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A review on BIPV-induced temperature effects on urban heat islands

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ABSTRACT

Urban Heat Islands (UHI) occur in and around cities, leading to warmer temperatures than in surrounding rural areas. The UHI effect increases energy demand, air pollution levels, and heat-related illness and mortality. Solar energy is one of the most widely adopted renewable energy generation technologies in the built environment. Solar photovoltaic (PV) systems, integrated into building envelopes, can form a cohesive design, construction and energy solution for buildings, namely, building-integrated photovoltaic system (BIPV). However, the BIPV panels might potentially exacerbate the UHI intensity by trapping more heat in urban areas. This review paper uses a detailed literature survey of over 100 sources to evaluate whether the uptake of BIPV systems in urban areas contributes to an aggravation of the UHI effect. The survey found both direct and indirect impacts of BIPV systems on UHI, which also identified the fundamental causes of UHI such as the albedo effect and heat dispersion and how this would be embodied in the BIPV installations. Furthermore, this paper discusses how to mitigate the impact of BIPV systems on the UHI, as well as the future research directions around this concern in relation to the urban design.

1. Introduction

In recent years, there has been a tremendous increase in energy use due to technical improvements that have led to lifestyles of using more energy (Ren et al., 2021). The utilisation of energy and the form it takes to influence the economy's progression is both longitudinal and quantitative (Wang et al., 2022). It should be noted that urban areas are responsible for using 60%–80% of the total energy and producing 75% of the carbon emissions globally, despite this they only account for 3% of the overall land area (Leal Filho et al., 2017).

Photovoltaic (PV) systems are clean and sustainable energy sources (Tawalbeh et al., 2021). When they are integrated into the

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Nomenclature

BAPV	building attached photovoltaic
BIPV	building-integrated photovoltaic
NIR	near-infrared
PV	photovoltaic
UHI	urban heat island
UV	ultraviolet
VIS	visibility

building structure they are known as Building-Integrated Photovoltaic (BIPV), while they are known as Building Attached Photovoltaic (BAPV) if they are fixed onto a building component or structure (Ghosh, 2020). Fig. 1 shows the schematics of both BIPV and BAPV. The BAPVs have no significant effect on the functionality of building envelope, but the BIPVs will have a direct impact on the envelope being a part of the building component and a fundamental variable parameter for the energy balance of the building (Biyik et al., 2017; Yang et al., 2021a). Even though their overall efficiency is not yet optimised, BIPVs are considered to have significant potential to help reduce carbon emissions and tackle climate change (Khalifeeh et al., 2021; Attia et al., 2022). The uptake of BIPV has the potential to alleviate the growing financial and environmental expenses of energy production using fossil fuels, which lessens the harm that is done to the ecosystem by traditional energy sources, as well as minimises the amount of damage that is done to the ecosystem (Attoye and Hassan, 2017).

BIPVs can be integrated into building materials and elements, such as roofing tiles and building facades (Yang et al., 2018b; Yang et al., 2018c), which can cover a degree of energy consumption of a building. Many BIPV systems are also connected to the electrical grid, allowing them to send any excess energy to the grid (Shukla et al., 2016). However, these technologies do come with drawbacks, one of which was already highlighted: like all other type of PV systems, BIPV's efficacy cannot always be relied upon as the primary power source due to diurnal variations in solar irradiance (Vourvoulias, 2022b). Moreover, BIPV systems gather energy from the sun and transform it into electricity, so there is the potential for adverse effects on the surrounding environment (Vourvoulias, 2022b). Specifically, BIPV can act as a heat storage device mainly due to its low albedo and heat dispersion (Shirazi et al., 2019; Lai and Hokoi, 2015), which may gradually cause the surrounding environment to get warmer. This can exacerbate a phenomenon described as the Urban Heat Island (UHI) which manifests as urban areas experiencing higher temperature than the surrounding rural landscape; this has been the subject of much inquiry and investigation, and a variety of factors compound to cause this effect (Sailor et al., 2021).

Primarily, the anthropogenic changes in land use that lead to the UHI effect (Ren et al., 2023), which is common in large cities, such as New York and London, as well as in smaller urban areas (Aleksandrowicz et al., 2017). The low albedo of most man-made structures and the thermal mass of heavy weight materials, which, mean that heat from the sun is absorbed and stored more easily in built-up areas (Levermore et al., 2015a). Meteorological factors have a direct effect on the UHI, for example, low wind speed has been linked to the effect, and this can be more common where the buildings are compact and close to one another, and thus restrict air circulation (Leal Filho et al., 2017). In addition to local microclimate impacts, the UHI has been shown to contribute to global warming and therefore climate change (Parker, 2010; Qi et al., 2023). The idea that climate change has been intensively investigated and well-proven in related literature by a large number of highly regarded scientific researchers (Lehmann et al., 2021). Fossil fuels continue to be the most abundant primary energy source, and the burning of fossil fuels is the primary cause of climate change (Ağbulut and Sarıdemir, 2021). To maintain a sustainable economy that can provide the necessary public services and lay the groundwork for effective support mechanisms for climate change mitigation and adaptation efforts, a major revolution is required in how energy is produced and used (Erdinc, 2017). Due to the urgent need to address climate change, the orientation to use renewable or clean energy will rise globally (Jiang et al., 2020). In comparison to the use of energy derived from fossil fuels, there has been substantial growth in the deployment of renewable energy sources for mitigating the worst effects of climate change (Erdinc, 2017).

As stated earlier, BIPV as a renewable energy technology not only serves as a building structure but also produces energy for buildings in a low-impact way and will, in turn, benefit from mitigating climate change. PV surfaces inherently have a higher solar

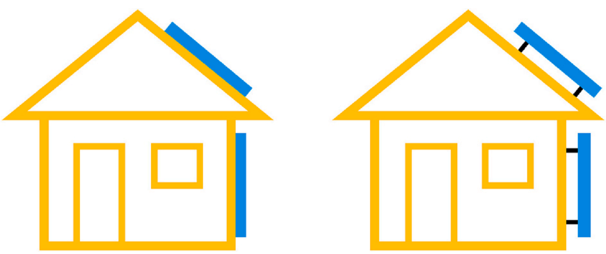

Fig. 1. BIPV (left) and BAPV (right) applications. Each colour of the schematics represents the building (yellow), PV panels (blue) and PV panel mounting brackets (black), respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

absorptivity as they are designed to harvest solar irradiation; an unintended consequence of this is that they can become another factor contributing to the UHI (Wang et al., 2006). In comparison, the use of cool roofs or facades is well-recognised as an efficient strategy for reducing the urban cooling load and mitigating the UHI (Kolokotsa et al., 2013; Yang et al., 2018a). However, cool roofs or facades are considered passive approaches to improving the demand-side of energy consumption in hot seasons only (Costanzo et al., 2016). On the supply-side, BIPVs are favourable systems responsible for the provision of energy production, which help to reduce building related carbon emissions (Costanzo et al., 2018). On the other hand, higher urban temperatures may restrain the PV efficiency (Wang et al., 2006).

However, as noted above, BIPV could also lead to the aggravation of the UHI effect because of its nature of low albedo and heat dispersion. Fundamentally, an urban canyon absorbs solar energy during the daytime and is released in the form of long-wave thermal radiation as the sun goes down (Hu et al., 2016). There is little research on how BIPV contributes to the UHI in terms of albedo and heat dispersion, while some research studies show contradictory conclusions. For example, Masson et al. (2014) report that the shading effect of a BIPV with low albedo might lower the UHI by reducing ambient air temperature by as much as 0.2°C during the day and 0.3°C at night in Paris, though they indicated this might not have general applicability elsewhere. Through simulation modelling, Cortes et al. (2015) echoed the cooling effect of BIPV on urban air, but they also pointed out the position of the sun might lead to BIPV warming and thus dispersing heat. Overall, the relationship between BIPV and urban heat is not yet understood definitively in previous research.

The fundamental aim of this review was to use a critical evaluation of the existing literature to understand the implications that BIPV systems might have for the UHI, particularly by focusing on albedo effect and heat dispersion from the BIPV. In addition, suggestions on urban design in relation to BIPV applications were also discussed.

2. Methods

It is well established that renewable energy generation can play a crucial role in combating climate change (Panepinto et al., 2021). The usage of BIPV systems is an example of one of the innovative technologies that show great promise (Yang et al., 2017). The purpose of this review study was to evaluate the influence that such systems have on urban microclimate and in particular the UHI. Analysis of

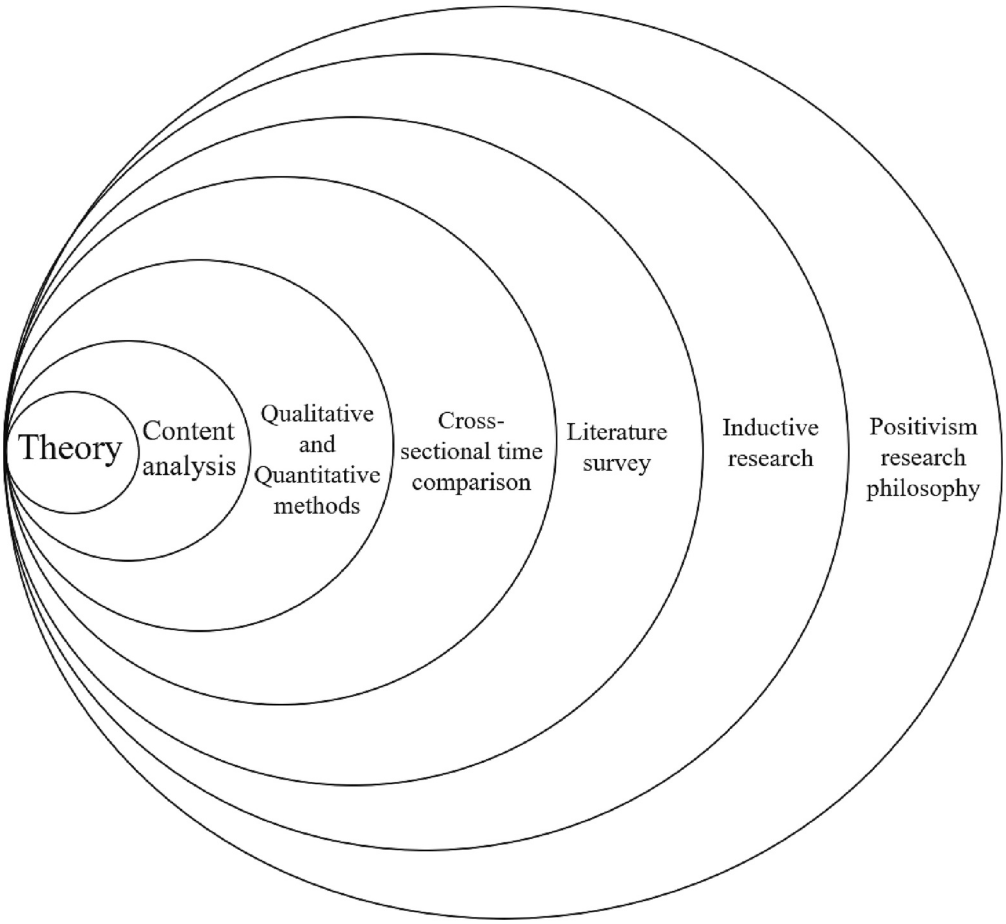

Fig. 2. Research design framework.

the published data informs the development of a theory of how BIPV influences the UHI, and how significant it might be. Specifically, the review and analysis were conducted using the methods described as follows.

2.1. Research design

The proposed study was based on the idea of positivism research philosophy (Žukauskas et al., 2018), where data collected from experiment findings have been used to describe the correlations between BIPV and the UHI. Specifically, the research was based on secondary data and scientific facts from experimental to statistical data with the ongoing building of hypotheses and theories about BIPV's effects on UHI. An inductive approach (Thomas, 2006) was adopted to generate a hypothesis from the ground up to address the research aim – to evaluate the implications of BIPV systems for the UHI. A mix of qualitative and quantitative research strategies was adopted to reach and build a comprehensive conclusion about BIPV's implications in the UHI from relevant literature data, conclusions, and findings. The general framework of the research design is further illustrated in Fig. 2.

2.2. Data collection approach

In this review study, we conducted data searches using renowned databases including Web of Science and Google Scholar predominantly (Attoye and Hassan, 2017; Sequeira and Santos, 2018; Siddaway et al., 2019; Silva and Andrade, 2020), while other most relevant internet resources were accessed as well. Most of the data we searched was within the last 5–10 years, which reflect the newest discoveries, theories, processes and best practices. Qualitative data collection was for theories, hypotheses, and predictions of the probability of the expansion of BIPV systems implementation due to some factors being the ever-growing change in the climate, as well as the causation of UHI. While quantitative data collection took place when gathering the scientific facts, conclusions, and empirical findings based on secondary data from the previous literature on the UHI phenomenon and BIPV systems characteristics.

2.3. Data analysis

Since the data collection of this review has lied on a combined qualitative and quantitative method, the analysis of the collected data for the literature survey also took a mixed approach. When diving deeply into the literature of this review, we came across quite a few contents from public statements and committees' conclusions to hypotheses and theories generated based on observations for the usage of BIPV systems in the future and how effective they are and what is the nature of UHI including why and how it happens. This wide variety of data was analysed as qualitative content to generate a common ground as a base for the literature survey. To analyse the generated theory and hypothesis about the impact of BIPV on the UHI, a more scientific approach was followed by examining a number

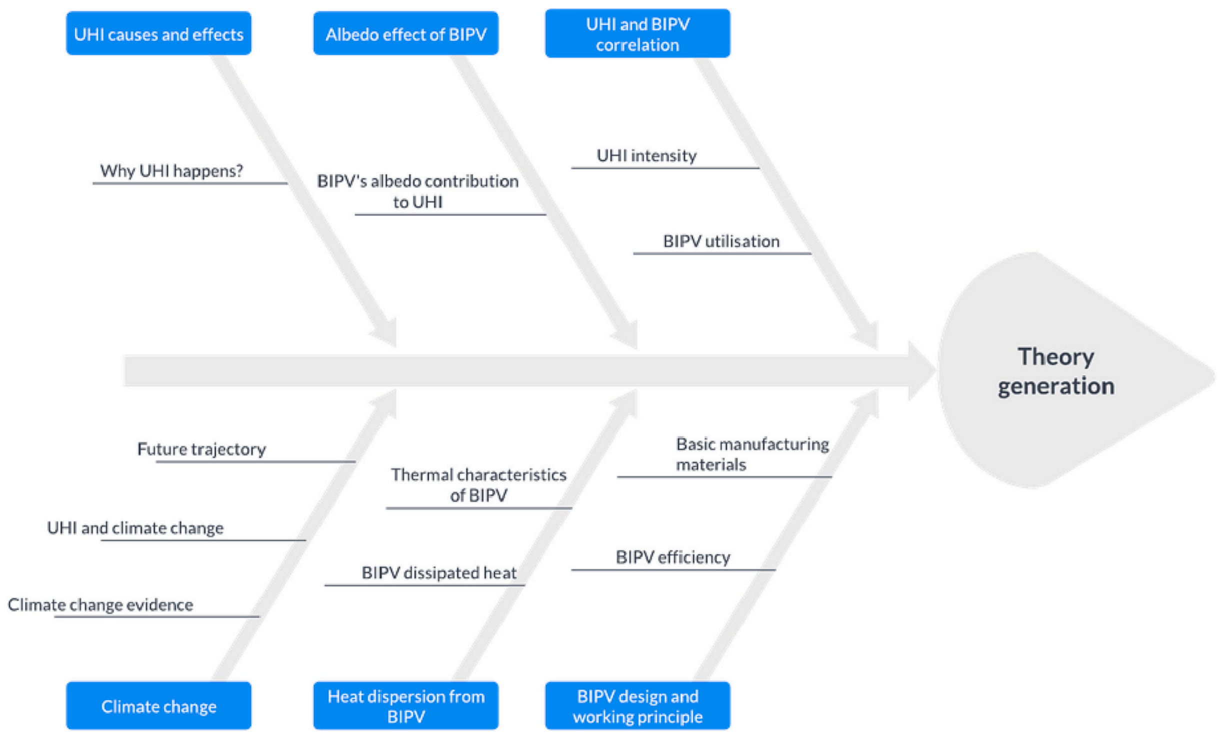

Fig. 3. Research flow chart for reaching the generated theory.

of experiments conducted for case studies and cross-referencing the statistical data to reach convincing proof for the theory and hypothesis. For example, experiments were conducted for investigation of the albedo effect and thermal properties of BIPV materials when exposed to sunlight; while the general outcome of those experiments was that light colours have high reflectiveness and dark colours have low reflectiveness, and thus dark coloured BIPVs in urban areas absorb more heat and contribute more to UHI. In this case, the correlation drove us to the hypothesis that BIPV certainly will impact UHI, generally because BIPV materials are mainly constructed with dark colours. Fundamentally, BIPV panels ought to be dark to absorb as many photons as possible to deliver the desired outcome: converting sunlight (photons) to electricity (Peharz and Ulm, 2018).

During our investigation, finding research that directly addresses the issue at hand was difficult to come across in the available literature. Specifically, the connections between BIPV and UHI were not well described by a large number of secondary data sources. However, we could find a solution to this problem by dissecting the two aspects, BIPV and UHI, and thus obtaining information from the databases. This can be illustrated in the fishbone diagram of Fig. 3. Firstly, the context of climate change (with evidence in literature), correlations between climate change and the UHI, future trajectory of climate change, and reasons for the UHI were discussed to position the intention of the proposed study. Then, the likelihood of BIPV-induced UHI due to both significant factors – albedo effect and heat dispersion – from the BIPV itself was thoroughly reviewed. Further, BIPV utilisation in urban area and UHI intensity were investigated to reflect the correlations between the UHI and BIPV. Moreover, to further understand how BIPV correlates with the surrounding environments, the BIPV design and working principle in terms of its manufacturing materials and power conversion efficiency were reviewed.

Following the solution, we were able to obtain the literature on each of the two aspects with plenty of specifics as a result of doing so. After that, we broke each component into more specific subparts. By doing so, we could cross-reference and locate a point of convergence between the definition of UHI and the design, implementation, performance and operating principle of BIPV, as well as the reasons for UHI, its contribution to climate change, its intensity and distribution across the world. Consequently, we were able to determine to what extent BIPV contributes to UHI.

3. Climate change and urban heat island

3.1. The background

A climate change projection was published stating that multiple climate model simulations provide similar results that by 2040 the average temperature of the globe might be 1.5°C higher than it is now (Lee et al., 2021). On the other hand, carbon dioxide and other greenhouse gases produced by human activities are the primary cause of this warming trend largely due to the combustion of fossil fuels (Yue and Gao, 2018; Hepple et al., 2023). In addition to the prementioned causes of climate change, a significant cause emerged is the UHI effect, which has been seen and recorded all over the globe as a result of continued urbanisation (Parker, 2010). Roughly half of the world's population already resides in urban areas, and this number is expected to rise to more than 60% by 2030 (Parker, 2021). It is reported that the UHI effect may raise city temperatures by several degrees compared to their surroundings due to the entrapped heat by urban structures (Gago et al., 2013), which can threaten human health as growing urban populations amplify the warming effects of climate change (Harvey, 2019). Measurements earlier taken in Manchester revealed a UHI intensity (that is, the difference in temperature between the city and the surrounding countryside) of 8°C during the summer, which would significantly contribute to climate change issues (Levermore et al., 2015b).

3.2. Characteristics and implications of the urban heat island effect

The primary contributors to the UHI effect are the massive amounts of heat produced by urban buildings when they absorb and re-radiate solar radiations and anthropogenic heat sources (Rizwan et al., 2008). This is crucial because buildings need to grow cooler at night to release the heat that has been trapped within them (Levermore et al., 2015b). In addition to the absorption of the sun's radiation in the urban concrete and buildings, UHI is also driven by other factors, such as heat gains in the urban areas due to cars and transports, and the energy use of buildings, cities, and towns are warmer at night than rural areas (Levermore et al., 2015b). It is feasible to characterise a UHI and its intensity using either surface temperature, air temperature, or both (Sheng et al., 2017). During the day, the surface temperatures in urban areas are several degrees higher than in rural areas (Azevedo et al., 2016). Night-time UHI can be more intense than daytime in terms of surface temperature when it is harder for structures to implement efficient night-time cooling and consequently increase the risk of overheating (Mathew et al., 2018). The midday air temperature in urban areas can be similar to that in rural areas, while evening temperatures in urban areas will be higher than in rural areas (Nichol et al., 2009).

The UHI may worsen existing health problems by altering rainfall patterns, making air pollution worse by combining with other environmental factors, raising the danger of flooding, and lowering the quality of water (Heaviside et al., 2017; Chen et al., 2023). Numerous studies have anticipated the likely effects of heat on mortality due to the UHI effect (He et al., 2022; Paravantis et al., 2017; Lowe, 2016; Taylor et al., 2015). Despite some studies reporting that an increase in urban temperature could decrease cold-related mortality (Macintyre et al., 2021; Vardoulakis et al., 2014), benefits are likely to be undermined by the increase in heat-related deaths due to the accumulation of predicted future increased temperature and heat wave frequency and rapidly aging growing population (He et al., 2022; Lowe, 2016). On the other hand, overheating in the summer causes occupants of houses to have trouble sleeping and may lead them to install fans or full air-conditioning systems, which, in turn, leads to more electricity consumption, and this even occurs in modern and well-insulated buildings (Levermore et al., 2015b).

Table 1 summarises the relevant literature (both Section 3.1 and Section 3.2) on the implications of climate change and the UHI effect and how they are connected and interact.

4. The albedo effects and such effects from BIPV on urban heat island

The term "albedo effect" refers to the phenomenon in which darker colours reflect less light and store more heat, so urban structures such as those made of concrete, cement, or asphalt will stock a lot of heat during the day and release it at night-time (Ramírez and Muñoz, 2012). These structures have a relatively low albedo, which means they absorb more solar radiation than other structures with a high albedo (Li et al., 2013). On a scale ranging from 0 to 1, albedo can be numerically expressed as a percentage. A value of 0 indicates that the surface of a material absorbs almost all of the sunlight that makes contact with it and thus 0% of the sunlight is reflected; if the value is larger than 0, it indicates that the material reflects a significant portion of the sunlight that is incident onto it, while a value of 1 for albedo indicates that 100% of the incident sunlight is reflected (Dobos, 2020). A numerical study by Feinberg (2020) emphasises the impact of UHI on global warming, from which it was found that global warming could be reduced by 30% by raising the UHI albedo value from 0.25 (average global land surface albedo) to 0.48.

Nuruzzaman (2015) published a dedicated literature survey on UHI, which created an illustrated list of likely reasons that lead to the UHI (as shown in Fig. 4). At the top of this list is the low quantity of evapotranspiration that occurs as a result of the absence of vegetation in urban areas. This survey also highlighted the low-albedo materials are commonly used in the construction cities, and due to the dense urbanisations, the general surface of cities has a low albedo; in addition, the concentration of people in metropolitan settings causes a significant quantity of heat to be produced by human activity (Nuruzzaman, 2015). Other than these, the survey also pointed out other UHI causes including human gathering, increased use of air conditioners, destruction of trees, urban canopy, wind blocking and air pollutants.

Kaloustian and Diab (2015) report a study of urban heat island in the city of Beirut, where is classified as a Mediterranean climate zone. It was found that high albedo values for urban surfaces would help mitigate the occurrence of urban heat island in Beirut, given that most of the city's urban surfaces have relatively low albedo values from 0.11 to 0.225. By means of simulation for the Italian cities, Morini et al. (2018) demonstrated the increase in materials' albedo could reduce urban temperature so as to mitigate UHI. However, this was effective for the specific locations only, as the increase of urban temperatures were found in some areas. A systematic review presented by Yang et al. (2015) lends colour to the benefits of urban temperature reduction being given by high-albedo materials. On the other hand, they point out that "reflected solar radiation can increase the temperature of the surrounding built environment and consequently increase its cooling load", which means the high-albedo materials may not be able to mitigate the UHI effect once and for all. Further, Manoli et al. (2019) revealed that high urban albedo is more effective for arid regions, while addressing UHI in tropical cities necessitate the explorations of new solutions rather than modifying albedo.

In addition, the phenomenon known as the albedo effect refers, very simply, to the way that various intensities of colour pigments have varying degrees of their capacity to reflect lights (Ramírez and Muñoz, 2012). To gain a better understanding of this phenomenon

Table 1
A summary of key studies on implications of climate change and UHI and their connections.

Reference	Research focus	Research location	Main findings
(Parker, 2010)	UHI effects on the estimation of observed climate change	Globe	Global near-surface temperature trends were not significantly affected by urban warming
(Harvey, 2019)	Overview of the effects of UHI on climate change	Globe	UHI effect may raise city temperatures by several degrees in comparison to their surroundings, which can be a threat to human health as growing urban populations amplify the warming effects of climate change
(Rizwan et al., 2008)	Investigation on the most important features of UHI	Globe	Urban buildings absorbed and re-radiated solar radiations and anthropogenic heat sources are the primary contributors to the UHI effect
(Levermore et al., 2015b)	Measurement of UHI intensity	Manchester, UK	Apart from the absorption of solar radiation in the urban concrete and buildings, UHI is also driven by other factors, including urban heat gains coming from cars and transports, the energy use of buildings, and cities and towns are warmer at night than rural areas
(Sheng et al., 2017)	Quantification of UHI intensity	Hangzhou, China	Urban surface temperature and ambient air temperature can be used to quantify the UHI intensity
(Azevedo et al., 2016)	Quantification of the day- and night-time UHI intensity	Birmingham, UK	Surface temperatures in urban areas are several degrees higher than in rural areas during the day
(Mathew et al., 2018)	Assessment of surface UHI effect	India wide	Night-time UHI can be more intense than daytime in terms of surface temperature
(Heaviside et al., 2017)	UHI effects on health	Globe	UHI effects lead to existing health problems worse by altering rainfall patterns, make air pollution worse by combining with other environmental factors, raise the danger of flooding, and lower the quality of water
(Macintyre et al., 2021)	Impacts of UHI on cold-related mortality	West Midlands, UK	A protective effect of winter UHI can avoid 15% of the total cold-related mortality
(Vardoulakis et al., 2014)	Impacts of climate change on heat- and cold-related mortality	UK and Australia wide	Climate change may lead to an increase in heat-related mortality but the decrease in cold-related deaths
(He et al., 2022)	Investigation of public responses to urban heat and heat-related illness	Nanchang, Shenyang and Xi'an, China	Urban heat problems and related illness and even mortality are evidenced, while the knowledge of heat-related risks is relatively low
(Lowe, 2016)	Assessment of the UHI impact on energy and mortality	USA wide	UHI-led to more energy usage in southern areas than in the north; the highest UHI in large city centres did have the highest mortality

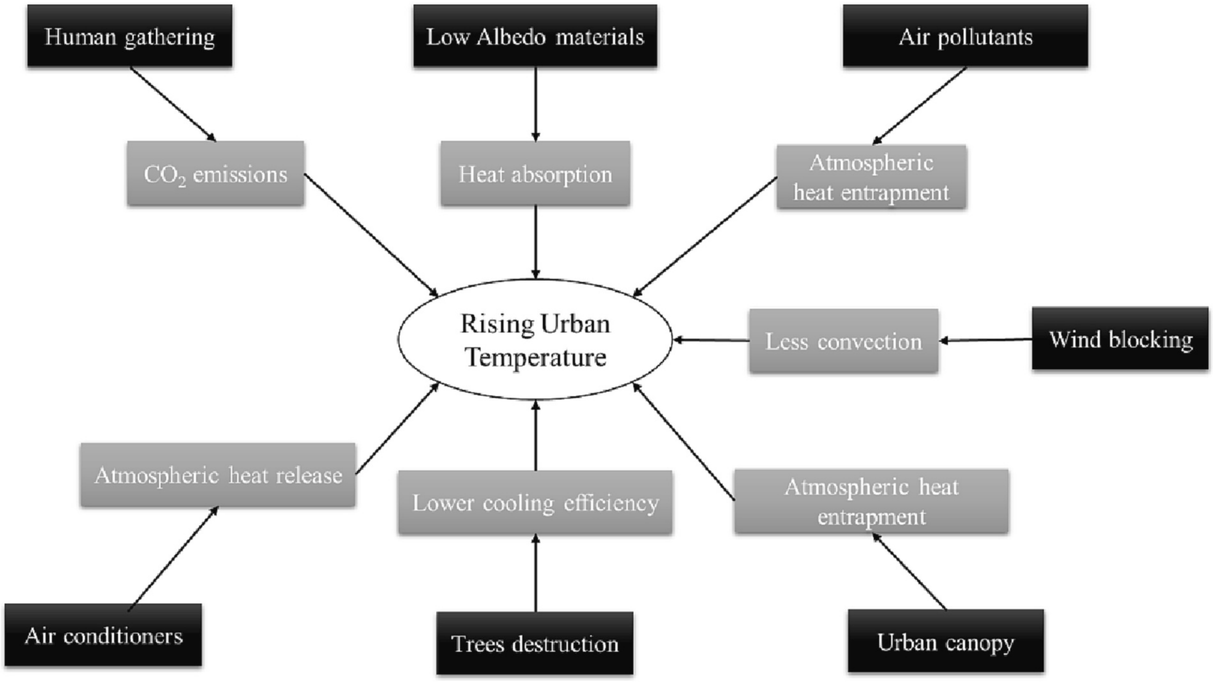

Fig. 4. Causes of urban heat island (Nuruzzaman, 2015).

in the built environment, a great deal of investigation in the form of studies and tests has been carried out. Reagan and Acklam (1979), as early as 1970s, conducted on the albedo effect equivalent studies about how different colours had different refraction abilities. It was shown that changing the colour of a building's roof from a dark shade to a light one altered the capacity of the roof to absorb solar radiation. According to an earlier study from Bansal et al. (1992), when solar radiation was at its peak during the day, the temperature inside the black-painted building reached a maximum that was 7°C higher than the temperature inside the white-painted structure. Under a no wind condition, Synnefa et al. (2007) found that the temperature of a black insulated surface with a solar reflectance of 5% was approximately 40°C higher than ambient air temperature when the sun was at its peak intensity (about 1000 $W \cdot m^{-2}$), while a cool black surface temperature could be about 10°C lower than a standard black surface; the similar characteristics were found being applied to other dark colours such as brown and blue, but their standard colour surfaces' solar reflectance were much higher (around or even above 20%). Furthermore, according to a study of Kolokotsa et al. (2012), cool white paints exhibit a notable high solar reflection of 89%.

Dornelles et al. (2010) report their experiments on a range of colour samples for the spectral reflectance curves through the spectrophotometric measurements including ultraviolet (UV), visibility (VIS), and near-infrared (NIR), which can be summarised in Fig. 5. As it turns out, all these white paints within the sampling were efficient solar reflectors; to put it another way, they all have a

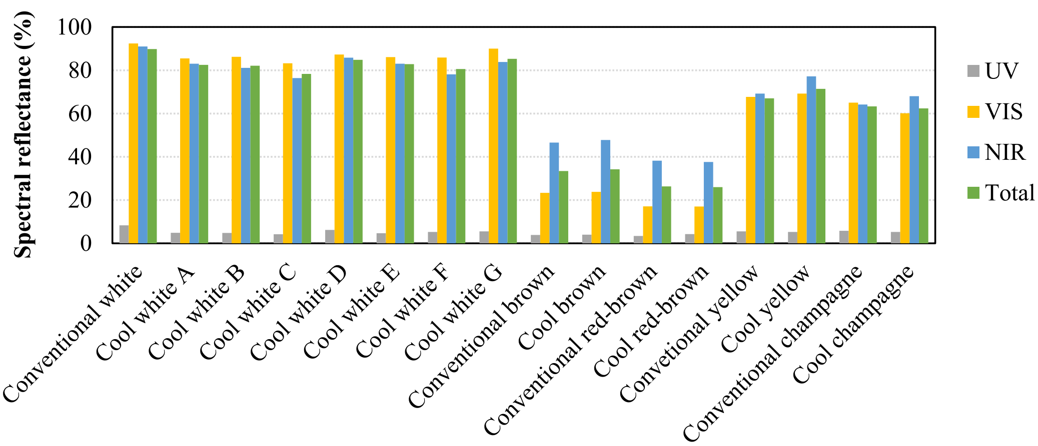

Fig. 5. Reflectance of different colours (Dornelles et al., 2010).

high degree of reflection in other words a high albedo in comparison with the other colour samples. Although there was a little difference between yellow- and champagne-coloured paints in spectral reflectance, brown coatings had noticeably higher reflectance than that of the red-brown, which is a further proof of lighter colours are better at reflecting the sun's ultraviolet, visible, and near-infrared rays than darker ones. In an experiment done by Uemoto et al. (2010), it was found that cool paints absorbed less solar energy and thus obtained a lower surface temperature and decrease in heat transfer through radiation.

In more recent years, extensive theoretical and practical investigations into the influence that the colour of buildings and constructions' exterior surfaces on their albedos have been carried out by researchers. Mansouri et al. (2017) conducted tests in Israel on tiny structures of varying outside colours for unventilated buildings, where they observed that temperature inside the buildings with white walls was around 3°C lower in the summer than the temperature inside the identical structures when they were painted grey. Mansouri et al. (2017) also clarified that a standard concrete has an albedo in the range of 0.35 to 0.40 when first created, but these values may decline to somewhere in the range of 0.25 to 0.30 with routine use. Concrete typically has a greater albedo than almost every other material which is often seen in metropolitan environments, while a concrete pavement can have albedo as high as 0.70 if slag or white cement is used in the mix (Ramírez and Muñoz, 2012). Asphalt is a commonly used pavement surface material (Zhong et al., 2021), while the inherent black colour of asphalt determines its albedo of relatively low (Chen et al., 2019). The albedo of asphalt pavement may vary from roughly 0.05 to 0.20, depending on its age and the components that make it up (Sen and Roesler, 2019). Taking aging factor into consideration, the light colour of grey concrete surfaces possess noticeably higher albedo than the dark black asphalt surfaces (Sanjuán et al., 2021).

The reviewed literature on one of the crucial factors that contributing to the UHI, namely "albedo effect", and how it is affected by colours is summarised in Table 2.

BIPV, as introduced earlier, can achieve a significant reduction in greenhouse gas emissions, which in turn will result in a reduction

Table 2
A summary of key studies on albedo effect.

Reference	Research focus	Research location	Main findings
(Feinberg, 2020)	Impact of UHI on global warming	Globe	Global warming could be reduced by 30% through raising the UHI albedo value from 0.25 to 0.48
(Nuruzzaman, 2015)	Causes and effects of UHI and the mitigation measures	Globe	Low-albedo materials are commonly used in the construction cities, which lead to the general surface of cities has a low albedo due to the dense urbanisations
(Kaloustian and Diab, 2015)	Effects of urbanisation on UHI	Beirut, Lebanon	High albedo values for urban surfaces would help mitigate the occurrence of urban heat island in Beirut, given that most of the city's urban surfaces have relatively low albedo values from 0.11 to 0.225
(Morini et al., 2018)	Mitigating UHI impacts through albedo enhancement	Rome, Italy	UHI mitigation through albedo enhancement was only effective for the specific locations, as the increase of urban temperatures were found in some areas
(Yang et al., 2015)	Environmental impacts of reflective materials	Globe	High-albedo materials might not be able to mitigate the UHI effects once and for all
(Manoli et al., 2019)	Influence of climatic condition dominated factors on UHI	Globe	High urban albedo is more effective for arid regions, while addressing UHI in tropical cities necessitate the explorations of new solutions rather than modifying albedo
(Reagan and Acklam, 1979)	Impact of colours on surface albedo	Tucson, USA	Changing the colour of a building's roof from a dark shade to a light one altered the capacity of the roof to absorb solar radiation
(Bansal et al., 1992)	Effect of external surface colour on thermal performance of buildings	Unspecified	Black-painted building had a higher temperature than the white-painted structure during the day
(Synnefa et al., 2007)	Thermal performance of cool coloured coatings	Athens, Greece	A regular black insulated surface with a solar reflectance of 5% was 40°C higher than ambient air temperature at peak intensity of solar irradiance, while a cool black surface temperature could be about 10°C lower than a standard black surface
(Kolokotsa et al., 2012)	Mineral based coatings for buildings and urban structures	Unspecified	Cool white paints exhibit a notable high solar reflection of 89%
(Dornelles et al., 2010)	Effect of cool paints on buildings in hot climates	Brazil wide	Lighter colours are better at reflecting the sun's ultraviolet, visible, and near-infrared rays than darker ones
(Uemoto et al., 2010)	Thermal performance of cool coloured paints	Unspecified	Cool paints absorbed less solar energy and thus obtained a lower surface temperature and decrease in heat transfer through radiation
(Mansouri et al., 2017)	Albedo effect of external surfaces on energy demand and thermal comfort of buildings	Skikda, Algeria	- Indoor temperature of a building with white walls was 3°C lower than that of grey walls in summer - A standard concrete has an albedo in the range of 0.35 to 0.40 when first created, but these values may decline to somewhere in the range of 0.25 to 0.30 with routine use
(Ramírez and Muñoz, 2012)	Urban albedo effects	Globe	Concrete typically has a greater albedo than almost every other material, while a concrete pavement can have albedo as high as 0.70 if slag or white cement is used in the mix
(Sen and Roesler, 2019)	Thermal and optical characteristics of asphalt in relation to UHI	Illinois, USA	The albedo of asphalt pavement may vary from roughly 0.05 to 0.20, depending on its age and the components that make it up
(Sanjuán et al., 2021)	Effect of precast concrete pavement albedo on climate change mitigation	Spain wide	In terms of aging factor, light grey concrete surfaces possess noticeably higher albedo than the dark black asphalt surfaces

in the amount of heat that is accumulated in urban areas (Chae et al., 2014). However, most BIPV panels are black and blue due to the material they are usually made of the special type of silicon such as monocrystalline and polycrystalline (Lee et al., 2014). These colours with minimum reflection ensure the BIPV itself to be capable of absorbing sunlight (measured in photons) and therefore achieve a higher efficiency (Peharz and Ulm, 2018). For example, a silicon mould is cut into PV cells and coated with a special blue shade of anti-reflective chemical to absorb more sunlight and be more efficient in turning the sunlight into electricity (Glenn, 2019).

Modern metropolitan areas often have darker surfaces than their surroundings, which has an influence not only on the weather but also on the amount of energy that is used (Mansouri et al., 2017). Studies have demonstrated that increasing the albedo of surfaces in urban areas through the use of cool roofs and pavements may effectively limit or attenuate the UHI effect (Kolokotsa et al., 2013; Yang et al., 2018a; Imran et al., 2018). However, as aforementioned, BIPVs are designed to be dark for absorbing more sunlight. As a result, they absorb more heat, which will warm the air in metropolitan areas (Kant et al., 2020). BIPV systems are available in dark colours predominantly ranging from black to blue, and even bronze and purple and other colours (Pelle et al., 2020), which means they have relatively low albedo leading to the percentage of solar radiation reflected by them is much lower than the solar radiation projected to them, and thus the radiation percentage gap is incurred (Shukla et al., 2016).

Previous research shows that a BIPV roof could lead to up to 8–9 times UHI heat load in comparison with a cool roof (Gentle et al., 2011). A study by Cortes et al. (2015) conclude that even if it was taken into consideration the varying albedo of the glass and silicon layers of a BIPV panel, the overall albedo of the BIPV structure was still lower than the cool roofs and walls. However, most of PV systems including BIPV have greater thermal conductivity and lower thermal capacity than roofs and walls, which implies that the temperature of PV-equipped surfaces can be increased more quickly, and the stored heat can then be discharged quicker from PV-equipped surfaces than from non-PV-equipped surfaces (Cortes et al., 2015). A most recent study of Ghenai et al. (2022) justified that the effectiveness of combining PVs/BIPVs and cool roofs could boost the PV power production up to about 15% with an increase in surface albedo value from 0.2 to 0.8. While Brito (2020) report that PV efficiency might decrease linearly with the increase of albedo; in this case, a dark PV panel with 10% albedo had an efficiency of 20%, but a light-coloured PV panel with 50% albedo might only have an efficiency of 10%. There is a reasonable prospect that the same applies to the BIPV applications.

The reviewed literature on how the albedo effect from the BIPV impacts the UHI is summarised in Table 3.

5. The contribution of BIPV's heat dispersion to urban heat island effect

It may no longer have a negative influence on the built environment by utilising BIPV systems as a potential energy source once this technology is put into place with high efficiency (Chae et al., 2014). It is important to keep in mind that different types of solar cells have temperature-induced drops in open-circuit voltage, efficiency, fill-factor and maximum power output, while the band gap of the material (such as monocrystalline and polycrystalline) used in the cells limits the amount of sunlight to be converted by BIPV panels into usable power and the remaining sunlight is either lost as sensible heat or reflected (Bazilian et al., 2002). On the other hand, incorporating PV into buildings might impact its operating temperature due to the negative temperature coefficient for solar cells (Kaplanis et al., 2022).

Table 3
A summary of key studies on BIPV's albedo effect on the UHI.

Reference	Research focus	Research location	Main findings
(Peharz and Ulm, 2018)	The nature of BIPV's colour	Unspecified	The dark coloured BIPV with minimum reflection (such as blue or black) ensure itself to be capable of absorbing sunlight and therefore achieve a higher efficiency
(Glenn, 2019)	The impact of PV coating on its conversion efficiency	USA wide	PV cells coated with a special blue shade of anti-reflective chemical can absorb more sunlight and be more efficient in turning the sunlight into electricity
(Pelle et al., 2020)	Coloured BIPV technologies assessment	Italy wide	BIPV systems are available in dark colours predominantly ranging from black to blue, and even bronze and purple and other colours
(Shukla et al., 2016)	Design of BIPV systems	Globe	Dark BIPVs have relatively low albedo leading to the percentage of solar radiation reflected by them is much lower than the solar radiation projected to them
(Gentle et al., 2011)	Albedo and thermal emittance of cool roofs	Sydney, Australia	A roof BIPV panel could lead to up to 8–9 times UHI heat load in comparison with a cool roof
(Cortes et al., 2015)	Effects of PV installation on urban thermal environment	Osaka, Japan	- Overall albedo of PV panels is always less than roofs and walls - PV panels have greater thermal conductivity and lower thermal capacity than roofs and walls - PV's thermal characteristics imply that the temperature of PV-equipped surfaces can be increased more quickly, and the stored heat can then be discharged quicker from PV-equipped surfaces than from non-PV-equipped surfaces
(Ghenai et al., 2022)	Effect of bifacial solar PV on roof surface albedo in buildings	Unspecified	The effectiveness of combining PVs/BIPVs and cool roofs could boost the PV power production up to about 15% with an increase in surface albedo value from 0.2 to 0.8
Brito (2020)	The impact of rooftop and façade incorporated PV on the urban microclimate	Unspecified	PV efficiency might decrease linearly with the increase of albedo: a dark PV panel with 10% albedo had an efficiency of 20%, but a light-coloured PV panel with 50% albedo might only have an efficiency of 10%

One of the ways to increase the efficiency of BIPV is to incorporate it in building surfaces such as roofs and facades by providing an airflow that goes through them to stay ventilated and thus gain more electrical production (Yang et al., 2020). However, structures in urban areas can heat the air around them by collecting sunlight and getting heated due to their imperviousness (Qaid et al., 2016), while studies have reported the likely UHI induced by the heat dispersion from BIPV (Wang et al., 2006). On a bright sunny day, the temperature of a BIPV roof was demonstrated to be significantly higher than that of the surrounding roofing, which would affect both the thermal performance of the BIPV systems and the building envelope (Agathokleous and Kalogirou, 2016). Lai and Hokoi (2015) explained this circumstance from the building physics point of view, where they conclude that the greater the solar heat flux was, the greater the convective heat transfer from a ventilated BIPV curtain wall; thus more heat will be transmitted to the ambient air.

When conducting the literature survey, we found that there has been a limited research on the correlations between BIPV and the UHI effect other than the albedo effect. In the earlier years, Tian et al. (2007a) report that BIPV temperature in the urban areas was lower than the rural case and thus resulted a relatively higher urban PV efficiency, although this was only measured for a particular location – Sao Paulo. In the meantime, Tian et al. (2007b), through simulation modelling, found that the BIPV roof and facade with a ventilated air gap could reduce the building surface temperatures during the day- and night-time, while the BIPV shade and natural airflow in the gap could minimise building cooling demands as well as reduce anthropogenic heat by 15%. They further conclude that few differences might be seen between the ambient air temperatures with and without a BIPV panel within an urban canyon, however, BIPV roofing and regular roofs had equal impacts on urban canyon diurnal heat fluxes. It was also found that the increased BIPV conversion efficiency would boost electricity generation and cool urban canyon air. In recent years, Boccalatte et al. (2020) published a study around the linkages between BIPV and UHI, but focusing merely on the impact of UHI on BIPV performance; it was found that the UHI-led high air temperature could slightly decrease the electrical production of the BIPV.

Based on a meteorological modelling of the Los Angeles region, Taha (2013) found that the reasonable high deployment of PVs in the urban areas can bring an ambient cooling effect if the PV efficiency was high enough, for example around 30%, and in this case the cooling effect could reach up to 0.15°C. The theory behind this finding relies on using highly efficient PV panels but less quantities, and in association with cool roofs and pavements of high albedos being heavily implemented on urban surfaces. This can in a sense reduce

Table 4
A summary of key studies on the impact of BIPV systems on UHI.

Reference	Research focus	Research location	Main findings
(Bazilian et al., 2002)	Thermographic analysis of the BIPV systems	Sydney, Australia	The material, such as monocrystalline and polycrystalline, used in the solar cell limits the amount of sunlight to be converted by BIPV panels into usable power and the remaining sunlight is either lost as sensible heat or reflected
(Kaplanis et al., 2022)	Temperature and heat transfer characteristics of BIPV systems	Globe	Incorporating PV into buildings might impact its operating temperature due to the negative temperature coefficient for solar cells
(Yang et al., 2020)	The impact of BIPV façades on building energy consumption	Australia wide	The ventilated BIPV structure was demonstrated to improve the PV conversion efficiency
(Agathokleous and Kalogirou, 2016)	Configurations and heat transfer characteristics of BIPV systems	Unspecified	- BIPV panel temperature was significantly higher than the surrounding roofing on a bright sunny day - The considerable high BIPV temperature would affect both the thermal performance of the BIPV systems and the building envelope
(Lai and Hokoi, 2015)	Thermal performance of the ventilated BIPV curtain walls	Unspecified	The greater the solar heat flux was, the greater the convective heat transfer from a ventilated BIPV curtain wall, and thus more heat will be transmitted to the ambient air
(Tian et al., 2007a)	Effect of urban climate on BIPV performance	Sao Paulo, Brazil	BIPV temperature in the urban areas was lower than the rural case and thus resulted a relatively higher urban PV efficiency
(Tian et al., 2007b)	Effect of BIPV on microclimate of urban canopy layer	Tianjin, China	- BIPV roof and facade with a ventilated air gap could reduce the building surface temperatures during the day- and night-time - BIPV shade and natural airflow in the air gap could minimise building cooling demands and reduce anthropogenic heat by 15% - Few differences may be seen between the ambient air temperatures with and without a BIPV panel within an urban canyon - BIPV roofing and regular roofs had equal impacts on urban canyon diurnal heat fluxes - Increased BIPV conversion efficiency would boost electricity generation and cool urban canyon air
(Boccalatte et al., 2020)	Impacts of UHI on BIPV performance	Europe wide	UHI-led higher air temperature could slightly decrease the PV power production
(Taha, 2013)	Impact of large-scale deployment of urban PV systems on ambient air temperature	Los Angeles, USA	- A PV with efficiency of 30% can bring an ambient cooling effect up to 0.15°C - The cooling effect relied on using highly efficient PV panels but less quantities, and in association with cool roofs and pavements of high albedos being heavily implemented on urban surfaces - The combination of PV and cool surfaces can reduce urban energy consumption through both demand- and supply-sides as well as cool the ambient air temperature down
(Chen et al., 2022)	Effect of BIPV window on the built environment	Phoenix, USA	The uptake of BIPV window glazing could help reduce ambient air temperature and hence mitigate nocturnal UHI effect in summer

urban energy consumption through both demand- and supply-sides as well as cool the ambient air temperature down, albeit the study was confined to the specific areas (Los Angeles) and the situation of BIPV was not within the scope of the study. In addition to BIPV roofing and façade applications, another latest study by Chen et al. (2022) found that the uptake of BIPV window glazing could help reduce ambient air temperature and hence mitigate nocturnal UHI effect in summer for the city of Phoenix.

Table 4 summarises the reviewed literature with regard to the possible impact of BIPV's heat dispersion on the UHI in terms of the nature of BIPVs and the relation between BIPV and UHI.

6. Discussion and conclusions

6.1. BIPV-induced temperature effects on urban heat islands

The knowledge gained from the literature survey on the application of BIPV systems has significantly given us a better understanding of how these systems may raise the surrounding heat (Kant et al., 2020). Materials used in the manufacture of BIPVs, their operating principles, and the level of their efficiencies are main factors of aggravating UHI to a certain extent (Bazilian et al., 2002; Agathokleous and Kalogirou, 2016; Taha, 2013). Solar cells (including BIPV) are designed with dark colours, usually blue or black, to increase the light absorption capabilities so as to make the cells more photon-absorbent and more light can be converted into electricity, which is done to maximise the efficiency of the PV panels but influence on the urban thermal environment potentially (Glenn, 2019). Although the phenomenon of UHI is a multi-variant equation, one of the variants has a close relation with how BIPV systems are constructed and what their working principle is. Fundamentally, the efficiency of BIPV downgrades when its temperature increases (Čurpek and Čekon, 2020), while its excess temperature gain not only affects the BIPV efficiency but also heats the surrounding air and the surfaces of urban buildings where the BIPV systems mounted on and thus intensifies the UHI effect (Peharz and Ulm, 2018; Gentle et al., 2011). Further, these buildings are going to consume more energy to cool the indoor spaces, thereby making the severity of UHI worse as the cooling units are dispensing the heat outside (Salamanca et al., 2014). Although some research show BIPV may not affect the urban thermal environment in particular areas (Tian et al., 2007a; Masson et al., 2014), BIPV's broad impact on UHI is anticipated (Hu et al., 2016; Shukla et al., 2016; Kant et al., 2020), while the significance of that impact is still to be investigated further to come to hard evidential conclusions.

Thermal control in BIPV, through the panel-integrated ventilation mechanism (Yang et al., 2020), is a commonly introduced method to lower and regulate the BIPV temperature for improving the PV electrical production, as well as reducing the effects of the excess temperature on the building and the surrounding area. In addition to the application of ventilation mechanism for BIPV, some research found that the implementation of the BIPV system on roofs and facades of buildings provides a degree of shading onto the building that acts as a cooling mechanism (Tian et al., 2007b). On the other hand, UHI-led higher ambient air temperature may decrease the BIPV electrical production (Boccalatte et al., 2020), which reflects that the uptake of BIPV and the UHI are interconnected.

In general, the albedo effect of urban structural materials is considered one of the major factors that contribute to UHI (Morini et al., 2018; Yang et al., 2015). Based on the findings from the literature survey, the common view is that bright colours have a high albedo (high reflectiveness), while dark colours have a low albedo (low reflectiveness) (Bansal et al., 1992; Synnefa et al., 2007; Kolokotsa et al., 2012; Dornelles et al., 2010); it demonstrates that the dark surfaces of the urban areas reflect less sunlight during the day, store the sunlight as thermal heat, and then release it back to heat the surroundings up and add further to the UHI effect (Qin, 2015). BIPV panels are meant to be low albedo for the sake of optimum electrical power conversion efficiency (Broadbent et al., 2019), consequently the temperature of BIPV-equipped surfaces can be increased more quickly and the stored heat can then be discharged quicker from the BIPV surfaces than from the non-BIPV-equipped surfaces (Cortes et al., 2015). Research found that a sensible high deployment of BIPV systems in specific urban areas can bring an ambient cooling effect if the PV power efficiency is high enough, while the rationale is to install highly efficient BIPV panels but less quantities (Taha, 2013); however, the BIPV panels are still not very efficient (Vourvoulias, 2022a). Moreover, the UHI effect in areas with less BIPV utilisation was rarely studied (Tian et al., 2007b).

In terms of mitigation strategies, creating more green spaces inside cities can help reduce the UHI effect from both the social and environmental dimensions (Wong et al., 2021). There is a reasonable prospect that the mitigation effect will be significant when afforesting is implemented on a larger global scale, as vegetation has a high albedo (Miller et al., 2016). In addition, the transition to more environmentally friendly sources of energy will have a major influence on climate change and the UHI (Ucal and Xydis, 2020; He, 2019). There is no doubt that BIPV systems are low-impact energy sources (Mancini and Nastasi, 2020). Although the installation of BIPV systems outside urban areas may assist in mitigating the environmental impacts, it is difficult to completely avoid the effects of these systems on the UHI since BIPVs are designed to be incorporated into the building structures of the city (Gholami et al., 2019; Shirazi et al., 2019; Yang et al., 2021b; Hasan et al., 2021). In summary, a positive feedback loop is created, in which the greater our reliance on BIPV systems to reduce our reliance on fossil fuels, the greater our contribution to the possible warming of our cities.

6.2. BIPV in urban design

From the urban design point of view, the uptake of BIPV within existing urban areas is still in its early stages due to various factors, such as the shading effect from adjacent buildings as well as vegetations and trees, other architectural elements, and the scruples of BIPV-induced temperature effects on the UHI (Saretta et al., 2020). These factors are manifest in the mutual effect between BIPV and the urban environments, as the UHI-led high ambient temperature and urban shadings can decrease the electrical production of the BIPV, while BIPV will in turn intensify the UHI. To maximise the BIPV electrical production, the BIPV-equipped surfaces need to be exposed to the highest solar radiation in the given urban regions (Shirazi et al., 2019), which, however, are consequent on the deterioration of the UHI. The deployment of BIPV with high conversion efficiency has been demonstrated to be positive for urban cooling due to the less quantities of BIPVs (Taha, 2013), hence BIPV efficiency is crucial to the mitigation of the BIPV-aggravated UHI effect. Although BIPV panels are still not very efficient, the best applications in urban areas are desired. In general, the electrical power conversion efficiency of monocrystalline-based solar cells is higher than that of the polycrystalline-based solar cells (Hidayanti, 2020), whereas monocrystalline-based solar cells are more expensive (Kazem et al., 2022). In this context, monocrystalline-based BIPV panels can be used in urban areas in order to minimise consequent UHI effect; in the meantime, the financial support and incentives from public sectors are indispensable (Qi et al., 2022).

On the other hand, BIPVs, particularly the roof-configured BIPV due to its low albedo, may contribute more to the UHI compared with many other roofing structure such as the cool roofs (Gentle et al., 2011). However, studies have revealed that the combination of BIPV and cool roofs can improve both BIPV surface albedo and electrical production (Ghenai et al., 2022). Thus, rationalised planning of BIPV and cool roofs in urban environments will help to mitigate the UHI effect. In addition, the use of novel semi-transparent BIPV glazing on the vertical part of the buildings in urban areas, has shown its capability in mitigating the UHI effect during the particular periods of time (Chen et al., 2022). As a matter of fact, semi-transparent BIPV has been a promising technology in controlling visual and thermal comfort and building energy consumption towards sustainability (Roberts et al., 2023; Yang et al., 2023). This is worthy to be evaluated in urban design.

6.3. Limitation and future research

Like any review article else, this paper may have potential bias; for example, gaps in literature searching on a somewhat lopsided evidence, and therefore ignoring research that points the other way (Snyder, 2019). As a result, more empirical research is required to investigate the linkage between BIPV and UHI based on actual observations or experiments. Thanks to technology, mitigation of UHI is possible. For instance, implementing more green spaces as vegetation, which, has a high albedo can mitigate the UHI effects. As a mitigation strategy in relation to BIPV applications, attempting to deploy BIPV systems outside the urban areas may help lessen the UHI effects. However, BIPVs are directly mounted on urban buildings or used as a part of the building structure, ergo it may be impossible to completely avoid their effects on UHI. This is something that still requires further investigation.

This literature survey, on the other hand, was focused mainly on the UHI effect intensified by the BIPV, which may lead to the omission of relevant causes come from solar PVs of various types such as BAPV hence a lack of thorough understanding of the PV-induced UHI. In this regard, future research should look into the applications of different types of PV panels in urban areas, and thus expand the knowledge about the linkage between the UHI and a full range of the urban solar PV utilisation.

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CRediT authorship contribution statement

Tarek S. Elhabodi: Resources, Data curation, Formal analysis, Visualization, Writing – original draft. **Siliang Yang:** Resources, Data curation, Formal analysis, Visualization, Writing – review & editing. **James Parker:** Resources, Writing – review & editing. **Sanober Khattak:** Visualization, Writing – review & editing. **Bao-Jie He:** Resources, Writing – review & editing. **Shady Attia:** Resources, 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

Data will be made available on request.

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