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From concrete jungles to cooler cities: dealing with the Urban Heat Island effect for a sustainable future

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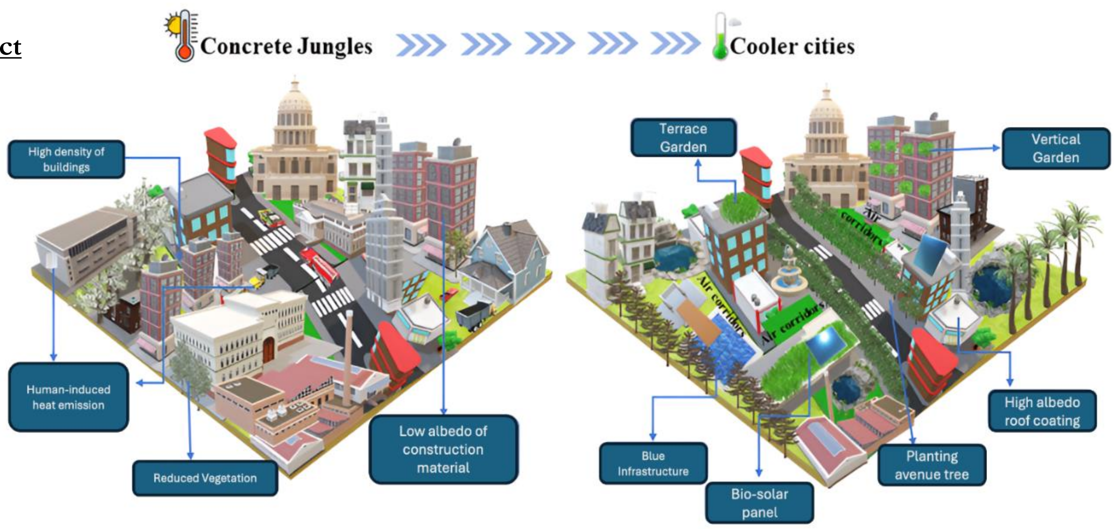
Abstract
With the rapid pace of urbanization, the Urban Heat Island (UHI) effect has emerged as a significant obstacle to sustainable urban living, characterized by elevated temperatures in cities relative to surrounding rural areas. This article explores the intricate mechanisms driving UHI development, emphasizing key contributors such as the reduction of green spaces, heat-retaining construction materials, compact city layouts, and anthropogenic heat emissions. Meteorological factors further compound UHI intensity, underlining its multifaceted nature. The consequences are far-reaching ranging from increased energy demands and diminished air quality to elevated greenhouse gas emissions and negative impacts on public health and thermal comfort. Climate change exacerbates these effects by altering local weather dynamics and intensifying heat stress. A comprehensive assessment of detection techniques is provided, alongside a diverse set of mitigation approaches. These include nature-based interventions such as green roofs, vertical gardens, urban forestry, and blue infrastructure, as well as technological innovations like reflective roofs and permeable pavements. The article also evaluates the complex role of solar panels, which can both alleviate and contribute to heat accumulation in urban settings. This work contributes to the creation of heat-resilient cities and promotes a shift from concrete-dominated landscapes toward cooler, greener, and more sustainable urban environments.

Keywords*:* *Urban Heat Island, Concrete jungles, urban planning, sustainable future, climate change*

Graphical abstract



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Introduction

Urbanization and climate change are two of the biggest environmental issues facing the world in the twenty-first century. Cities have caused unusual environmental alterations at regional to global scales, despite making up a very small portion of the world's land surface (a continental average of 0.5%) (Qiu *et al.*, 2020). Urban areas undergo landscape changes as they grow. Roads, buildings, and other infrastructure take the place of open space and vegetation. Typically, areas that were once moist and permeable turn dry and impermeable. This transformation leads to the formation of urban heat islands (UHIs) (Figure 1) (EPA, 2017). Buildings and roads in urban areas alter the local climate by affecting radiation, heat, and water balances. As a result, cities' thermal dynamics and solar radiation differ greatly from those of the nearby rural areas. According to (Oke, 1982; Ward *et al.*, 2016), the UHI effect is the result of higher temperatures in urban (areas relative to their surroundings. However, these elevated temperatures are accompanied by changes in precipitation patterns, climate extremes, and the effects of air pollution as well. Surface and Atmospheric UHI SUHI and AU HI) are two types of heat islands in urban areas (Van Hove *et al.*, 2011). SUHI results from elevated surface temperatures, with day and night variations ranging from 10°C to 15°C during the day and 5°C to 10°C at night, especially in summer (Martin *et al.*, 2015). AUHI has two layers: the urban canopy layer (UCL) close to the ground and the urban boun-dary layer (UBL) above it, forming a heat "dome" (Sol-tani and Sharifi, 2017) that spreads out as a "plume" (Oke, 1982). AUHI is most noticeable at night, with temperature differences of 1°C to 3°C. Surface temperatures are detected via thermal infrared remote sensing, while air temperatures are recorded through weather stations (Vujovic *et al.*, 2021). This study examines the

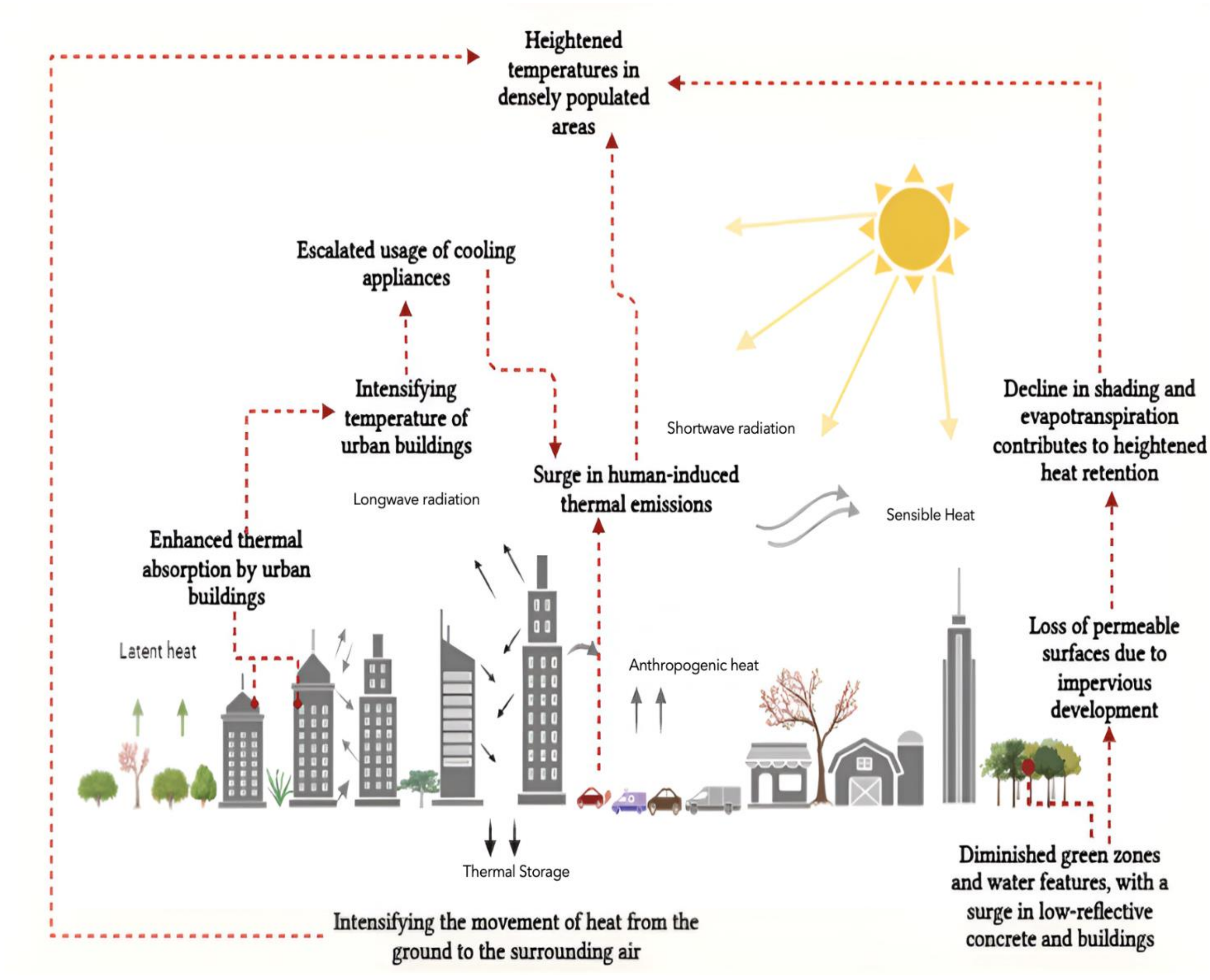

Figure 1. *Urban Heat Island development process*

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urbanization and climate change mechanics underlying the UHI effect, reviews ways to mitigate it, and assesses its effects on urban environments. The study intends to improve knowledge of UHI dynamics and provide guidance for sustainable urban development practices by combining the body of existing literature with fresh discoveries. In the end, it aims to offer insights that support more sustainable and healthy urban ecosystems in the face of rapidly increasing

Exploring the dynamics of urban Heat Island creation

Urban green cover depletion

Vegetation cover is essential for environmental sustainability in urban areas, supporting soil conservation, water regulation, temperature control, and biodiversity (Waseem and Khayyam, 2019). However, urbanization and land-use changes have reduced vegetation, raising carbon emissions, Land surface temperature (LST), and disaster risks, thereby contributing to climate change and threatening urban ecosystems and residents (Al Rakib *et al.,* 2020). Empirical studies illustrate this impact. Kafy *et al.* (2022) reported that a 9% reduction in vegetation cover over a 25-year period led to an 11°C rise in average temperature, while Rahaman *et al.* (2022) found that a 17% decrease in forest cover over the same period resulted in a 13°C increase in temperature. Building on this evidence, Singh and Kapoor, (2025) investigated UHI formation in Jhansi, India (2001–2021) using GIS-based remote sensing and meteorological data. Built-up areas increased from 7% to 26%, largely replacing green and natural surfaces, leading to a significant rise in land surface temperatures (LST), especially in urban cores. UHI intensity increased by 1.51°C, underscoring the strong link between urban expansion, vegetation loss, and localized warming. The study highlights vegetation's vital role in regulating urban heat. In rural areas, vegetation cools the environment through shade and evapotranspiration (Locke *et al.*, 2024). In contrast, urbanization replaces greenery with heat-retaining impervious surfaces, reducing natural cooling and increasing urban temperatures, thereby intensifying the UHI effect (Akbari *et al.*, 2001). This process is illustrated in Figure 2.

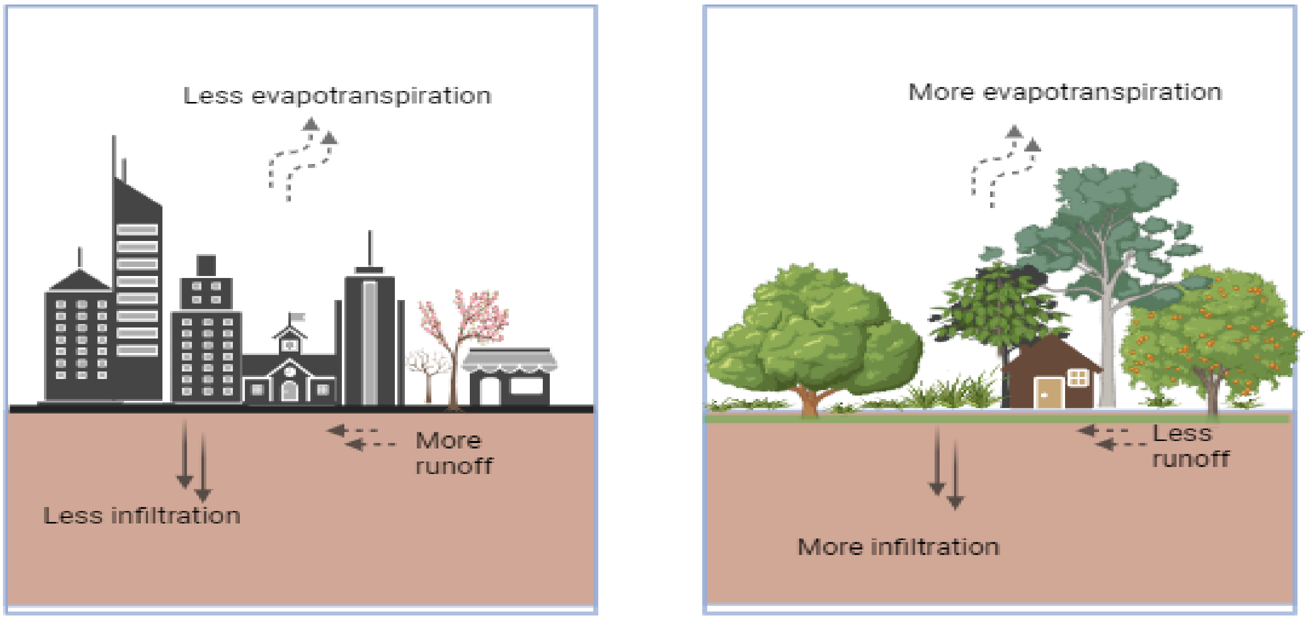

Figure 1. *Urban Heat Island: the role of surface permeability.*

(Highly developed urban areas with more non-permeable surfaces have less surface moisture for evapotranspiration than natural ground cover, leading to higher surface and air temperatures.)

Attributes of urban construction materials

Urban surfaces can be 20-30ºC hotter than the air due to solar absorption, especially in hot climates. This stored heat is released at night, worsening the UHI effect (Di Maria *et al.*, 2013). The thermal behaviour of these urban materials depends on the combined ef-

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fect of various properties like thermal conductivity, specific heat capacity, density, albedo, and thermal emissivity, rather than any single property (Sreedhar and Biligiri, 2016). Past simulations and studies show that a material's performance under the sun is linked to its solar reflectance (ability to reflect sunlight) and infrared emittance (ability to release absorbed heat). Low values of either reflectance or emittance mean the material is not cool (Radhi *et al.*, 2014). Urban areas absorb more solar radiation due to lower albedo materials like paving and roofing (Santamouris *et al.*, 2007)), and with urban materials like steel, stone and asphalt concrete (AC) having higher heat capacities than rural materials, cities store more heat, contributing to UHIs (Mohajerani *et al.*, 2017). Among these materials, AC stands out as a major contributor due to its low solar reflectance and high heat retention, with surface temperatures often exceeding 60°C on hot days, further amplifying urban thermal stress.

Urban layout

Urban layout, characterized by the height and spacing of buildings, significantly impacts the formation of heat islands (Yang *et al.*, 2021; Johansson, 2006) by altering wind patterns, enhancing energy absorption, and affecting heat dissipation. Because of the canyon effect and building materials, urban areas-especially those with higher buildings-absorb and reradiate a lot of solar radiation (Alobaydi *et al.*, 2016). By changing the number of exposed surfaces, building density influences the UHI effect. Urban canyon shape also affects natural ventilation system airflow and provides people with shaded walkways. A metric of urban geometry is the aspect ratio, which is the ratio of street width to building height (Perini and Magliocco, 2014; Alobaydi *et al.*, 2016). According to Bakarman and Chang (2015); Ren and Stroud (2022) the intensity of the UHI impact increases when the height-to-width (H/W) ratio of urban canyons diminishes.

Human-induced heat emissions

Human-induced heat emissions in cities, from sources such as building heating and cooling, manufacturing, transportation, and lighting, contribute to the UHI effect by warming the urban atmosphere through conduction, convection, and radiation, with variations influenced by latitude and season (Shahmohamadi *et al.*, 2011). Heat from air conditioning systems can increase metropolitan temperatures by 0.2-2.5 °C (Wen and Lian, 2009; Salamanca *et al.*, 2012; de Munck *et al.*, 2013). Furthermore, increased traffic and industrial activity generate a lot of heat, making industrial regions much warmer than their surroundings (Assaf and Assaad, 2023; Zhao *et al.*, 2024). Supporting this, Raj *et al.* (2020) analyzed satellite data from 44 major Indian cities (2000–2017) and found persistent increases in nighttime Surface UHI Intensity (SUHII) across all seasons. This rise was closely linked to rapid urbanization, built-up expansion, artificial lighting, and aerosol emissions, which together reduced vegetation cover and altered land surfaces further intensifying urban warming. These findings emphasize the urgent need for climate-sensitive urban planning and mitigation strategies to counteract anthropogenic heat stress.

Meteorological drivers

Cloud cover and wind speed are key meteorological factors in UHI development; a decrease in both allows more solar energy to reach city surfaces and reduces heat convection, leading to stronger UHI effects (He, 2018; Santamouris and Kolokotsa, 2016). Conversely, higher wind speeds and increased cloud cover can mitigate UHI formation by dispersing and reflecting heat, thus influencing radiative and turbulent energy exchanges (Zheng *et al.*, 2023). Supporting this, Huang *et al.* (2020) analyzed long-term meteorological data (1979–2013) in Shanghai and found that nocturnal UHI intensity (UHII) was highest in autumn and winter and lowest in summer. Conditions favoring stronger UHIs included calm winds, clear skies, low humidity, and minimal precipitation, while higher atmospheric pres-sure also correlated positively with UHII. Similarly, Lokoshchenko and Alekseeva (2023) examined UHI patterns in Moscow, reporting average and peak intensities of 0.9°C and 1.9°C, respectively, with extreme values reaching 11–12°C under strong anticyclonic conditions. Their findings highlighted low cloud cover, large diurnal temperature ranges, and surface tempera-tures as the most influential factors, with low cloudi-ness showing a strong negative correlation ($r = -0.67$). Wind speed, total cloudiness, and humidity also in-fluenced UHI, with a combined correlation of 0.76–0.82. Additionally, UHI intensity decreased significantly with wind speeds over 10 m/s and cloud cover above 50%.

In Salamanca, Spain, Alonso *et al.* (2007) also confirmed the presence of a nocturnal UHI, finding that wind speeds above 6 m/s suppressed UHI development, while high cloud cover enhanced it, particularly at night. They also observed atmospheric

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pressure variations affecting UHI via atmospheric stability. Notably, the study recorded microclimatic impacts, such as earlier spring onset in urban areas compared to rural surroundings. Collectively, these studies show that key meteorological factors like wind, cloud cover, humidity, and pressure strongly influence UHI intensity and patterns.

Environmental and social impacts

A catalyst for higher energy use

Urban areas account for approximately 75% of global energy consumption, with residential and commercial buildings using a substantial portion mainly in the form of electricity (Habitat, 2023). Rising ambient temperatures further intensify this demand. Studies show that for each 1°C increase in temperature, energy demand rises by 2–4% during summer (Akbari *et al.*, 2001), while peak electricity demand increases by 0.45% to 4.6% per degree (Santamouris *et al.*, 2015). The UHI effect contributes significantly to this rise by intensifying urban temperatures, especially during warm seasons. UHI not only increases cooling energy demand but can also lead to decreases in winter heating needs, creating a dual effect (Phelan *et al.*, 2015). For instance, Li *et al.* (2019) reported that UHIs could lead to a 19.0% increase in cooling energy use and an 18.7% decrease in heating energy use. Similarly, Kumari *et al.* (2021) observed an 11.4% average rise in annual electricity consumption across eight districts in Delhi (April 2012–March 2017) due to UHI formation. In a more localized analysis, Liu *et al.* (2025) analyzed neighborhood-scale temperature variations in a high-density subtropical city and found that urban areas consumed up to five times more cooling energy than rural ones. A 1000 °C·h increase in daytime UHI degree hours led to a 4.7 kWh/m² rise in cooling energy use, while a 1°C rise in maximum temperature increased peak load by 1.02 kW, highlighting the importance of high-resolution UHI data for energy planning. Complementing this,, Hashemi *et al.* (2025) used a microclimate-adjusted Urban Building Energy Modeling (UBEM) framework to project the combined effects of UHI and climate change on building energy use in Des Moines, Iowa. Their findings suggest UHI intensity will rise from 0.55°C to 0.63°C by 2080, increasing cooling demand by 91% by 2050 and 154% by 2080, with UHI alone contributing 2.3%–6.2% to the rise. While heating demand may decrease by up to 40.1%, the long-term effectiveness of insulation in reducing heating loads diminishes, underscoring the need for adaptive building strategies and UHI mitigation. Collectively, these studies highlight how UHI significantly amplifies urban energy consumption, especially in warmer seasons, making it a critical factor in urban energy planning and climate resilience.

Urban heat-pollution nexus: impacts on air quality

A variety of studies have indicated a relationship between the UHI phenomenon and air pollution (Wang *et al.*, 2021; Li *et al.*, 2018; Mathew *et al.*, 2025; Nasar-u-Minallah *et al.*, 2025; Plocoste *et al.*, 2014) Mathew and Arunab (2025) investigated the correlation between UHI and multiple air pollutants (CO, NO_2, HCHO, SO_2, O_3, and aerosols) in Bangalore using satellite-based datasets (TROPOMI and MODIS) for the period 2019–2022. Their study found a strong positive correlation between UHI indicators and most pollutants, except SO_2, which showed a negative correlation. A weighted Urban Pollution Island (UPI) index developed using Fuzzy AHP, along with spatial analysis of thermal risk zones, revealed that high-risk zones (HRZs) had significantly elevated pollutant concentrations and were on average 2.2 °C warmer than low-risk zones (LRZs), emphasizing the dual burden of heat and pollution in densely urbanized regions. In a tropical context, **Swamy *et al.* (2017)** explored UHI and air quality dynamics in Chennai using the Envi-Met model. They found that commercial and residential areas exhibited higher air temperatures than urban background zones, with UHI effects exacerbated by wind speeds between 0.2 and 5 m/s, which altered the atmospheric boundary layer (ABL) and mixing heights. Importantly, the lowest nocturnal mixing height (60 m) recorded in residential areas coincided with peak ozone (O_3) concentrations, suggesting that UHI may enhance secondary pollutant formation by influencing vertical mixing and dispersion. Wang *et al.* (2021) further confirmed the linkage in the Yangtze River Delta (YRD) region. Their study showed a positive correlation between daytime UHI intensity and ozone concentrations, while other pollutants like $PM_{2.5}$, PM_{10}, NO_2, and SO_2 were negatively correlated. Inland cities showed worse air quality than coastal cities, with LST emerging as the most influential factor driving both UHI and pollutant distribution, followed by vegetation cover and topography. Similarly, Li *et al.* (2018) examined the interaction between UHI and Urban Pollution Island (UPI) effects in Berlin using a combination of in-situ and remote sensing observations. They found spatial alignment between elevated temperatures and pollution levels, and a

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negative nighttime correlation (r = –0.31) between atmospheric UHI (AUHI) and near-surface pollution (NSUPI), indicating that enhanced turbulence from UHI can reduce pollutant concentrations near the surface. However, aerosols also contributed to enhanced nighttime SUHI (~12%) by increasing atmospheric longwave radiation. In the Paris region, Sarrat *et al.* (2006) used a coupled meteorological-chemical model (Meso-NHC with TEB) to simulate urban effects. Their results confirmed that urban land cover significantly altered local meteorology, deepening the nocturnal UHI and changing the structure of the boundary layer. This, in turn, influenced the spatial distribution of both primary and secondary pollutants, particularly ozone and NOx, due to increased turbulence and vertical mixing. Overall, these studies underscore the mutual reinforcement between UHI and air pollution, where urban warming can amplify pollutant concentrations and vice versa. This bidirectional relationship not only compromises urban air quality but also amplifies health risks, especially during extreme heat events. A deeper understanding of this interplay is essential for formulating integrated urban strategies that address both heat mitigation and pollution control in growing cities.

Human health, comfort, and quality of life

The health impacts of UHIs are significant and diverse, affecting both physical and mental well-being (Singh *et al.*, 2023; Ebi *et al.*, 2021). Heat exposure, in particular, has been increasingly associated with higher rates of anxiety, depression, and other mental health disorders, as elevated temperatures tend to worsen stress and exacerbate existing psychological conditions (Dai and Liu, 2022; Hsu *et al.*, 2021). In this context, Dai and Liu (2022) conducted a comprehensive study in Tianjin (2006–2020) to examine the health impacts of global warming and UHIs and found that UHI-affected zones expanded to 373 km², with growing impacts on respiratory, cardiovascular, and mental health, particularly in downtown areas and along traffic corridors in Binhai New District. Highlighting the broader health implications,, Tong *et al.* (2021) reported that the UHI effect was responsible for more than 50% of total heat-related mortality in certain regions during extreme heatwaves. Extending this perspective, Bao *et al.* (2025) analysed data from 338,363 urban residents in the UK and found that higher summer UHI intensity significantly elevated the risk of mental health disorders, including substance use (HR 1.12), depression (HR 1.08), and anxiety (HR 1.06), particularly among women and individuals with hypertension or heart disease. UHI exposure was also associated with worsened psychiatric symptoms and alterations in brain white matter. Collectively, these findings underscore UHI as a serious environmental health stressor and highlight the need for climate-adaptive urban planning to enhance public health resilience and reduce mental health burdens.

Water quality deterioration

Streams UHIs often have higher baseflow temperatures than rural and forested streams due to elevated urban air and ground temperatures, extensive paved surfaces, and reduced riparian canopies. Urban infrastructure, including impervious surfaces and storm drains, channels runoff over these heated areas, causing rapid and significant temperature increases (Somers *et al.*, 2013; Nelson and Palmer, 2007). Increased stream temperatures reduce dissolved oxygen by boosting microbial activity, oxygen demand, and lowering diffusion and solubility. Warmer water impacts the growth, metabolism, and reproduction of aquatic life, and can be lethal if temperatures exceed their thermal limits (Vannote and Sweeney, 1980; Imberger *et al.*, 2008; Hester and Doyle, 2011). Higher baseflow temperatures are often negatively correlated with species richness, mainly due to the loss of temperature-sensitive taxa (Beitinger *et al.*, 2000; Sponseller *et al.*, 2001; Wang and Kanehl, 2003; Jones *et al.*, 2006; Nelson and Palmer, 2007).

Modifications in rainfall patterns induced by UHI effects

The UHI effect influences local precipitation patterns by altering atmospheric conditions (Figure 3). Studies by (Wan *et al.*, 2013; Zhong *et al.*, 2017; Argüeso *et al.*, 2016; Liu and Niyogi, 2019)) demonstrated that UHI alters circulation patterns, potentially increasing precipitation. High urban temperatures create unstable air masses, causing warm air to rise, cool, and condense into rain-producing clouds. As this warm air mixes with cooler layers, precipitation increases downwind of cities (Lin *et al.*, 2011; Mishra and Kannan, 2023). In addition to thermal effects, urban areas also emit aerosols that act as cloud condensation nuclei, enhancing cloud microphysical processes and improving precipitation efficiency (Lalonde *et al.*, 2023). Lin *et al.* (2011) employed the WRF model coupled with the Noah land surface and urban canopy models to study the UHI effect on precipitation in northern Taiwan's complex terrain. Under dominant southerly winds and elevated temperatures, urban areas acted as warm, dry zones

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that initially restricted moisture transport and delayed thunderstorm formation. However, intensified surface heating eventually increased atmospheric instability and enhanced rainfall, particularly downwind, with precipitation increasing by up to 28%. Similarly, Zhong *et al.* (2015) used the WRF-Chem model to investigate the combined effects of UHI and elevated anthropogenic aerosols on a heavy rainfall event in the Greater Beijing Metropolitan Area (GBMA). Their simulations showed that while UHI increased rainfall in the upstream (northwest) region and decreased it downstream (southeast), aerosols had the opposite effect suppressing rainfall upstream and enhancing it downstream. Indirect aerosol effects dominated, with smaller cloud droplets promoting evaporative cooling and weakening early convection upstream, while latent heat release from droplet freezing later intensified convection and rainfall downstream. Steensen *et al.* (2022) conducted a 20-year regional simulation for Paris and Shanghai to assess how the UHI effect on precipitation might change under future warming. Their results indicated a projected decline in UHI-induced enhancement of both mean and extreme precipitation. In Paris, UHI currently contributes to a modest increase in mean precipitation (~2.2%), which slightly diminishes in future scenarios. Shanghai shows minimal UHI influence, both currently and under future warming, with the reduction primarily attributed to decreased summer rainfall. Interannual variability in UHI-induced precipitation was more pronounced in Shanghai than in Paris. Contrary to the conventional understanding, Ding *et al.* (2025) examined over 1.3 million trans-urban wind paths globally and found that stronger UHI intensities are actually linked to weaker downwind precipitation enhancement. Instead, they identified background wind speed as the dominant factor influencing rainfall. Strong winds promote convergence due to surface roughness contrasts between urban and rural areas, thus enhancing downwind precipitation. The study concludes that dynamic factors like wind speed outweigh thermodynamic factors such as UHI intensity in determining rainfall patterns, particularly in mid-to high-latitude regions, with important implications for urban planning and flood risk mitigation.

Climate change: fuelling the urban Heat Island effect

Climate change significantly fuelling heat stress risks in cities (Corburn, 2009; Oleson *et al.*, 2015; Argüeso *et al.*, 2015), particularly in Asia, at warming levels of 1.5 °C and 2 °C. As global temperatures rise, the UHI effect worsens, increasing heatwave risks for nearly half of the urban population while deteriorating health and economic productivity (IPCC, 2021)

Figure 3: *Mechanisms of urban Heat Island influence on precipitation*

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Sachindra *et al.* (2016) investigated the impact of climate change on UHI intensity in Melbourne's central business district (CBD), using Laverton, a less urbanized location, as a rural reference. Their analysis of temperature records from 1952 to 2010 showed a significant upward trend in nocturnal UHI intensity, whereas diurnal UHI remained relatively unchanged. Using gene expression programming (GEP) to downscale outputs from GCMs (HadCM3, GFDL2.0, and ECHAM5) under the A2 emission scenario, they projected a gradual rise in minimum temperatures from 2000 to 2099 and a strengthening of UHI effects across all seasons. Similarly, Keppas *et al.* (2021) assessed future UHI behavior in the Mediterranean cities of Rome and Thessaloniki using the WRF-ARW model under the RCP 8.5 scenario. Through three 5-year time-slice simulations (2006–2010, 2046–2050, and 2096–2100) at a 2 km resolution, they found that urban areas consistently recorded higher nighttime and early morning minimum temperatures (Tmin) than rural surroundings, with a UHI intensity of +1.5 to +3 °C. Although the UHI magnitude remained relatively stable (~±0.2 °C) under future warming scenarios, the frequency of nights with Tmin ≥ 20 °C is projected to rise, particularly in coastal urban areas, along with a significant increase in thermal discomfort in low-lying zones. Additionally, rising global temperatures drive greater cooling energy demands and amplify anthropogenic heat emissions, further intensifying the UHI effect (Oleson, 2012). Urbanization and land use changes exacerbate this through a reinforcing feedback loop, where increased emissions accelerate urban warming (Hayes *et al.*, 2022; Wang *et al.*, 2022).

Urban Heat Island detection: a methodological overview

Several approaches are employed to assess and retrieve UHI, each offering distinct advantages and applications depending on the study's objectives and context. The following table 1 summarizes various methods.

Table 1. *Overview of methods for assessing urban Heat Island effects*

Methods of quantifying UHIs effect	**Overview**
In-Situ Measurement	It involves taking direct readings of temperature, humidity, and other meteorological parameters within an urban area using technologies such as fixed stations (Sun et al., 2019; Siu and Hart, 2013), mobile transects (Bottyán et al., 2005; Sun et al., 2019; Rodríguez et al., 2020) with sensor-equipped vehicles, and portable handheld sensors. Although these methods provide precise localized data, they are labour-intensive and have limited spatial coverage (Rodríguez et al., 2020).
Remote sensing	Remote sensing provides high-resolution data for monitoring UHI, with key methods such as LST measurement, which quantifies temperature variations between urban and rural areas (Majumder et al., 2021; Moazzam et al., 2022; Kimothi et al., 2023; Gadekar et al., 2023), and biophysical indices such as NDVI (Normalized Difference Vegetation Index), NDBI (Normalized Difference Built-up Index), and NDBaI (Normalized Difference Bareness Index) are used to evaluate how green cover, urban density, and surface bareness affect heat responsiveness (Jain et al., 2020; Pathak et al., 2021; Halder et al., 2021). These tools help reveal the link between vegetation loss and rising urban temperatures.
Modeling approach	(Bahi et al., 2020) summarized key meteorological models for identifying UHIs, including the CSU MM (Colorado State University Mesoscale Model), Model URBAN3, SHIM (Surface Heat Island Model), the TEB model (Town Energy Balance), a statistical mapping approach (Gousseff et al., 2024), the ENVI-met model (Cortes et al., 2022; Faragallah and Ragheb, 2022), and CFD (Computational Fluid Dynamics) (Mosca et al., 2024). The PLUS (Patch-generating Land Use Simulation)) and Markov models are widely used for simulating future urban scenarios and have proven highly effective in modeling land use changes (Zhao et al., 2025).

Solutions to combat urban Heat Island formation: paths to gooler cities

To effectively mitigate the UHI effect, a range of strategies can be employed, particularly through Nature-based solutions improve building materials, and optimize urban planning (Figure 4). Following are some actionable solutions for addressing UHI effect.

Sustainable nature-based solutions

A. Green roofs and vertical gardens. Green roofs are

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plant-covered surfaces, typically consisting of vegetation grown on a specialized substrate material placed on building rooftops (Jamei *et al.*, 2021). They cool the surrounding environment through shading, which blocks direct sunlight, and evapotranspiration, where plants absorb water and release it as vapor, thereby cooling the air (Lee *et al.*, 2024; Jamei *et al.*, 2023; Cascone, 2022). Greening roofs creates a local cooling effect ranging from 0.8°C to 1.5°C and promotes energy savings (Qin *et al.,*2023). Jahangir *et al.* (2024) found that adding vegetation to building roofs can lower UHI by an average of 0.68°C. Lee *et al.* (2024) emphasize that green roofs can reduce building temperatures by 4.3°C to 5.0°C during peak months, effectively mitigating the UHI effect. Furthermore, green roofs can reduce cooling loads by up to 70%, lower indoor temperatures by as much as 15°C, and enhance thermal comfort, while also decreasing pollutants and sequestering carbon (Mihalakakou *et al.*, 2023). Vertical gardens can mitigate UHIs by converting unused vertical surfaces into green spaces, enhancing biodiversity, energy conservation, thermal insulation, and environmental quality, ultimately leading to cooler urban environ-ments (Zat'ovičová and Majorošová, 2023; Lombardo *et al.,* 2022).

B. Urban greening strategies: traditional vegetation and Miyawaki Forests. Trees significantly reduce local air temperatures, offering cooling effects 2–3 times more effective than other urban green spaces, making them a key solution for combating UHIs (Kim *et al.*, 2024). Guo *et al.* (2023) observed that increasing tree cover significantly reduces UHI effects, with tree-covered areas exhibiting LST approximately 2.23°C lower than surrounding built-up areas during summer. Pace *et al.* (2023) found that a 10% increase in tree cover can reduce maximum hourly air temperature by 0.2°C, highlighting a direct relationship between tree cover and UHI mitigation. Adams and Smith (2014) noted that a 14% increase in tree cover could completely counteract the heat generated by urban materials. Utilizing native, drought-tolerant plants in roadside planters and vacant lots can help alleviate heat by integrating small green spaces into urban areas (Irfeey *et al.*, 2023). Barradas *et al.* (2022) studied fifteen urban tree species in Mexico, finding that *Liquidambar styraciflua* L. had a high midday transpiration rate of 0.0357 g m^2 s^{-1}, indicating strong cooling potential and effectiveness in reducing urban heat. These results can assist urban planners in redesigning urban parks to mitigate heat while increasing tree diversity. The Miyawaki Forest method, developed by Japanese botanist Dr. Akira Miyawaki (Miyawaki and Golley, 1993), offers a promising and relatively rapid solution for urban greening. This technique has been successfully implemented in Japan and has shown encouraging results in other Asian countries, including Thailand, Malaysia, and India (Singh and Saini, 2019). By planting dense, multilayered native forests using a mix of species, Miyawaki micro-forests establish self-sustaining ecosystems that attract diverse wildlife such as birds, butterflies, and insects. Beyond biodiversity enhancement, these urban forests play a vital role in mitigating pollution, lowering ambient temperatures, and providing crucial ecological and social benefits, including disaster risk reduction.

C. Blue infrastructure. Urban water bodies reduce the UHI effect and enhance thermal comfort, influenced by proximity to residences, vegetation, and urban design (Xie *et al.*, 2023; Wu and Zhang, 2019). Wang *et al.* (2023) reported that large urban water bodies, such as Meijiang Lake, can reduce the UHI effect by up to 14.44% within a 130-meter radius, providing significant cooling to nearby residential areas. Zeeshan and Ali (2023) found that water bodies reduce the UHI effect by lowering air temperature by 0.9°C and surface temperature by 3.5°C. Rahul and Mukherjee (2023) found that water bodies, such as Sukhna Lake in Chandigarh, significantly reduce UHII during summer, with cooling effects reaching up to 3.52 °C in areas with dense trees. Supporting this, Lin *et al.* (2020) found that a 10% increase in water body coverage in the Pearl River Delta led to an 11.33% reduction in SUHI intensity, with cooling effects extending up to 100 meters beyond their edges. While water features are often efficient at reducing the UHI effect during the day, they can also add to the UHI effect at night. Studies show that surrounding temperatures can rise significantly at night, sometimes matching those in residential areas (Yao *et al.*, 2023), due to the thermal inertia of water bodies, which retain heat (Xie *et al.*, 2023).

C. Cool roofs and cool pavements. Cool roofs and cool pavements reduce cooling energy use in air-conditioned buildings, improve thermal comfort, and mitigate the UHI effect (Akbari and Matthews, 2012) by reflecting more sunlight than conventional roofs and pavements, thereby reducing the amount of solar energy absorbed. Lee *et al.* (2023) observed significant surface temperature reductions after installing these so-

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lutions, with slab and panel roofs reducing temperatures by 15.5°C and 11.6°C, respectively, while cool pavements lowered temperatures by at least 4°C. Furthermore, Kolokotsa *et al.* (2018) demonstrated that the application of cool roofs and pavements resulted in a 17% reduction in energy use and a 10K reduction in surface temperature. In a related study, Akpınar and Sevin (2018) found that reflective concrete pavements coated with high-reflectance paint exhibited albedo values that were 60% higher, with surface temperatures and heat gradients 40% and 38% lower, respectively, compared to uncoated surfaces. Building upon this, Stache *et al.* (2022) quantified the surface energy balance of urban materials and vegetation types, highlighting vegetation's role in UHI mitigation. Moss emerged as the most effective, converting 50% of absorbed energy into latent heat, while sedum was least efficient, directing 73% into convectional heat. Albedo differences also influenced cooling potential, with ivy showing the highest (0.10) and moss the lowest (0.07). Complementing these nature-based strategies, material innovations offer promising UHI solutions. Wanniarachchi *et al.* (2025) developed a resin-based composite paving material with high porosity (27.14%) and increased albedo (over 100%) when coated with aluminum powder. Similarly, Chen *et al.* (2025) introduced a heat-reflective pavement coating using bismuth vanadate and iron oxide yellow, reducing surface temperatures by 15.2°C while ensuring durability and low glare. Together, these studies underscore the potential of both vegetation selection and reflective urban materials in enhancing urban thermal comfort and resilience.

Other solutions

Optimizing urban layout through lower building coverage, adjusted floor area ratios, and wind corridors improves ventilation and helps reduce UHI intensity. (Hsieh *et al.*, 2023; Makvandi *et al.*, 2023). (slands (2014) emphasized that community awareness can be enhanced through educational campaigns, while policies like tree planting and reflective surfaces are essential for effective UHI mitigation. Moreover, Kolbe (2019) highlighted that transitioning from conventional vehicles to electric or hydrogen-powered options can significantly reduce UHI intensity and CO_2 emissions, especially when powered by renewable energy. Furthermore, improving public transport, particularly metro systems, offers notable benefits for reducing urban heat and emissions, emphasizing the role of sustainable mobility in UHI mitigation(Maruthu and Shanmugavel, 2023; Luthra, 2023). Promoting employment opportunities in rural areas offers a promising approach to mitigating UHIs. Creating jobs outside urban centres can reduce migration-driven population density, which eases pressure on urban infrastructure and lowers heat generation. The green surroundings in rural areas aid in naturally cooling the environment, while lower energy demands and reduced commuting further limit emissions and heat production. Initiatives such as remote work, rural entrepreneurship, and government incentives support sustainable development and enhance quality of life in these regions. Collectively, these efforts present a balanced and comprehensive strategy for addressing UHI challenges.

<u>Dual perspectives: the contribution of solar panels to urban Heat Island alleviation and potential intensification</u>

The installation of solar panels, particularly photovoltaic (PV) systems, can both mitigate and intensify the UHI effect, with their impact on urban temperatures depending on factors such as placement and urban design. Solar panels have emerged as a promising solution to mitigate the UHI effect, providing both cooling benefits and renewable energy generation. Masson *et al.* (2014) demonstrated that solar panels reduce air conditioning energy consumption by 12% and lower the UHI effect by 0.2 K during the day and 0.3 K at night, highlighting their global benefits in renewable energy generation and climate warming mitigation, as well as local advantages in reducing health risks associated with UHI, especially in summer. Ma *et al.*, (2017) studied the impact of rooftop solar PV systems in cities, showing that in Sydney, Australia, they can reduce summer maximum temperatures by up to 1°C by generating local energy and lessening the need for imported energy. However, studies have shown that PV installations can worsen the UHI effect (Elhabodi *et al.*, 2023; He *et al.*, 2024) in densely populated areas while cooling sparsely vegetated regions, highlighting a complex interaction with urban heat dynamics (Mandavgane *et al.*). Khan and Santamouris (2023) reported that deploying photovoltaic solar panels can increase ambient temperatures by up to 1.4 °C and surface temperatures by 2.3 °C in urban environments. While essential for sustainable energy, the deployment of solar panels in urban areas requires careful management to prevent worsening the UHI effect, emphasizing the need for strategic urban planning.

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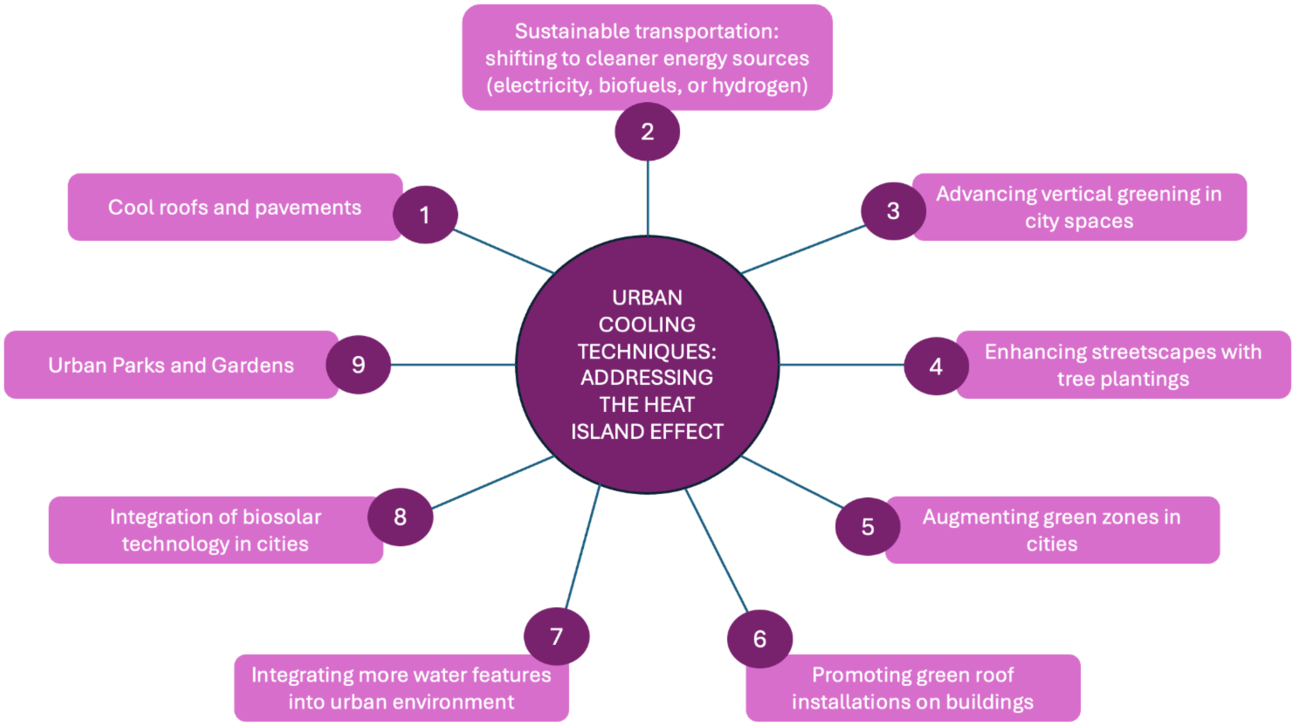

Figure 4. *Urban cooling techniques: addressing the urban heat island effect*

Reimagining urban Heat Island studies: future insights

Future insights into the UHI effect emphasize the complex interplay between urbanization, climate change, and land use dynamics. With continued urban expansion, the UHI effect is projected to intensify, posing significant challenges to urban sustainability and public health. Effective UHI management should prioritize customized urban planning strategies that address the diverse impacts of urban morphology across different functional zones. Further research is necessary to explore the broader implications of the UHI effect on urban climate and precipitation patterns. Additionally, future studies should consider socio-economic factors and climate change scenarios to more accurately predict UHI patterns and associated risks.

Conclusion

The investigation into Urban Heat Island (UHI) dynamics reveals it as a pressing challenge to urban sustainnability, stemming from multiple interlinked factors such as loss of vegetation, use of heat-absorbing construction materials, compact urban forms, and human-induced heat emissions. Intensified by climate change, UHI contributes to rising energy demands, deteriorating air quality, and heightened health vulnerabilities. While both technological and nature-based interventions are vital, green infrastructure including urban forestry, green roofs, and blue spaces-stands out for its multifunctional benefits. Additionally, the complex role of solar panels necessitates careful urban integration to prevent localized heating. Implications of this review suggest a pressing need for interdisciplinary urban planning that aligns climate resilience with equity and sustainability goals. Policymakers should prioritize investment in green infrastructure and adaptive urban design, while researchers must explore context-specific models that incorporate both climatic and social dimensions. By bridging science, policy, and community action, cities can transition toward cooler, healthier, and more inclusive urban environments.

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