechanisms of such changes on urban heat. This paper clarified the phenomenological characteristics, drivers, and impact outcomes of the new challenges faced by urban heat during the pandemic. By now, another trend is that the majority of regions around the world have entered the post-pandemic era. However, the post-pandemic era is not the same as the pre-pandemic era. The increased risk of disease heightened awareness of self-protection, and psychological disorders present in the post-pandemic era have led to altered behavioral patterns in coping with urban heat so that human beings are still suffering from severe survival and health pressure in the post-pandemic context. In the post-pandemic era, it is important to promote society forward and to make up for the losses caused by the pandemic by urging industries to resume work and promoting economic recovery. Meanwhile, the legacy of the pandemic will continue to affect public health, safety and well-being (Fig. 10). Therefore, in this section, the heat-related contradictions the public may face in the post-pandemic were analyzed. The analysis reflects practices in urban management, urban planning, and public participation and provides strategic recommendations in different participatory roles of cities.

5.1. The trade-off: economic recovery and environmental benefits

Economic recovery is an urgent issue for all countries in the post-pandemic era. The economic recovery drives urbanization, with far-reaching implications for environmental sustainability, making economic recovery and environment protection a dilemma. During the pandemic, there was a decrease in anthropogenic heat, an improvement in air quality, and a reduction in urban temperature, all of which were the result of the general cessation of human activity. The important implication is that countries are still dominated by carbon-intensive economies, and if the post-pandemic era cannot balance the relationship between economic growth and climate environment, humanity will face greater crises and challenges.

The global pandemic is gradually under control, energy use inevitably stimulates air pollution during the economic recovery. It is found that global CO_2 emissions due to economic activities already showed a slow increase since May 2020 compared to January–April 2020 (Feng et al., 2022). As the pandemic crisis gradually lifted and production activities resumed in the energy, industry, and manufacturing sectors, PM_{10} and NO_2 in China from August 2020 increased to 44% and 87%, respectively (Wang et al., 2021a). Cities or regions that experienced a large decrease in pollution during the pandemic also experienced a large rebound in the post-pandemic period. The relevant studies reported that Wuhan experienced significant improvement in air quality during the pandemic, even reaching standard levels, while the changes in New York were not as pronounced(Weiyu et al., 2022). However, Wuhan with the full resumption of work led to more severe pollution. In addition, the secondary pollution event during COVID-19 suggested that unbalanced changes in NO_X and VOC may increase ozone pollution. It is not reasonable to carry out motor vehicle emission reduction alone, but the simultaneous reduction of NO_X and VOC in cities is the appropriate choice to reduce ozone levels. But reducing VOC emissions is difficult to implement because there are multiple small-scale sources (e.g., solvents, paints, trees) that are not as easily regulated as vehicles which are a major source of NO_x (Oke et al., 2017). Anthropogenic heat emissions are also closely related to economic development. It was noted that energy use and the number of residential vehicles in China were the main factors influencing total anthropogenic heat, followed by gross domestic product per capita (Yile et al., 2021). A large-scale reduction in heat emissions would require the implementation of measures such as a widespread cessation of human activity, but in the context of a post-pandemic economic recovery, implementing such measures is difficult and counterintuitive. With increased anthropogenic heat in cities and pollutants acting as insulation, UHII can naturally rise, promoting a UHI rebound during the latter period of the pandemic. Overall, it is important to consider the trade-offs between economic recovery and environmental sustainability in the post-pandemic era to restart the economy and promote a sustainable and resilient living environment.

5.2. The relationship between the legacy of the COVID-19 and heat health

The post-pandemic era has to face many issues left over from the pandemic, and the issues differ from nations given the national conditions, cultural attributes, and social backgrounds. This section discusses the issues in three aspects, including normalized management, psychological illness, and behavior change. For countries that are implementing a regular pandemic prevention and control, daily mask wearing, COVID-19 testing, and health code checks are essential for residents settling in low-risk areas. For medium and high-risk areas, more stringent control and travel restrictions are in place (CCDC, 2022). Under normalized pandemic management, the implementation of heat adaptation and mitigation is bound to be hindered. The negative psychological impact of the pandemic on the public extends to the later stages of the pandemic, where the fear of the new coronavirus, and economic and employment pressure add to the public's mental illness. In Hubei, China, 25.9% of young people with depression in late COVID-19 (Wang et al., 2022). The prevalence of depressive symptoms in residents aged above 16 in Sichuan Province was 22.2%, and the one among residents aged above 18 in Shandong Province was 21.8% (Li et al., 2022). Although the findings varied across regions, the regular control of the pandemic was associated with an increase in depressive symptoms. In the post-pandemic era, mental health problems remain prevalent. The hot weather repeatedly breaks historical records (NASA, 2022), and extreme heat further challenges human physical and mental health. Before the pandemic, for instance, a survey of mental illness in the Kuala Lumpur community indicated that there were up to 67% of heat-related depressed patients (Wong et al., 2017). The dual effects of urban heat and COVID-19 will still be a challenge after the pandemic. The way the public socializes, travels, and consumes will be changed in post-pandemic era. The behavior changes are related to pandemic risk perception and social norm impacts. The risk perception mainly includes direct risks perceived by feelings and indirect risks perceived by rational analysis. Direct risks often have an impact on protective behaviors (Savadori et al., 2022; Dryhurst et al., 2020), which are related to exposure to pandemic-related information, past illness experiences, and psychological tolerance. For example, it is found that exposure to disease-related information was positively associated with risk perception (Tagini et al., 2021). Having a coronavirus experience was associated with greater perceived risk than those without firsthand experience (Dryhurst et al., 2020). Social norms refer to rules of behavior and beliefs that are agreed upon by the entire social group (Young, 2007). Collective effects and self-awareness work together to create protective behaviors. For example, public transportation can return to normal in the post-pandemic era, but travel patterns can be more complex and diverse. Public transportation travel will remain low for a long time and will be replaced by other modes such as private transportation, non-motorized vehicles, and walking (Nian et al., 2020). Each increase in public risk awareness leads to the probability of residents using public transportation for travel to decrease by a factor of 0.229 (Tang et al., 2022). Private transportation could elevate energy use and anthropogenic heat, and walking and non-motorized vehicles increases heat risk to residents. The post-pandemic heat environment will undoubtedly increase the risk perception of residents, especially those who have had novel coronavirus, and thus engage in inappropriate and overly protective behaviors, aggravating anxiety, depression and illnesses.

5.3. Recommendations

Responding to the aforementioned dilemmas, this subsection proposes recommendations on the pandemic-heat co-occurrence with the respects of stakeholders including city managers, planners, the public, and researchers (Fig. 11). The government is the highest management institution of a city or region, so that its responsibilities for dealing with heatwaves and pandemics should be well defined (i.e. coordinating departments and formulating high-temperature guidelines). Heat vulnerability in the post-pandemic era can be stronger than that before the pandemic. It is essential to amend heatwave alerting threshold, vulnerable group scope, the entry and exit regulations of public cooling places (GHHIN, 2020b), and ensure public infrastructure such as the water and electricity operate in hot climates. For areas with sudden outbreaks and large population in isolation, energy distribution in public areas and residential areas should be reconsidered, and with the relaxation of restrictions, the energy demand will be transferred back to commercial and industrial centers (GHHIN, 2020b). The energy-saving building standards should be improved to ensure that indoor temperature is in a safe range without mechanical refrigeration (WSROC, 2022). Community and non-social organizations have played an important role in pandemic prevention, and they are the key link to fully understand public health. Community network can be further enhanced to avoid heat and pandemic situation. Meanwhile, it is essential to improve the welfare of community organization staff, strengthen the identification and contact of vulnerable groups, and organize the community to make emergency preparations to cope with multiple challenges (WSROC, 2022). Some subsidies should be given for economic losses and energy burdens incurred by quarantining homes. In addition, city managers can use the news media and social opinion to form new social norms in line with the post-pandemic era (Young et al., 2021). Science education about the response to the pandemic and high temperatures is needed to develop accurate risk perceptions.

Since people show a higher willingness to walk and non-motorize in the post-pandemic era, cities should add healthy and cool chronic trails that link the various functions of recreation, living, and working to reduce the pressure of infection from people taking public transportation in urban planning and design, when providing new safeguards for adapting to high temperatures. The high albedo materials are effective to reduce neighborhood temperatures, and there is often concern about adverse effects on the ozone. In a study in Sacramento, increasing the albedo of the city lowered the air temperature by 3 °C and decreased the daily average ozone concentration by 13% (Taha, 2008). This phenomenon is explainable by the fact that the slowing of chemical reactions by temperature compensates for the effect of reflected shortwave radiation (Fallmann et al., 2016). However, the same pattern of meteorological scenarios (increased solar radiation and decreased temperature) existed during the pandemic without a decrease in ozone concentrations. Two possible reasons can be inferred from this are (1) the main cause of the increase in ozone concentration during the pandemic was the change in the relative concentration of precursors. The amount of solar radiation and the temperature change had a smaller effect on it, and (2) The additional increase in solar radiation has a greater effect on ozone and the decrease in temperature has a smaller effect on ozone formation.

Residents' social space and distance were severely compressed during the pandemic era. After this, people's travel demand is still low, while the travel demand for community life increases significantly (Nian et al., 2020). Strengthening community system renewal and improvement should be prioritized. The regular management had to be controlled and managed on a community basis. However, due to the thermal characteristics of building maintenance structures, poor public infrastructure, and low-income levels of residents, the majority of old communities lack the capacity to deal with high temperatures, and they must rely on cooling resources in urban centers. Once these communities are closed and controlled, it makes many people bear the increased heat risk. Therefore, cooling measures in urban communities, especially older ones, should be increased. People who have been isolated are concerned about the open of public spaces, and it is a common wish of residents to build community gardens and green corridors. A survey in Wuhan showed that 82.5% of respondents supported this idea (Zheng et al., 2022). The community green parks can effectively relieve people's anxiety during the quarantine period on the one hand, and can achieve community cooling and provide a convenient and effective escape point from the heat for the isolated community residents on the other. The community as the smallest isolation unit should have perfect supporting facilities to meet the basic needs of prevention and control, medical care, summer vacation, and living (Fig. 11).

From the public perspective, it is essential to launch the initiatives to learn about the pandemic and urban heat and to respond scientifically to avoid unnecessary panic and anxiety. First, the public should check whether their air conditioners and other cooling facilities are functioning properly, listen to the news about the pandemic and heat, and learn appropriate ways to avoid the heat in home isolation. During the heat period, the entire population should reduce unnecessary electricity use, for instance by turning off landscape lighting. Second, sensors should be installed in the uniforms of healthcare staff and those who work outdoors in high temperatures to alert them when their body temperature exceeds the threshold and remind them to take a break. Temporary areas with air conditioning and temporary water sources should be located nearby. It is recommended to reduce the shift length and frequently leave the PPE to rest. The continuous use of PPE should not exceed six hours, and users should rest in non-contaminated areas every two to three hours to rehydrate and reduce the risk of skin reactions (Lee and Goh, 2021). Third, when people are suspected of suffering from heat-related diseases or COVID-19, they should seek medical advice promptly. If people feel symptoms such as anxiety, panic or depression, they should also actively seek help from the outside world for psychological counseling (Fig. 11).

For the scientists, the field measurement experiment is a main concern after the pandemic. However, when recording the experimental logs, in addition to meteorological conditions and surrounding conditions, the need to investigate and record the social background of COVID-19 in the area is an important issue. The intervention of wearing masks and the experience of COVID-19 illness should also be included. The methods for heat investigation during the pandemic were direct comparisons between the pandemic year and the average of the years preceding the pandemic, while very few used mathematical modeling to construct counterfactual control groups. Mathematical modeling presupposes an understanding of the process of exposure to intervening factors in the experiment, by controlling and adjusting the covariates that affect the outcome so that these variables are known and accurately measured (Craig et al., 2017). Besides, if it is no longer possible to set up a control group in reality, numerical simulation is an approach. In a study in Beijing, for instance, the authors conducted four simulation scenarios to compare the effects of anthropogenic heat intervention levels on urban heat (Hua et al., 2004). Another study compared the thermal environment of a site with a museum to that of a site with extensive vegetation before the museum was constructed (Raman et al., 2021). The proper setting or post-treatment of the control group is an important prerequisite for causal inference between the intervention factors and the experimental results. This is particularly important in both field and natural experiments (Fig. 11).

6. Conclusion

This study provides a comprehensive review of the negative urban temperature anomalies, the challenges of increased urban heat during the pandemic, and the scientific approach to urban heat studies. The results show that lockdown measures resulted in a change in the total heat input to the city, associated with a decrease in anthropogenic heat emissions and an increase in solar radiation incidence, which was the main reason for the negative spatiotemporal anomalies of urban temperatures. Lockdown measures brought additional challenges to urban heat by secondary pollution in the atmosphere, increased energy burden, and an expanded range of vulnerable groups, which in turn increased heat threats among the public. Mathematical modeling and numerical simulation were good options in experiments of outdoor thermal environments, but it was difficult to establish a control group in reality. Overall, this paper provides a clearer and more thorough understanding of the role of human activity in UHI and air pollution. Moreover, changes in social norms and public behavior patterns in response to such large public health events can have a substantial impact on economic growth and energy allocation, thereby putting more people at risk for health problems. Through this study, it is clearer to understand the trade-offs and challenges in coping with high temperatures in the post-pandemic era. Therefore, four types of recommendations were proposed in aspects of urban management, planning, public participation, and scientific research, to inform the heat response system in the post-pandemic era and to provide ideas for future emergency preparedness in cities facing multiple major challenges occurring together.

CRediT authorship contribution statement

Wei Wang: Formal analysis, Investigation, Methodology, Writing – original draft. **Bao-Jie He:** Conceptualization, Project administration, Resources, Software, Validation, Visualization, Writing – review & editing.

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

No data was used for the research described in the article.

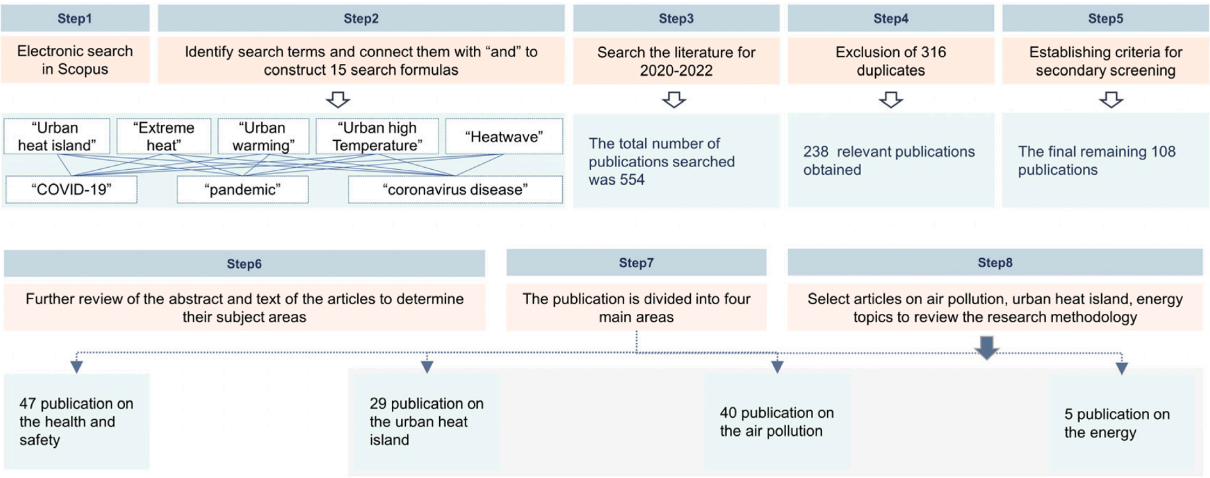
Acknowledgements

State Key Laboratory of Subtropical Building Science, South China University of Technology (Grant No. 2022ZA01). Graduate Scientific Research and Innovation Foundation of Chongqing, China (CYB22035; CYS22058).This research is additionally supported by the National Natural Science Foundation of China (Grant No. 52108011); Guangzhou Philosophy and Social Science Planning 2022 Annual Project(Grant No. 2022GZQN14); Department of Housing and Urban–Rural Development of Guangdong Province (Grant No. 2021-K2-305243); Department of Education of Guangdong Province (Grant No. 2021KTSCX004); Science and Technology Program of Guangzhou, China (Grant No. 202102020302); China Postdoctoral Science Foundation (Grant No. 2021M701249).

Ethical statement

This paper does NOT have ethical issues on Hazards and Human or Animal Subjects.

Appendix



Appendix 1. Flowchart for screening relevant literature on heat and outbreak research.

References

Agni, A. M., Pangi, P., Septiarani, B., & Astuti, K. D. (2021). *The social restrictions impact on urban heat island phenomena (Case Study: Cities in Java Island)*. IOP Publishing Ltd.

Ali, G., Abbas, S., Qamer, F. M., Wong, M. S., Rasul, G., Irteza, S. M., & Shahzad, N. (2021). Environmental impacts of shifts in energy, emissions, and urban heat island during the COVID-19 lockdown across Pakistan. *Journal of Cleaner Production*, 291. https://doi.org/10.1016/j.jclepro.2021.125806

Alqasemi, A. S., Hereher, M. E., Kaplan, G., Al-Quraishi, A. M. F., & Saibi, H. (2021). Impact of COVID-19 lockdown upon the air quality and surface urban heat island intensity over the United Arab Emirates. *Science of the Total Environment, 767*, Article 144330. https://doi.org/10.1016/j.scitotenv.2020.144330

Bouttell, J., Craig, P., Lewsey, J., Robinson, M., & Popham, F. (2018). Synthetic control methodology as a tool for evaluating population-level health interventions. *Journal of Epidemiology and Community Health, 72*, 673–678. https://doi.org/10.1136/jech-2017-210106

Broede, P., Fiala, D., Lemke, B., & Kjellstrom, T. (2018). Estimated work ability in warm outdoor environments depends on the chosen heat stress assessment metric. *International Journal of Biometeorology, 62*, 331–345. https://doi.org/10.1007/s00484-017-1346-9

Bueno, B., Norford, L., Pigeon, G., & Britter, R. (2012). A resistance-capacitance network model for the analysis of the interactions between the energy performance of buildings and the urban climate. *Building and Environment, 54*, 116–125. https://doi.org/10.1016/j.buildenv.2012.01.023

Burns, J., Hoffmann, S., Kurz, C., Laxy, M., Polus, S., & Rehfuess, E. (2021). COVID-19 mitigation measures and nitrogen dioxide - A quasi-experimental study of air quality in Munich, Germany. *Atmospheric Environment, 246*, Article 118089. https://doi.org/10.1016/j.atmosenv.2020.118089

Cai, Z., Tang, Y., & Zhan, Q. (2021). A cooled city? Comparing human activity changes on the impact of urban thermal environment before and after city-wide lockdown. *Building and Environment, 195*. https://doi.org/10.1016/j.buildenv.2021.107729

Cao, C., Lee, X., Liu, S., Schultz, N., Xiao, W., Zhang, M., & Zhao, L. (2016). Urban heat islands in China enhanced by haze pollution. *Nature Communications, 7*. https://doi.org/10.1038/ncomms12509

CCDC. 2022. Available: https://www.chinacdc.cn/jkzt/crb/zl/szkb_11803/jszl_11815/202206/t20220628_259882.html [Accessed].

Chakraborty, T. C., Sarangi, C., & Lee, X. (2021). Reduction in human activity can enhance the urban heat island: insights from the COVID-19 lockdown. *Environmental Research Letters, 16*. https://doi.org/10.1088/1748-9326/abef8e

Craig, P., Katikireddi, S. V., Leyland, A., & Popham, F. (2017). Natural experiments: An overview of methods, approaches, and contributions to public health intervention research. *Annual Review of Public Health, 38*, 39–56. https://doi.org/10.1146/annurev-publhealth-031816-044327

Das, M., Das, A., Pereira, P., & Mandal, A. (2021). Mapping the impact of COVID-19 lockdown on urban surface ecological status (USES): A case study of Kolkata metropolitan area (KMA), India. *Remote Sensing, 13*. https://doi.org/10.3390/rs13214395

Data, O. W. i. 2020. *Residential areas: How did the time spent at home change since the beginning of the pandemic?, Feb 23, 2022* [Online]. Available: https://ourworldindata.org/covid-google-mobility-trends [Accessed].

Davey, S. L., Lee, B. J., Robbins, T., Randeva, H., & Thake, C. D. (2021). Heat stress and PPE during COVID-19: impact on healthcare workers' performance, safety and well-being in NHS settings. *Journal of Hospital Infection, 108*, 185–188. https://doi.org/10.1016/j.jhin.2020.11.027

Doan, V. Q., Kusaka, H., & Nguyen, T. M. (2019). Roles of past, present, and future land use and anthropogenic heat release changes on urban heat island effects in Hanoi, Vietnam: Numerical experiments with a regional climate model. *Sustainable Cities and Society, 47*, Article 101479.

Dou, J., & Miao, S. (2017). Impact of mass human migration during Chinese New Year on Beijing urban heat island. *International Journal of Climatology, 37*, 4199–4210.

Dryhurst, S., Schneider, C. R., Kerr, J., Freeman, A. L., Recchia, G., Van Der Bles, A. M., Spiegelhalter, D., & Van Der Linden, S. (2020). Risk perceptions of COVID-19 around the world. *Journal of Risk Research, 23*, 994–1006.

El Kenawy, A. M., Lopez-Moreno, J. I., McCabe, M. F., Domínguez-Castro, F., Peña-Angulo, D., Gaber, I. M., … Vicente-Serrano, S. M. (2021). The impact of COVID-19 lockdowns on surface urban heat island changes and air-quality improvements across 21 major cities in the Middle East. *Environmental Pollution, 288*, 117802. https://doi.org/10.1016/j.envpol.2021.117802

Fallmann, J., Forkel, R., & Emeis, S. (2016). Secondary effects of urban heat island mitigation measures on air quality. *Atmospheric Environment, 125*, 199–211.

Fan, L., Fu, S., Wang, X., Fu, Q., Jia, H., Xu, H., Qin, G., Hu, X., & Cheng, J. (2021). Spatiotemporal variations of ambient air pollutants and meteorological influences over typical urban agglomerations in China during the COVID-19 lockdown. *Journal of Environmental Sciences (China), 106*, 26–38. https://doi.org/10.1016/j.jes.2021.01.006

Farahat, A., Chauhan, A., Al Otaibi, M., & Singh, R. P. (2021). Air quality over major cities of Saudi Arabia during Hajj periods of 2019 and 2020. *Earth Systems and Environment, 5*, 101–114. https://doi.org/10.1007/s41748-021-00202-z

Feng, T., Du, H., Lin, Z., Chen, X., Chen, Z., & Tu, Q. (2022). Green recovery or pollution rebound? Evidence from air pollution of China in the post-COVID-19 era. *Journal of environmental Management*, Article 116360.

Fouillet, A., Rey, G., Wagner, V., Laaidi, K., Empereur-Bissonnet, P., Le Tertre, A., Frayssinet, P., Bessemoulin, P., Laurent, F., & De Crouy-Chanel, P. (2008). Has the impact of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *International Journal of Epidemiology, 37*, 309–317.

Fuse-Nagase, Y. (2022). Mental health status among university students during COVID-19 pandemic in Japan: A longitudinal study with one year interval. *Asian Journal of Psychiatry, 68*. https://doi.org/10.1016/j.ajp.2021.102973

Ghasempour, F., Sekertekin, A., & Kutoglu, S. H. (2021). Google Earth Engine based spatio-temporal analysis of air pollutants before and during the first wave COVID-19 outbreak over Turkey via remote sensing. *Journal of Cleaner Production, 319*, Article 128599. https://doi.org/10.1016/j.jclepro.2021.128599

GHHIN. 2020a. *How to distinguish between fever caused by infection, and environment and or exercise-induced hyperthermia and heat illness?* [Online]. Available: https://ghhin.org/faq/fever-covid/ [Accessed].

GHHIN. 2020b. *MANAGING HEAT RISK DURING THE COVID-19 PANDEMIC* [Online]. Available: https://ghhin.org/wp-content/uploads/Checklist-COVID-HEAT-final.pdf [Accessed].

GHHIN. 2020c. *Protecting Health from Hot Weather during the COVID-19 Pandemic* [Online]. Available: https://ghhin.org/resources/technical-brief-protecting-health-from-hot-weather-during-the-covid-19-pandemic/ [Accessed].

GHHIN. 2020d. *What specific considerations apply for heatwaves in urban informal settlements during the COVID-19 pandemic?* [Online]. Available: https://ghhin.org/faq/what-specific-considerations-apply-for-heatwaves-in-urban-informal-settlements-during-the-covid-19-pandemic/ [Accessed].

GHHIN. 2021. Available: https://ghhin.org/heat-and-health/ [Accessed].

Gupta, M., Chauhan, T., Murtugudde, R., & Ghosh, S. (2020). Pollutants control the process networks of urban environmental-meteorology. *Environmental Research Letters, 16*. https://doi.org/10.1088/1748-9326/abce28

He, X., Jiang, W., Chen, Y., & Liu, G. (2007). Numerical simulation of the impacts of anthropogenic heat on the structure of the urban boundary layer. *Chinese Journal of Geophysics, 50*, 74–82.

He, B.-J., Wang, J., Zhu, J., & Qi, J. (2022). Beating the urban heat: Situation, background, impacts and the way forward in China. *Renewable and Sustainable Energy Reviews, 161*, Article 112350. https://doi.org/10.1016/j.rser.2022.112350

He, B.-J. (2022). Green building: A comprehensive solution to urban heat. *Energy and Buildings, 271*, Article 112306. https://doi.org/10.1016/j.enbuild.2022.112306

Henao, J. J., Rendón, A. M., & Salazar, J. F. (2020). Trade-off between urban heat island mitigation and air quality in urban valleys. *Urban Climate, 31*, Article 100542.

Hidalgo Garcia, D., & Arco Diaz, J (2022). Impacts of the COVID-19 confinement on air quality, the Land Surface Temperature and the urban heat island in eight cities of Andalusia (Spain). *Remote Sensing Application, 25*, Article 100667. https://doi.org/10.1016/j.rsase.2021.100667

Hou, H., Su, H., Liu, K., Li, X., Chen, S., Wang, W., & Lin, J. (2022). Driving forces of UHI changes in China's major cities from the perspective of land surface energy balance. *Science of the Total Environment, 829*, Article 154710. https://doi.org/10.1016/j.scitotenv.2022.154710

Hua, T., Huizhi, L., Jianguo, S., & Fei, H. (2004). *The impact of urban anthropogenic heat on Beijing heat environment* (pp. 409–421). Climatic and Environmental Research.

Huang, Z., Gou, Z., & Cheng, B. (2020). An investigation of outdoor thermal environments with different ground surfaces in the hot summer-cold winter climate region. *Journal of Building Engineering, 27*, Article 100994. https://doi.org/10.1016/j.jobe.2019.100994

IEA. 2021. *Covid-19 impact on electricity* [Online]. Available: https://www.iea.org/reports/covid-19-impact-on-electricity [Accessed].

IMF. 2020. *The great lockdown: Worst economic downturn since the great depression* [Online]. Available: https://blogs.imf.org/2020/04/14/the-great-lockdown-worst-economic-downturn-since-the-great-depression/ [Accessed].

Kang, H., An, J., Kim, H., Ji, C., Hong, T., & Lee, S. (2021). Changes in energy consumption according to building use type under COVID-19 pandemic in South Korea. *Renewable and Sustainable Energy Reviews, 148*, Article 111294. https://doi.org/10.1016/j.rser.2021.111294

Keshtkar, M., Heidari, H., Moazzeni, N., & Azadi, H. (2022). Analysis of changes in air pollution quality and impact of COVID-19 on environmental health in Iran: application of interpolation models and spatial autocorrelation. *Environmental Science and Pollution Research International, 29*, 38505–38526. https://doi.org/10.1007/s11356-021-17955-9

Kimura, F., & Takahashi, S. (1991). The effects of land-use and anthropogenic heating on the surface temperature in the Tokyo metropolitan area: A numerical experiment. *Atmospheric Environment. Part B. Urban Atmosphere, 25*, 155–164.

Lee, S.-H., & Baik, J.-J. (2010). Statistical and dynamical characteristics of the urban heat island intensity in Seoul. *Theoretical and Applied Climatology, 100*, 227–237. https://doi.org/10.1007/s00704-009-0247-1

Lee, H. C., & Goh, C. L. (2021). Occupational dermatoses from Personal Protective Equipment during the COVID-19 pandemic in the tropics - A review. *Journal of the European Academy of Dermatology and Venereology, 35*, 589–596. https://doi.org/10.1111/jdv.16925

Lele, N., Nigam, R., & Bhattacharya, B. K. (2021). New findings on impact of COVID lockdown over terrestrial ecosystems from LEO-GEO satellites. *Remote Sensing Application, 22*, Article 100476. https://doi.org/10.1016/j.rsase.2021.100476

Li, Z., Zhou, R., Wang, Y., Wang, G., Chen, M., Li, Y., Wang, Y., Yi, Y., Hou, Z., Guo, Q., & Meng, J. (2021). Characteristics and sources of amine-containing particles in the urban atmosphere of Liaocheng, a seriously polluted city in North China during the COVID-19 outbreak. *Environmental Pollution, 289*, Article 117887. https://doi.org/10.1016/j.envpol.2021.117887

Li, S., Guo, B., Yang, Q., Yin, J., Jiang, Y., Tian, L., Ji, Y., & Zhu, H. (2022). Factors associated with depression in residents in the post-epidemic era. *QJM: An International Journal of Medicine, 115*, 605–609.

Liang, Z., Huang, J., Wang, Y., Wei, F., Wu, S., Jiang, H., Zhang, X., & Li, S. (2021). The mediating effect of air pollution in the impacts of urban form on nighttime urban heat island intensity. *Sustainable Cities and Society, 74*. https://doi.org/10.1016/j.scs.2021.102985

Lin, Y. C., Zhang, Y. L., Xie, F., Fan, M. Y., & Liu, X. (2021). Substantial decreases of light absorption, concentrations and relative contributions of fossil fuel to light-absorbing carbonaceous aerosols attributed to the COVID-19 lockdown in east China. *Environmental Pollution, 275*, Article 116615. https://doi.org/10.1016/j.envpol.2021.116615

Liu, C., Li, G., He, Y., Zhang, Z., & Ding, Y. (2020). Effects of wearing masks on human health and comfort during the COVID-19 pandemic. In *3rd International conference of green buildings and environmental management (GBEM)*. Jun 12-14 2020 Electr Network.

Liu, Z., Cheng, K. Y., He, Y., Jim, C. Y., Brown, R. D., Shi, Y., Lau, K., & Ng, E. (2022a). Microclimatic measurements in tropical cities: Systematic review and proposed guidelines. *Building and Environment, 222*. https://doi.org/10.1016/j.buildenv.2022.109411

Liu, Z., Lai, J., Zhan, W., Bechtel, B., Voogt, J., Quan, J., Hu, L., Fu, P., Huang, F., Li, L., Guo, Z., & Li, J. (2022b). Urban Heat Islands Significantly Reduced by COVID-19 Lockdown. *Geophysical Research Letters, 49*. https://doi.org/10.1029/2021gl096842

Loa, P., Hossain, S., Mashrur, S. M., Liu, Y., Wang, K., Ong, F., & Habib, K. N. (2021). Exploring the impacts of the COVID-19 pandemic on modality profiles for non-mandatory trips in the Greater Toronto Area. *Transport Policy, 110*, 71–85. https://doi.org/10.1016/j.tranpol.2021.05.028

Lou, J., Qiu, Y., Ku, A. L., Nock, D., & Xing, B. (2021). Inequitable and heterogeneous impacts on electricity consumption from COVID-19 mitigation measures. *Iscience, 24*. https://doi.org/10.1016/j.isci.2021.103231

Maithani, S., Nautiyal, G., & Sharma, A. (2020). Investigating the Effect of Lockdown During COVID-19 on Land Surface Temperature: Study of Dehradun City, India. *Journal of the Indian Society of Remote Sensing, 48*, 1297–1311. https://doi.org/10.1007/s12524-020-01157-w

Miller, P. W., Reesman, C., Grossman, M. K., Nelson, S. A., Liu, V., & Wang, P. (2021). Marginal warming associated with a COVID-19 quarantine and the implications for disease transmission. *Science of the Total Environment, 780*, Article 146579. https://doi.org/10.1016/j.scitotenv.2021.146579

Morabito, M., Messeri, A., Crisci, A., Pratali, L., Bonafede, M., Marinaccio, A., & Group, W. C. (2020). Heat warning and public and workers' health at the time of COVID-19 pandemic. *Science of the Total Environment, 738*, Article 140347. https://doi.org/10.1016/j.scitotenv.2020.140347

Nakajima, K., Takane, Y., Kikegawa, Y., Furuta, Y., & Takamatsu, H. (2021). Human behaviour change and its impact on urban climate: Restrictions with the G20 Osaka Summit and COVID-19 outbreak. *Urban Climate, 35*. https://doi.org/10.1016/j.uclim.2020.100728

Nanda, D., Mishra, D. R., & Swain, D. (2021). COVID-19 lockdowns induced land surface temperature variability in mega urban agglomerations in India. *Environmental Science: Processes and Impacts, 23*, 144–159. https://doi.org/10.1039/d0em00358a

NASA. 2022. *Heatwaves and Fires Scorch Europe, Africa, and Asia* [Online]. Available: https://earthobservatory.nasa.gov/images/150083/heatwaves-and-fires-scorch-europe-africa-and-asia?utm_source=TWITTER&utm_medium=NASAEarth&utm_campaign=NASASocial&linkId=173253037 [Accessed].

Nian, G., Peng, B., Sun, D., Ma, W., Peng, B., & Huang, T. (2020). Impact of COVID-19 on urban mobility during post-epidemic period in megacities: From the perspectives of taxi travel and social vitality. *Sustainability, 12*. https://doi.org/10.3390/su12197954

NOAA. (2020). May 2020 Global. *Climate Report* [Online]. Available https://www.ncei.noaa.gov/access/monitoring/monthly-report/global/202005 [Accessed].

NSW. 2022. *Climate change impacts on urban heat* [Online]. Available: https://www.climatechange.environment.nsw.gov.au/urban-heat [Accessed].

Nundy, S., Ghosh, A., Mesloub, A., Albaqawy, G. A., & Alnaim, M. M. (2021). Impact of COVID-19 pandemic on socio-economic, energy-environment and transport sector globally and sustainable development goal (SDG). *Journal of Cleaner Production, 312*. https://doi.org/10.1016/j.jclepro.2021.127705

Oke, T. R., Mills, G., Christen, A., & Voogt, J. A. (2017). *Urban climates*. Cambridge University Press.

Oke, T. R. (1982). The energetic basis of the urban heat island. *Quarterly Journal of the Royal Meteorological Society, 108*, 1–24.

Oke, T. R. 2004. Initial guidance to obtain representative meteorological observations at urban sites.

Pal, S., Das, P., Mandal, I., Sarda, R., Mahato, S., Nguyen, K. A., Liou, Y. A., Talukdar, S., Debanshi, S., & Saha, T. K. (2021). Effects of lockdown due to COVID-19 outbreak on air quality and anthropogenic heat in an industrial belt of India. *Journal of Cleaner Production, 297*, Article 126674. https://doi.org/10.1016/j.jclepro.2021.126674

Pal, S. C., Chowdhuri, I., Saha, A., Ghosh, M., Roy, P., Das, B., Chakrabortty, R., & Shit, M. (2022). COVID-19 strict lockdown impact on urban air quality and atmospheric temperature in four megacities of India. *Geoscience Frontiers*. https://doi.org/10.1016/j.gsf.2022.101368

Parida, B. R., Bar, S., Kaskaoutis, D., Pandey, A. C., Polade, S. D., & Goswami, S. (2021). Impact of COVID-19 induced lockdown on land surface temperature, aerosol, and urban heat in Europe and North America. *Sustainable Cities and Society, 75*. https://doi.org/10.1016/j.scs.2021.103336

Perillo, H. A., Broderick, B. M., Gill, L. W., McNabola, A., Kumar, P., & Gallagher, J. (2022). Spatiotemporal representativeness of air pollution monitoring in Dublin, Ireland. *Science of the Total Environment, 827*, Article 154299. https://doi.org/10.1016/j.scitotenv.2022.154299

Potter, C., & Alexander, O. (2021). Impacts of the San Francisco Bay Area shelter-in-place during the COVID-19 pandemic on urban heat fluxes. *Urban Climate, 37*, Article 100828. https://doi.org/10.1016/j.uclim.2021.100828

Raman, V., Kumar, M., Sharma, A., Froehlich, D., & Matzarakis, A. (2021). Quantification of thermal stress abatement by trees, its dependence on morphology and wind: A case study at Patna, Bihar, India. *Urban Forestry & Urban Greening, 63*. https://doi.org/10.1016/j.ufug.2021.127213

Ren, J., Yang, J., Wu, F., Sun, W., Xiao, X., & Xia, J. (2022). Regional thermal environment changes: Integration of satellite data and land use/land cover. *iScience*. , Article 105820. https://doi.org/10.1016/j.isci.2022.105820

Roshan, G., Sarli, R., & Grab, S. W. (2021). The case of Tehran's urban heat island, Iran: Impacts of urban 'lockdown' associated with the COVID-19 pandemic. *Sustainable Cities and Society, 75*. https://doi.org/10.1016/j.scs.2021.103263

Roshan, G., Sarli, R., & Fitchett, J. M. (2022). Urban heat island and thermal comfort of Esfahan City (Iran) during COVID-19 lockdown. *Journal of Cleaner Production, 352*. https://doi.org/10.1016/j.jclepro.2022.131498

Sai, B. T., & Singh, U. K. (2021). Synergic relation between urban pollution island and meteorological parameters over urban heat island for the city of Hyderabad during lockdown. *Disaster Advances*, 14–21. https://doi.org/10.25303/148da1421

Santamouris, M., Cartalis, C., Synnefa, A., & Kolokotsa, D. (2015). On the impact of urban heat island and global warming on the power demand and electricity consumption of buildings—A review. *Energy and Buildings, 98*, 119–124.

Santamouris, M. (2020). Recent progress on urban overheating and heat island research. Integrated assessment of the energy, environmental, vulnerability and health impact. Synergies with the global climate change. *Energy and Buildings, 207*. https://doi.org/10.1016/j.enbuild.2019.109482

Savadori, L., & Lauriola, M. (2022). Risk perceptions and COVID-19 protective behaviors: A two-wave longitudinal study of epidemic and post-epidemic periods. *Social Science & Medicine, 301*, Article 114949. https://doi.org/10.1016/j.socscimed.2022.114949

Shikwambana, L., Kganyago, M., & Mhangara, P. (2021). Temporal analysis of changes in anthropogenic emissions and urban heat islands during COVID-19 Restrictions in Gauteng Province, South Africa. *Aerosol and Air Quality Research, 21*. https://doi.org/10.4209/aaqr.200437

Shumake-Guillemot, J., Amir, S., Anwar, N., Arrighi, J., Böse-O'Reilly, S., Brearley, M., Cross, J., Daanen, H., de'Donato, F., & Eggen, B. (2020). Protecting health from hot weather during the COVID-19 pandemic. Global Heat Health Information Network (GHHIN). 2020. https://ghhin.org/wp-content/uploads/technical-brief-COVID-and-Heat-finalv2-1.pdf.

Sicard, P., De Marco, A., Agathokleous, E., Feng, Z., Xu, X., Paoletti, E., Rodriguez, J. J. D., & Calatayud, V. (2020). Amplified ozone pollution in cities during the COVID-19 lockdown. *Science of the Total Environment, 735*, Article 139542.

Singh, V. K., Mughal, M. O., Martilli, A., Acero, J. A., Ivanchev, J., & Norford, L. K. (2022). Numerical analysis of the impact of anthropogenic emissions on the urban environment of Singapore. *Science of The Total Environment, 806*, Article 150534. https://doi.org/10.1016/j.scitotenv.2021.150534

Snow, J. (1849). *On the mode of communication of cholera*. John Churchill.

Soltani, A., & Sharifi, E. (2017). Daily variation of urban heat island effect and its correlations to urban greenery: A case study of Adelaide. *Frontiers of Architectural Research, 6*, 529–538. https://doi.org/10.1016/j.foar.2017.08.001

Syed, A., Zhang, J., Moniruzzaman, M., Rousta, I., Omer, T., Ying, G., & Olafsson, H. (2021). Situation of urban mobility in Pakistan: Before, during, and after the COVID-19 lockdown with climatic risk perceptions. *Atmosphere, 12*. https://doi.org/10.3390/atmos12091190

Tagini, S., Brugnera, A., Ferrucci, R., Mazzocco, K., Compare, A., Silani, V., Pravettoni, G., & Poletti, B. (2021). It won't happen to me! Psychosocial factors influencing risk perception for respiratory infectious diseases: A scoping review. *Applied Psychology: Health and Well-Being, 13*, 835–852.

Taha, H. (2008). Meso-urban meteorological and photochemical modeling of heat island mitigation. *Atmospheric Environment, 42*, 8795–8809.

Tang, L., Jiao, L., Huo, X., & Zhang, Y. (2022). Research on Residents' choice behavior of public transport travel mode during the post-epidemic period. In *International symposium on advancement of construction management and real estate* (pp. 929–942). Springer.

Taoufik, M., Laghlimi, M., & Fekri, A. (2021). Comparison of land surface temperature before, during and after the Covid-19 lockdown using landsat imagery: A Case study of Casablanca City, Morocco. *Geomatics and Environmental Engineering, 15*, 105–120. https://doi.org/10.7494/geom.2021.15.2.105

Teufel, B., Sushama, L., Poitras, V., Dukhan, T., Bélair, S., Miranda-Moreno, L., Sun, L., Sasmito, A. P., & Bitsuamlak, G. (2021). Impact of COVID-19-related traffic slowdown on urban heat characteristics. *Atmosphere, 12*. https://doi.org/10.3390/atmos12020243

Tubelo, R., Naghiyev, E., Gillott, M., Rodrigues, L., & Shipman, R. (2022). Assessing the impact of lockdown due to COVID-19 on the electricity consumption of a housing development in the UK. *Sustainability in Energy and Buildings. 2021*.

Vuong, Q. T., Thang, P. Q., Park, M. K., & Choi, S. D. (2020). Effects of the COVID-19 lockdown on criteria air pollutants in the city of Daegu, the epicenter of South Korea's outbreak. *Environmental Science and Pollution Research International, 27*, 45983–45991. https://doi.org/10.1007/s11356-020-11360-4

Wai, C. Y., Muttil, N., Tariq, M. A. U. R., Paresi, P., Nnachi, R. C., & Ng, A. W. M. (2022). investigating the relationship between human activity and the urban heat island effect in Melbourne and four other international cities impacted by COVID-19. *Sustainability, 14*. https://doi.org/10.3390/su14010378

Wang, Q., & Yang, X. (2021a). How do pollutants change post-pandemic? Evidence from changes in five key pollutants in nine Chinese cities most affected by the COVID-19. *Environmental Research, 197*. https://doi.org/10.1016/j.envres.2021.111108

Wang, Z., & Zou, Q. (2022). Prevalence and associated factors of depressive symptoms among the young adults during the post-epidemic period - Evidence from the first wave of COVID-19 in Hubei Province, China. *Acta Psychologica, 226*, Article 103577. https://doi.org/10.1016/j.actpsy.2022.103577

Wang, Z., Hong, T., Li, H., & Ann Piette, M. (2021b). Predicting city-scale daily electricity consumption using data-driven models. *Advances in Applied Energy, 2*. https://doi.org/10.1016/j.adapen.2021.100025

Weiyu, L., Yuanyuan, X., Tong, S., & Jifei, W. (2022). Air quality dynamics and urban heat island effects during COVID-19. *Geospatial Data Analytics and Urban Applications*.

WHO. 2018. Heat and health [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/climate-change-heat-and-health [Accessed].

Wilhelmi, O. V., Howe, P. D., Hayden, M. H., & O'Lenick, C. R (2021). Compounding hazards and intersecting vulnerabilities: Experiences and responses to extreme heat during COVID-19. *Environmental Research Letters, 16*. https://doi.org/10.1088/1748-9326/ac1760

Wong, L. P., Alias, H., Aghamohammadi, N., Aghazadeh, S., Sulaiman, N., & Meriam, N. (2017). Urban heat island experience, control measures and health impact: A survey among working community in the city of Kuala Lumpur. *Sustainable Cities and Society, 35*, 660–668. https://doi.org/10.1016/j.scs.2017.09.026

WSROC. 2022. *Heat smart resilience framework* [Online]. Available: https://wsroc.com.au/media-a-resources/reports?task=download.send&id=310&catid=3&m=0 [Accessed].

Yang, L., Gao, X., Li, Z., & Jia, D. (2022). Quantitative effects of air pollution on regional daily global and diffuse solar radiation under clear sky conditions. *Energy Reports, 8*, 1935–1948. https://doi.org/10.1016/j.egyr.2021.12.081

Yile, C., Shisong, C., Mingyi, D., Shanfei, L., & Chen, S. (2021). Estimation and analysis of driving factors of total AHF in prefecture-level of China. *Journal of Geo-Information Science, 23*, 405–418.

Young, S. D., & Goldstein, N. J. (2021). Applying social norms interventions to increase adherence to COVID-19 prevention and control guidelines. *Preventive Medicine, 145*, Article 106424.

Young, H. P. 2007. *Social Norms* [Online]. Available: https://ora.ox.ac.uk/objects/uuid:178f8a5d-c2f7-40ed-abed-4cd373d1ae2d [Accessed].

Zhang, J., Wei, Y., & Fang, Z. (2019). Ozone pollution: a major health hazard worldwide. *Frontiers in Immunology, 10*, 2518.

Zhao, W. (2020). Changes of air quality during the pandemic and aerosol transmission issues. *National Science Review, NSR*. https://doi.org/10.1093/nsr/nwaa275/6000222

Zheng, H., Akita, N., & Zhang, F. (2022). Study of residents' willingness to construct community gardens in the post-epidemic era. *International Review for Spatial Planning and Sustainable Development, 10*, 33–49. https://doi.org/10.14246/irspsd.10.3_33