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Review

Synergistic control of urban heat island and urban pollution island effects using green infrastructure

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ABSTRACT

Urban heat island (UHI) and urban pollution island (UPI) effects are two major challenges that affect the liveability and sustainability of cities under the circumstance of climate change. However, existing studies mostly addressed them separately. Urban green infrastructure offers nature-based solutions to alleviate urban heat, enhance air quality and promote sustainability. This review paper provides a comprehensive synthesis of the roles of urban green spaces, street trees, street hedges, green roofs and vertical greenery in mitigating UHI and UPI effects. These types of green infrastructure can promote the thermal environment and air quality, but also potentially lead to conflicting impacts. Medium-sized urban green spaces are recommended for heat mitigation because they can provide a balance between cooling efficiency and magnitude. Conversely, street trees pose a complex challenge since they can provide cooling through shading and evapotranspiration while hindering pollutant dispersion due to reduced air ventilation. Integrated research that considers simultaneous UHI and UPI mitigation using green infrastructure, their interaction with building features, and the urban geographical environment is crucial to inform urban planning and maximize the benefits of green infrastructure installations.

1. Introduction

Rapid urbanization is a global trend. Over 50% of the world's population now live in urban areas, which is expected to approach 70% by 2050 (United Nations, 2019). While urbanization contributes to the welfare of human beings in terms of economy, society and environment, it brings major challenges to the sustainability and liveability of urban environments. Among these challenges, urban heat island (UHI) and urban pollution island (UPI) effects are two prominent manifestations of surface warming and air pollution in cities.

UHI refers to the phenomenon where the urban temperature is distinctly higher than that in surrounding non-urban areas (Fig. 1) (Kaloustian and Diab, 2015; Oke, 1982; Zhao et al., 2016). This effect emerges from certain features of densely built urban areas, characterized by more anthropogenic heat emissions, higher absorption rate of solar radiation, lower solar reflectivity, lower heat capacity and reduced turbulent heat transport (Kumar et al., 2024; Oke, 2002). The intensity of UHI can range from 0.4 to 11 °C and tends to be more pronounced at nighttime (Deilami et al., 2018; Santamouris, 2015).

Similarly, UPI is a consequence of concentrated air pollutants emitted from industries, transport and human activities, making urban areas more polluted than rural areas (Fig. 1) (Li et al., 2018). World Health Organization (2022) has identified key pollutants for public health concern, including particulate matter (PM), CO, NO_2, O_3 and SO_2. Other air pollutants, such as polycyclic aromatic hydrocarbons, heavy metals and volatile organic compounds also contribute to the degraded air quality (Swamy et al., 2012; Zavala et al., 2017). For example, the mean number of days with high concentrations of O_3 and $PM_{2.5}$ were 47.54 and 11.21 days, respectively during 2008–2012 in large central metropolitan areas of the US, compared to only 3.81 and 0.95 days in rural areas (Strosnider et al., 2017).

The UHI and UPI effects may pose substantial health risks. UHI can

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increase the potential of heat-related diseases such as thermoplegia (heat stroke), respiratory issues and cardiovascular diseases (Xi et al., 2023). The frequency and severity of these issues are escalating as a result of climate change. To illustrate, over 60,000 deaths were caused by heat-related diseases in Europe during the summer of 2022 (Ballester et al., 2023). Iungman et al. (2023) reported that 6700 premature deaths could be due to UHI effects in 93 European cities during the summer of 2015. Meanwhile, 99% of the world's population resided in areas that failed to meet WHO air quality guidelines in 2019 (WHO, 2022). Approximately 4.2 million premature deaths are caused by outdoor air pollution every year worldwide (WHO, 2022). Even in high-income countries with relatively low $PM_{2.5}$ concentrations, the mortality rate attributed to air pollution is largely underestimated (Weichenthal et al., 2022).

The UHI and UPI effects often appear to coexist, which suggests a complex interrelationship rather than two independent phenomena (Crutzen, 2004; Czarnecka and Nidzgorska-Lencewicz, 2014; Li et al., 2018). For instance, rising temperature may in turn enhance the dispersion of pollutants via promoting turbulent mixing, which may reduce the urban concentration of pollutants such as CO, NO, and C_6H_6 (Battista and de Lieto Vollaro, 2017; Sarrat et al., 2006). Meanwhile, an increased accumulation of aerosols, induced by UPI, can trap more infrared radiation emitted by the earth and reflect longwave radiation back to urban surfaces, which in turn surpasses the ability of aerosols to block solar radiation from reaching the ground (Li et al., 2018). Such an effect can lead to enhanced nocturnal UHI intensity by up to 0.7 °C in 39 cities in China (Cao et al., 2016). Moreover, the increasing heat and air conditioning usage during summer creates a positive feedback loop, intensifying air pollution generated by fossil fuel power stations (Hwang et al., 2020; Roxon et al., 2020).

The impact of green infrastructure, including urban green spaces (UGS), street trees, hedges, green roofs and vertical greenery, on UHI and UPI effects has been widely investigated in isolation (Janhäll, 2015; Pugh et al., 2012; Tomson et al., 2021; Wong et al., 2021). Many cities in different countries have been motivated to promote the development of green infrastructure (Liberalesso et al., 2020). Previous study indicated that expanding UGS area by 20% in Glasgow, UK could reduce surface temperature by up to 2 °C and decrease the expected UHI effect by 33–50% by the year 2050 (Emmanuel and Loconsole, 2015). Moreover, an increase of the abundance of UGS and the proportion of large greenspace patches could significantly reduce PM_{10} concentration in Beijing, China (Lei et al., 2021).

Despite the potential synergies of green infrastructure on mitigating UHI and UPI, most existing studies examined these two effects separately. Only a few studies investigated the impact of specific types of green infrastructure on both UHI and UPI effects. For example, Yang et al. (2023) studied how trees could mitigate heat and air pollution in urban neighbourhoods. (Li et al., 2023b) examined how different tree planting strategies could affect the thermal comfort and air quality in a street canyon in Hong Kong. So far, no comprehensive review has been conducted to evaluate the impact of different types of green infrastructure on the synergies between UHI and UPI effects and their mitigation potential. Therefore, this review is conducted to fill this gap, aiming to provide insights for policymakers to plan and manage urban development, ensuring the well-being of city inhabitants and greater sustainability.

The remaining of this paper is organised as follows. First, section 2 compares the key influencing mechanisms of green infrastructure on UHI and UPI effects. Subsequently, sections 3 and 4 categorize different types of green infrastructure to identify their potentials for mitigating UHI and UPI effects. Next, section 5 discusses the synergies and conflicts of urban green infrastructure in terms of mitigating both UHI and UPI effects. Finally, this review proposes suggestions for urban planning strategies and future research directions.

2. Influencing mechanisms of green infrastructure on UHI and UPI

2.1. Influencing mechanisms of green infrastructure on UHI

2.1.1. Shading

Green infrastructure influences the urban thermal environment mainly through four mechanisms, i.e., providing shading, facilitating evapotranspiration, altering surface albedo and facilitating multisensory interaction (Gunawardena et al., 2017; Lenzholzer and de Vries, 2020). Providing shading from intercepting solar radiation by canopies is one of the most important and direct cooling measures of green infrastructure. Shading can significantly lower the surface temperature of shaded areas by reducing heat storage and convection (Yu et al., 2020a). For example, in summer, tree shade can reduce the maximum road surface temperature by 19 °C in Bolzano, Italy (Speak et al., 2020). Moreover, shading affects human thermal comfort by altering the perceived temperature, which is often calculated using the physiological equivalent temperature. This calculation incorporates mean radiant temperature determined through the RayMan model (Li et al., 2023b). An individual in a shade experiences a cooler perceived temperature, which depends more on the radiation exchange between the human and the surrounding environment rather than convection (Matzarakis et al., 2007).

2.1.2. Evapotranspiration

Evapotranspiration by green infrastructure is considered the second most important process for mitigating the UHI effect (Winbourne et al.,

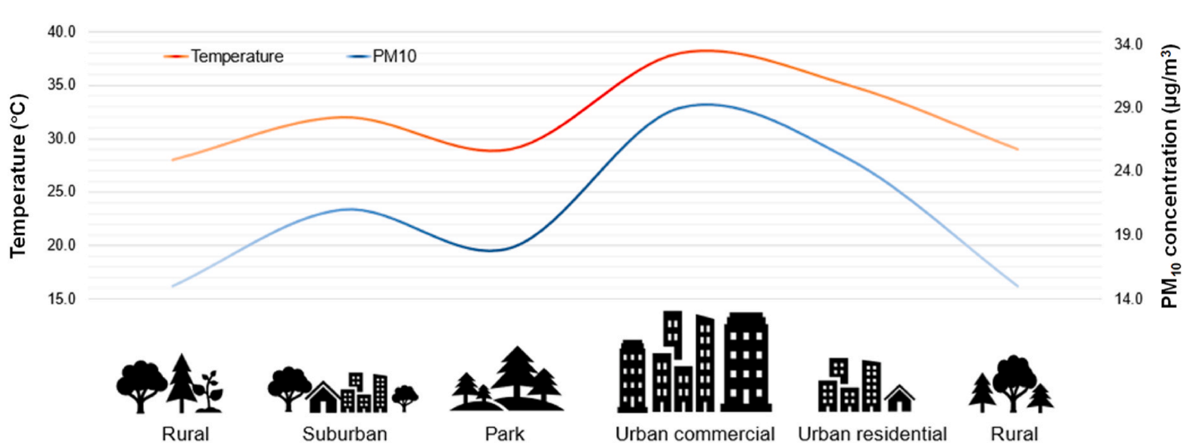

Fig. 1. A schematic of UHI and UPI effects in a city with humid continental climate. The typical heat and pollution distribution profiles show higher temperature and air pollution in built-up areas than in areas with more green cover. Generation of graph was based on data from Li et al. (2020, 2018). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

2020). Evapotranspiration is essentially the evaporation of water from vegetation leaves, thus converting sensible heat to latent heat and reducing the Bowen ratio (the ratio of sensible heat flux to latent heat flux) to lower the temperature of the surrounding environment (Gunawardena et al., 2017). Evapotranspiration cooling of a tree could reduce air temperature by up to 3 °C in Wurzburg, Germany (Rahman et al., 2020a). In certain oasis conditions, the Bowen ratio can be negative since latent heat flux can be greater than sensible heat flux, which makes air from drier surroundings transfer sensible heat to the moist greenspace (Taha, 1997).

2.1.3. Albedo modification

Artificial materials with lower albedo contribute to higher air temperatures in urban areas (Rizwan et al., 2008). Albedo refers to the ratio of reflected radiation over total incident radiation on a surface. Compared with built-up areas, green infrastructure tends to have higher albedo. For instance, the albedo of plants reaches up to 0.3, while the albedo of built-up surfaces typically ranges from 0.1 to 0.2 (Tan et al., 2015). Green infrastructure with a higher albedo leads to greater reflection of solar radiation, thus decreasing the radiation absorption and surface heating. However, since the range of albedo values of green infrastructure is not much higher than that of artificial surfaces, the cooling effect from increased albedo of green infrastructure is less impactful compared to shading and evapotranspiration (Sieber et al., 2022).

2.1.4. Multisensory interaction and thermal perception

Urban green infrastructure can also influence the thermal perception of individuals by psychological factors, which extend beyond the measurable physical modification it brings to the environment. This subjective thermal perception is based on our interpretation of sensory information from the real world, which is dependent but more complicated than unconscious body thermal sensation (Knez et al., 2009). For example, pedestrians in Rome, Italy reported cooler thermal perceptions in areas with higher green exposure, even when the objective universal thermal climate index was consistent across different locations (Peng et al., 2022). Moreover, noise pollution can alter subjects' physiological and psychological conditions, influencing their overall thermal comfort (Guan et al., 2020; Jin et al., 2020). Green infrastructure plays a strategic role in mitigating this discomfort by acting as a buffer against noise, thereby reducing the thermal stress of pedestrians (Chen et al., 2020; Nitidara et al., 2022).

2.1.5. Temporal variability

The cooling effect of green infrastructure varies diurnally and seasonally. Studies note that the highest heat reduction occurs during the day, mainly due to shading and evapotranspiration of vegetation (Hamada and Ohta, 2010; Jamei et al., 2016). Nighttime cooling is mainly attributed to the horizontal movement of air from vegetation evapotranspiration (Chang and Li, 2014). The peak of temperature reduction is usually in summer and in the transition seasons due to a larger temperature gradient between vegetation and the atmosphere (Gunawardena et al., 2017; Hamada and Ohta, 2010). During colder periods, the cooling effect of green infrastructure diminishes due to deciduous species providing less shading (Hamada and Ohta, 2010). However, this can be beneficial in temperate regions, as evidenced by simulations of tree effects on urban microclimate in Melbourne, Australia and Zurich, Switzerland (Meili et al., 2021; Yang and Bou-Zeid, 2018).

2.1.6. Research methods for assessing temperature reduction

The complexity of urban green infrastructure as a research subject, along with variations in the measurement indices for scale and cooling effects across studies, has resulted in a diversity of research methods for UHI. Further, the field has yet to mature to the extend in which there is a consensus for standardized testing. Common approaches include field observations, remote sensing, and model simulations to capture data on temperature, humidity, wind speed, radiation, and other relevant factors. When assessing cooling effects, a range of indices is used, including canopy air temperature, surface temperature, mean radiant temperature, and physiological equivalent temperature.

2.2. Influencing mechanisms of green infrastructure on UPI

2.2.1. Dispersion

Green infrastructure affects urban air pollution mainly through three mechanisms: dispersion, deposition and absorption (Abhijith et al., 2017). The combined effect of these mechanisms on air quality is complex. In general, green infrastructure is beneficial for air quality improvement and has been demonstrated to improve air quality by facilitating the different processes in numerous cases. However, there are also instances where it may not be as effective or even present challenges. Therefore, the overall efficacy of green infrastructure as a solution to air pollution is not entirely resolved, and further research on this is needed (Eisenman et al., 2019).

Dispersion involves the processes of physical transportation and dilution of pollutants. Studies have demonstrated the potential of green infrastructure, such as hedges, to improve the near-road pedestrian environment by presenting a semi-permeable barrier between roads and sidewalks in street canyons (Abhijith et al., 2017). Such green barriers can also be a passive pollution control method with proper design by blocking or deflecting pollutants and influencing local turbulence to alter the dispersion patterns (Gallagher et al., 2015; Gromke et al., 2016). However, green infrastructure in street environments can also negatively impact pollutant dispersion by reducing wind velocity, which substantially hinders the air exchange rate and decreases the efficacy of pollutant dispersion at ground level (Buccolieri et al., 2022; Kumar et al., 2019a).

2.2.2. Deposition

Compared to artificial materials that generally have smooth surfaces, green infrastructure has a larger surface area per unit volume to deposit more pollutants (Janhäll, 2015). For instance, simulations indicated that the green infrastructure's ability to deposit pollutants may overcome dispersion effects at the city level (Tiwari and Kumar, 2020). Equipped by surface deposition and aerodynamic dispersion, green infrastructure can remove up to 35% of NO_x and 21% of PM_{10} (Tiwari and Kumar, 2020). The deposition rate largely depends on the particle size (Fowler et al., 2009). Deposition of particles below 0.1 μm is controlled by diffusion; those between 1 and 10 μm are deposited due to impaction; and particles larger than 10 μm are deposited by sedimentation (Hinds and Zhu, 2022). Such deposition on green infrastructure can be simplified to a one-dimensional vertical process on a homogeneous layer (Janhäll, 2015). Deposition velocity (v_d) is defined as the inverse of total deposition resistance (R_{tot}), which is governed by:

$$v_d = \frac{1}{R_{tot}} = \frac{1}{R_a} + \frac{1}{R_b} + \frac{1}{R_c} \quad (1)$$

where R_a, R_b and R_c represent the aerodynamic, boundary and surface resistances, respectively (Davidson and Wu, 1990).

2.2.3. Absorption

Absorption by vegetation, particularly for gaseous pollutants, occurs through leaves and is driven by the metabolic process of plants (Barwise and Kumar, 2020). They can absorb gases without becoming saturated (Omasa et al., 2002). Some fine particles smaller than 2 μm can enter the stomatal cavity to be absorbed as well (Song et al., 2015). However, these absorption processes may harm the leaf tissues and affect stomata openness, reducing the capacity for pollutant removal (Bharti et al., 2018; Song et al., 2015). Therefore, the air pollution tolerance index is frequently used to evaluate the pollution tolerance of vegetation, which measures parameters potentially affected by air pollution, such as total chlorophyll content and pH of leaf extract (Molnár et al., 2020). In addition, aromatic hydrocarbons, such as benzene and toluene, can be absorbed by the epicuticular waxy layers of plants, contributing to further air pollution reduction (Holoubek et al., 2000; Treesubsuntorn et al., 2013).

2.2.4. bVOCs emissions

However, it should be noted that green infrastructure could be an additional pollution source because vegetation may emit pollens and biogenic volatile organic compounds (bVOCs) that have potential adverse health impacts (Gilles et al., 2009). It was indicated that urban areas might have 20% higher risks of allergies compared to rural areas due to the uniformity of allergen-inducing plant species and the interaction between pollen and other pollutants (Cuinica et al., 2015; D'Amato et al., 2007; Reinmuth-Selzle et al., 2017). bVOCs from vegetation, such as isoprene and monoterpenes, are significant sources of reactive hydrocarbon gases (Churkina et al., 2017). Importantly, O_3 - one of the key air pollutants in urban areas - can be formed by the photochemical-driven reaction between bVOCs and NO_x (Calfapietra et al., 2013). The oxidization process also generates secondary aerosols, contributing to higher PM concentrations (Wu et al., 2020).

2.2.5. Temporal variability

Seasonal factors can affect the performance of green infrastructure in mitigating UPI, particularly in mid-to high-latitude regions. Higher level of PM accumulation are typically recorded during winter due to weather conditions such as low wind regime, shallow thermal inversion, and increased biomass burning from household heating (Chen et al., 2020; Goodsite et al., 2021). The seasonal defoliation of deciduous trees in winter reduces their ability to deposit or absorb air pollutants, offering less contribution to reducing air pollution. In contrast, evergreen trees retain their leaves throughout the year, providing a continuous biological mechanism for pollutant capture in temperate regions (Moura et al., 2024).

2.2.6. Research methods for assessing air pollution reduction

The research methods for investigating the impact of green infrastructure on UPI effect can be divided into two main directions: measuring the impact of individual plants on air pollution and evaluating the collective impact of multiple plants or larger UGS on air quality. The first approach focuses on how specific plant species or particular plant parts (like leaves) absorb, deposit, and tolerate gaseous and particulate pollutants. This includes methods such as leaf sampling, chamber experiments, and phytoremediation studies. The second direction involves larger-scale methods such as air dispersion modelling, field measurements near UGS, and remote sensing. These methods analyze how UGS, green roofs, or clusters of street trees collectively reduce pollutant concentrations like NO_x, SO_2, or PM in urban environments. Hybrid methods also exist in which some studies have combined field measurements and model simulations to provide a more comprehensive analysis, allowing for generalization across larger areas.

3. UHI mitigation by green infrastructure

3.1. Urban green spaces

In general, these UGS show the potential of heat reductions, as indicated by remote sensing studies (Das et al., 2022; Tian et al., 2023), field observations (Skoulika et al., 2014; Yan et al., 2018), and numerical simulations (Arghavani et al., 2020; Lin and Lin, 2016; Sun et al., 2017).

The cooling effect varies among UGS. First, the canopy cover is often positively correlated to the cooling intensity of UGS, which can be attributed to shading, evapotranspiration and increased surface roughness by tree clusters (Feyisa et al., 2014; Kuang et al., 2015; Monteiro et al., 2016; Oke, 1989). However, UGS with high leaf area density, such as urban forest, may reduce the cooling effect during the night since higher canopy cover restricts radiation loss and provides a more stable understory thermal environment (Arghavani et al., 2020; Spronken--Smith and Oke, 1999; Wu et al., 2022). Moreover, in areas with a humid climate, UGS can contribute to thermal discomfort, which is attributed to excessive humidity - a consequence of evapotranspiration - and diminished wind speeds by canopy cover (Chow et al., 2016).

The landscape metrics of UGS also have strong influences on the cooling capacity (Aram et al., 2019; Jamei et al., 2016; Yang et al., 2024). Yu et al. (2017) suggested that regularly shaped UGS tend to demonstrate higher cooling efficiency, while those with complex shapes may interact with other land cover types, experiencing more thermal exchange and reducing their cooling capacity. However, Park et al. (2017) reported that a small polygonal UGS has a large cooling potential in Seoul, South Korea. Fig. 2 summarizes the reduction of land surface temperature by UGS during warmer seasons. As shown in Fig. 2a, the reduction of average land surface temperature by small to medium UGS (≤16 ha) was 2.41 ± 1.10 °C, with a median reduction of 2.42 °C. Large UGS showed an average land surface temperature reduction of 3.75 ± 1.68 °C, with a median reduction of 3.40 °C. Notably, two large UGS recorded temperature reductions over 8.5 °C. Therefore, UGS with larger areas have more significant cooling potential. However, as indicated by Jamei et al. (2016), excessively increasing the size of UGS might not be a feasible option for most cities. The cooling magnitude of UGS does not linearly increase with the size, and there is a threshold value beyond which heat removal potential becomes less significant, indicating the phenomenon of diminishing marginal utility (Lin et al., 2015; Yu et al., 2017, Yu et al., 2020b). Fig. 2b shows that the cooling efficiency (land surface temperature reduction per unit area) decreases nonlinearly in the form of a power law function with increasing size of UGS ($R^2 = 0.60$). Combining these observations in Fig. 2, a small to medium-sized UGS is preferred to balance cost and effectiveness for optimal cooling (Xu and Zhao, 2023).

To explore the optimized morphology of UGS, morphological spatial pattern analysis (MSPA) was developed which can improve the characterization of land use patterns in a spatially explicit approach, compared with traditional landscape metrics. This approach uses mathematical morphological operators to classify green spaces as seven mutually exclusive morphological categories revealing information about their size, shape, and connectivity degree to better reveal the impact of the morphological pattern of UGS on UHI intensity. Studies employing this method have found that low-density "islet" urban areas exhibit less significant surface UHI compared to areas with multiple compact urban cores, and vice versa, with larger, contiguous UGS core areas demonstrating better cooling effects than fragmented smaller islets in Shenzhen, China (Lin et al., 2023, 2024). Moreover, Shen et al. (2024) proposed that adopting stereoscopic urban morphology indices to represent the 3D structure of urban areas showed higher accuracy in predicting UHI. They demonstrated vegetation height as one of the stereoscopic urban morphology indices to represent the structures of urban areas more comprehensively. They found that large UGS with higher height variations and pocket UGS with lower height variations tend to offer better cooling effects.

UGS reduces urban heat not only in its domain but also in the built-up areas around them due to air movement and heat exchange (Cohen et al., 2012; Oke, 1989). Similar to the cooling inside UGS, this extended cooling effect, diminishing with distance, is more pronounced in larger UGS (Hamada and Ohta, 2010; Lin et al., 2015). The range of cooling extent varies. For example, UGS could provide cooling effects over 400 m away in Bengaluru, India (Shah et al., 2021). While the maximum cooling distance was 240 m in Addis Ababa, Ethiopia (Feyisa et al., 2014).

Moreover, recent studies have revealed mixed findings on whether water bodies can interact with UGS to enhance cooling or not. Some studies suggested a synergistic cooling effect (Du et al., 2017; Sahani

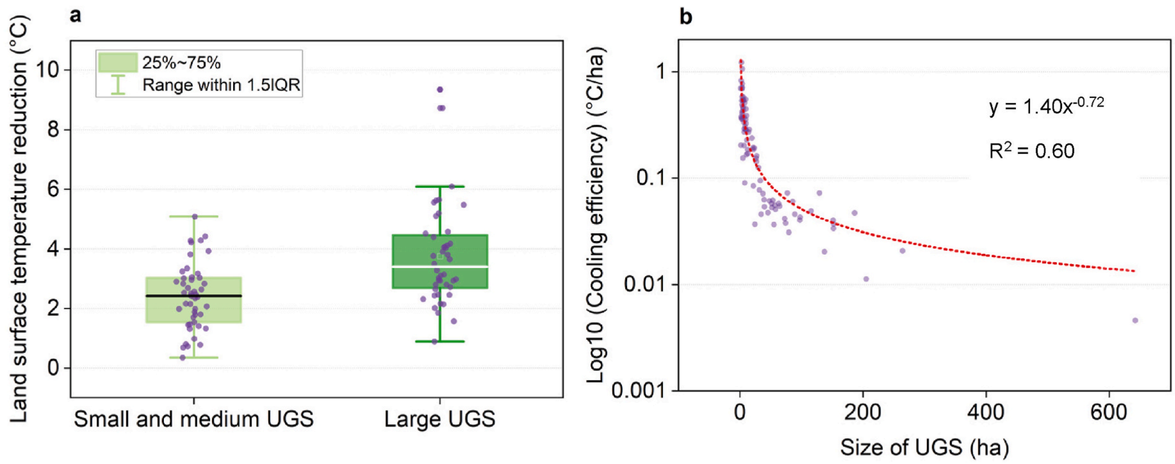

Fig. 2. Reduction of land surface temperature by UGS during warmer seasons: (a) Comparison of land surface temperature reductions between small-medium (≤16 ha) and large (>16 ha) scale UGS, and (b) Power-law fit relationship between size of UGS and cooling efficiency. Data were retrieved from remote sensing studies that investigated the cooling effect from July to September in the cities (Du et al., 2017; Lin et al., 2015; Xu and Zhao, 2023; Yu et al., 2017).

et al., 2023; Tan et al., 2021; Zhou et al., 2023). For example, Zhou et al. (2023) concluded that UGS with water bodies in Suzhou, China reduced temperatures more effectively than similar-sized spaces without water, and riverside UGS can be cooler than non-riverside ones by up to 4.2 °C in summer. However, other studies observed an opposite phenomenon, especially the negative impact of water bodies on nighttime UHI (Hu and Li, 2020; Yao et al., 2023). For example, water bodies may enhance the UHI and surrounding atmospheric humidity, increasing thermal discomfort by 4.2 °C in urban core areas in Madison, US (Hu and Li, 2020).

3.2. Street greenery

Street greenery includes trees and hedges. Street trees can significantly contribute to a better urban thermal environment, which are considered one of the most effective strategies for improving the thermal comfort of pedestrians on streets, even more effective than strategies like altering pavement surface albedo (Mohammad et al., 2021). Urban trees can reduce air temperature by an average of 0.8–2.6 °C across various climates, from arid to temperate, according to a meta-analysis by de Quadros and Mizgier (2023).

Tree shading is the key to bringing cooling effects at the urban street level. This effect depends on factors such as total canopy density, determined by the total number of trees and spacing between individuals (Aminipouri et al., 2019; Rahman et al., 2020a; Wang and Akbari, 2016; Ziter et al., 2019). For example, a simulation showed that increasing tree height from 10 to 20 m and canopy size from 9 to 12 m, along with decreasing planting density, could enhance the average air temperature reduction from 1.2 to 3.3 °C in Montreal, Canada (Wang and Akbari, 2016).

From the perspective of individual trees, traits such as leaf area, tree height, crown structure, shapes and leaf colour play significant roles (Lin and Lin, 2010; McPherson et al., 2018; Speak et al., 2020). For example, collectively better solar blocking offered by *C. pluviosa* in Brazil can reduce the air temperature by 7.8–14.4 °C during summertime due to their higher canopy coverage, plagiotropic trunks and small bipinnate leaves (de Abreu-Harbich et al., 2015). In contrast, instead of offering a cooling effect, species such as *C. macrocarpa* - a coniferous evergreen tree - may not provide enough shading but weaken street ventilation, increasing urban heat due to its small, cone-shaped crown and acicular-shaped leaves, as indicated in a scaled outdoor experiment (Chen et al., 2021).

Some studies have shown the potential enhancement of the UHI effect by trees during nighttime, as tree canopies may block heat dissipation (Wang et al., 2021). For example, trees could lead to a 0.2 °C rise in air temperature at night, coinciding with peak UHI in Cairo, Egypt (Aboelata and Sodoudi, 2019). A field experiment in Davis, US showed an increased nocturnal temperature of up to 2 °C within the tree (Taha et al., 1991). Further, sunlight is often desirable in mid to high latitude cities, especially during colder seasons, thus deciduous trees which allow more sunlight through might be more suited to these areas than evergreen trees (Aminipouri et al., 2019; Konarska et al., 2014).

Moreover, trees cool the ambient temperature through evapotranspiration processes, a factor that may have a more pronounced impact on UHI than commonly thought (Pace et al., 2021; Tams et al., 2023). Liu et al. (2017) suggested that simulations of latent heat flux can deviate from true values even at sites with a small proportion of tree coverage. Studies have shown that evapotranspiration can reduce air temperature by 1–8 °C under or within the canopy, influenced by traits such as leaf thickness, leaf colour and wood anatomy (Moss et al., 2019; Rahman et al., 2015, 2020b). However, such evaporative cooling effect is constrained by factors such as water stress, which can make some species more vulnerable during extreme heat waves (Haase and Hellwig, 2022).

A few studies have explored the cooling effects of street hedges. For instance, Zhang (2020) compared the cooling effects of five common roadside shrubs in Guangzhou, China, and found that *Murraya exotica* L. exhibited the best cooling effect. However, their influence on air temperature at pedestrian level or thermal comfort was not quantified. Li et al. (2021) reported that while shrubs did not alter air temperature at pedestrian level in Singapore, they raised the physiological equivalent temperature by increasing relative humidity, particularly at noon.

3.3. Green roofs and vertical greenery

Green roofs and vertical greenery systems have attracted increasing attention in urban environmental studies, particularly for their potential in mitigating the UHI effect (Besir and Cuce, 2018; Cascone et al., 2019). Approximately 20% of the total urban surface is comprised of roofs, indicating a substantial opportunity for urban greening (Akbari and Matthews, 2012). The combined implementation of green roofs and vertical greenery may lead to long-term UHI mitigation since they act as a building envelope to reduce building heat loads (Guo et al., 2024; Mihalakakou et al., 2023; Zhu et al., 2023). While the albedo enhancement from such urban greenery may not be as pronounced as that from cool roofs or walls (light-coloured building surfaces with typically albedo values around 0.8), they offer a sustainable alternative with lower embedded CO_2 emissions during construction, operation and maintenance (Susca et al., 2011).

Fleck et al. (2022) reported that green roofs can reduce rooftop surface temperature by up to 20 °C when ambient temperature exceed 40 °C, and can improve heat flow by up to 55.54%. In addition, Karteris et al. (2016) found that green roofs can reduce electricity consumption for cooling by up to 16% in Thessaloniki, Greece. Vertical greenery can also lower the maximum air and surface temperatures by around 3 and 16 °C on average, respectively (Wong et al., 2021). Similarly, Susca et al. (2022) reported that vertical greenery can reduce UHI by up to around 5 °C via a systematic review of different climate zones worldwide. The cooling capacities of green roofs and vertical greenery are influenced by plant traits such as foliage density, leaf size, leaf colour, and evapotranspiration rate (Besir and Cuce, 2018).

The planting features also significantly impact their cooling performance. In terms of green roofs, they can be classified into three types based on substrate depth: 1) intensive green roofs with deep substrates ranging from 150 to 400 mm can support large plants like flowerbeds (Fig. 3a); 2) semi-intensive green roofs with medium soil depth around 120–250 mm; 3) extensive green roofs with shallower soil depth, usually 60–200 mm, are suitable for smaller vegetation such as herbs and grasses (Mihalakakou et al., 2023; Vijayaraghavan, 2016). Intensive green roofs tend to offer more significant cooling effects due to their complex plant structure. For example, simulation results showed that green roofs with trees improve thermal comfort at both the outdoor pedestrian level and indoor environment, achieving up to 7.2 °C in Brisbane, Australia (Abuseif et al., 2021). This value is higher than the reduction achieved by green roofs without trees but with higher green cover rates. However, such enhancement comes at the costs of higher construction, maintenance and irrigation requirements (Besir and Cuce, 2018). Moreover, the volumetric water content, size of the soil particles, compaction of the material, and permeability of the substrate can significantly impact the cooling performance of green roofs since they determine their ability of evapotranspiration (Cascone et al., 2019).

Vertical greenery can be classified into green façades and living walls (Fig. 3b) (Irga et al., 2023). For direct green façades, shading by dense vegetation coverage could be the most critical feature in reducing wall and surrounding air temperatures (Yin et al., 2017). Studies suggested that living walls with pockets for vegetation and substrate or pre-planted modular fixtures could provide better insulation for buildings due to their modular structure and the increased leaf density provided by the substrate (Wong et al., 2009, 2010). Generally, modular systems incorporating a well-designed mixture of plants can optimize cooling effects by offering better evapotranspiration rate, shading, and higher thermal insulation (Besir and Cuce, 2018; Wong et al., 2010). However, this design also poses maintenance challenges. For instance, the One Central Park in Sydney, Australia - an apartment building that won the Best Tall Buildings Award by the Council on Tall Buildings and Urban Habitat in 2014 and is known for its vertical greenery on glass external walls - has been required to remove its loose planter boxes and flammable cladding (Segaert, 2023). Due to the nature of its difficulty in intervening after the installation, it is necessary to design the structural system of the building that accounts for not only the cooling performance but also the additional weight, life cycle, environmental impact, and economic efficiency.

The effectiveness of the green infrastructure is also dependent on the surrounding urban environment. Vertical greenery, often positioned closer to sidewalks, tends to provide better thermal benefits in urban canyons than green roofs because they are usually on roadsides and have more direct interactions with streets (Nasrollahi et al., 2020). However, such placement also subjects vertical greenery to factors such as overshadowing from nearby buildings and their orientation, which may impact their performance (Morakinyo et al., 2019; Yin et al., 2017). Moreover, vertical greenery tends to show better cooling performance in narrow streets surrounded by high-rise buildings (Susca et al., 2022).

4. UPI mitigation by green infrastructure

4.1. Urban green spaces

UGS serves as a natural filter for air pollutants (Chen et al., 2022). A meta-analysis by Gong et al. (2023) concluded that all types of UGS tend to alleviate PM, NO_x and SO_2 concentrations. Similar to their role in mitigating the UHI effect, UGS also show potential in reducing pollution levels in their extended surroundings (Irga et al., 2015; Lei et al., 2021; McDonald et al., 2007; O'Regan et al., 2022). For example, McDonald et al. (2007) observed that UGS could limit the diffusion of PM within a 100–500 m buffer zone in the West Midlands conurbation, UK. Similarly, in-situ experiments in Sydney, Australia indicated lower concentrations of total suspended PM, $PM_{2.5}$ and PM_{10} near UGS, with the consideration of traffic conditions (Irga et al., 2015).

The effectiveness of UGS in pollution reduction is influenced by several attributes. Studies have confirmed a positive correlation between the size of UGS and the reduction of $PM_{2.5}$ and PM_{10}

Fig. 3. The UTS Central building with intensive green roofs (a) and the One Central Park apartment building with living green walls (b) in Sydney, Australia. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

concentrations, highlighting a scale effect (Lei et al., 2021; Wu et al., 2015; Zhan et al., 2022). This may be because large UGS usually have clusters of trees with larger canopies that can alter wind profiles or create local inversions, thereby reducing air exchange to trap pollutants (Cavanagh et al., 2009). In addition, the morphology of the UGS, including agglomeration and irregularity, can impact the PM concentration. Generally, UGS with a higher degree of aggregation and complexity are more effective in blocking and retaining pollution due to their more pronounced edge effects (Bi et al., 2022; Chen et al., 2019a; Wu et al., 2015). For example, Bi et al. (2022) found that over 60% of the change in $PM_{2.5}$ concentration in UGS in Wuhan, China could be explained by their morphology, with the point–line–polygon morphology owning the best performance for pollutant removal. In contrast, smaller and more fragmented green patches have lower ability to mitigate air pollution (Bagheri et al., 2017; Chen et al., 2019a).

However, it is important to note the potential contribution of UGS to O_3 concentration. UGS may generate a considerable amount of bVOCs, inducing more O_3 in the urban environment due to the photochemical reaction (Calfapietra et al., 2013; Cohen et al., 2014; Vieno et al., 2010). For example, the primary cause of a 5.7 μg/m^3 increase in O_3 concentration in Beijing, China was bVOCs emitted from UGS in core urban areas, predominantly from tree species with high emission potentials, such as *Populus, Sophora and Salix* (Ren et al., 2017). Su et al. (2011) conducted land use regression modelling and field experiments in Los Angeles, US and found that parks had higher O_3 concentrations than surrounding urban areas. Some studies suggested that UGS could help lower O_3 concentrations (Nowak et al., 2014; Sicard et al., 2018; Yli-Pelkonen et al., 2017). Sicard et al. (2018) calculated the average removal rate of O_3 concentration by UGS and found it higher than that of green roofs. However, studies with similar conclusions only consider the stomatal and non-stomatal deposition, with no consideration of bVOC emissions from UGS (Nowak et al., 2014, 2018). In general, studies using various methods presented in Table 1, indicate that current UGS tend to contribute to increased O_3 pollution.

4.2. Street greenery

Street trees and hedges are two main types of greenery that can influence the UPI effect at the ground level. The majority of studies employing numerical simulations (Gromke and Blocken, 2015; Guo et al., 2023; Vranckx et al., 2015; Xue and Li, 2017), wind tunnel experiments (Buccolieri et al., 2009; Fellini et al., 2022; Gromke and Ruck, 2007, 2009, 2012) and field observations (Jin et al., 2014; Miao et al., 2021; Salmond et al., 2013) have reported adverse effects of street trees on air pollution.

Such a negative contribution of street trees is due to three key reasons. First, canopies, especially of larger and taller trees, may cover the top of streets and obstruct both the escape of pollutants and the entrance of clean air vertically (Salmond et al., 2013). Second, tree crowns may block corner eddies at the end of the streets which are essential for ventilation, resulting in elevated pollutant concentrations (Gromke and Ruck, 2007; Hang et al., 2023). Third, tree planting narrows the effective cross-section of street canyons, inhibiting canyon vortices and altering air exchange conditions (Li et al., 2023b). This is similar to the dynamics in catchment hydraulics, where vegetation can also increase roughness, lower flow velocity and increase sediment deposition (Luhar and Nepf, 2013; Nepf, 2012).

To further illustrate with examples, Hang et al. (2023) performed an atmospheric photolysis calculation and found that the diminished wind velocity caused by street trees could result in 95% and 66% increases in NO and NO_2 concentrations at ground level, respectively. Fellini et al. (2022) found in wind tunnel experiments that trees increased pollution levels at the upwind wall of street canyons. Salmond et al. (2013) undertook a field experiment in Auckland, New Zealand, and discovered that tree canopy decreased both vertical and horizontal transport of NO and NO_2 while reducing the penetration of clean air. A similar phenomenon was also observed by Jin et al. (2014), who reported that tree canopies limited the dispersion of $PM_{2.5}$ and decreased wind velocity in Shanghai, China, which was mainly determined by canopy density and leaf area index.

The extent of the influence that trees have on intensifying pollution is further affected by factors such as vegetation characteristics, aspect ratio (building height/street width) and spacing between trees. Notably, the aspect ratio greater than 0.5 is typically disadvantageous (Kumar et al., 2019). In deep street canyons, this can lead to two counter-rotating vortices; the vortex at lower position has lower velocity and results in higher pollution concentration (He et al., 2017). Moradpour et al. (2017) found that the presence of trees worsened such situation in terms of NO_x concentrations in a deep canyon. Small, lighter crowned species might be appliable on the windward side in shallow or wide street canyons (aspect ratio $\leq$0.5) (Kumar et al., 2019b).

On the other hand, hedges, typically with a lower height and located at the ground level, are recognized for their potential to improve the air quality in street canyons, acting as natural barriers that divert pollutants

Table 1
Summary of studies focusing on the impact of UGS on O_3 concentration.

Location	Research method	Remarks	Impact on O_3 concentration	References
Taiwan	Remote sensing; weather station measurement	Impact of UGS is minimal, while humidity and temperature are more influential.	Neutral	Nguyen and Liou (2024)
Shenzhen, China	Single leaf experiment; Remote sensing	89% of bVOCs were from less build-up urban areas. Significant positive correlation between bVOCs and O_3.	Increase	Cui et al. (2024)
Beijing, China	Remote sensing	UGS account for 39% of bVOCs Potential 37% underestimation by common datasets.	Increase	Li et al. (2022)
China	Spatial modelling	UGS-emitted bVOCs contribute to 13% of summer O_3 levels. Heat waves can increase such emissions by up to 92%.	Increase	Ma et al. (2022)
Fujian, China	Regression analysis	UGS fails to reduce O_3 because they serve as the sinks to promote O_3 formation.	Increase	Cai et al. (2022)
Canada	Deposition model	Urban forests removed 12,370 tons of O_3 in 86 cities in Canada in 2010.	Decrease	Nowak et al. (2018)
35 countries	Deposition model	Urban forests perform better at O_3 removal than green roofs.	Decrease	Sicard et al. (2018)
Beijing, China	Field experiment; Spatial modelling	UGS-emitted bVOCs led to a 5.7 μg m^{-3} increase in annual O_3 in 2015.	Increase	Ren et al. (2017)
Baltimore, US	Field experiment	O_3 was lower in tree-covered areas than open habitats.	Decrease	Yli-Pelkonen et al. (2017)
US	Deposition model	Trees and forests could remove 14.33 million tons of O_3 annually.	Decrease	Nowak et al. (2014)
Tel-Aviv, Israel	Field experiment	Urban parks increased O_3 levels.	Increase	Cohen et al. (2014)
Los Angeles, US	Land use regression modelling	Public parks have higher O_3 concentration than adjacent areas.	Increase	Su et al. (2011)

away from pedestrian pathways (Chen et al., 2015; Gromke et al., 2016; Li et al., 2016; Santiago et al., 2019). Unlike street trees, hedges do not reduce wind speed significantly but create local vortices that redirect traffic pollutants (Wania et al., 2012). For example, Kumar et al. (2022) observed that the maximum reduction of PM_1, PM_{10} and black carbon concentrations occurred at breathing height (1.5 m) behind hedges in west London, UK.

The effectiveness of hedges in pollutant removal is largely influenced by their design features, including configuration, permeability and height. Gromke et al. (2016) noted that continuous hedge rows have better efficiency in pollution reduction, while gaps in hedges may even result in increased pollutant concentration. Chen et al. (2015) conducted roadside measurement in Wuhan, China, and found that PM_{10} removal rate of greenbelt is negatively correlated to porosity. To prevent the downwind increase in pollutant concentrations, hedges should possess a leaf area density above a critical threshold (Barwise and Kumar, 2020). Selecting evergreen species with denser hairs, deep groove and wrinkled leaves can further enhance the deposition effect and improve air quality for pedestrians (Blanuša et al., 2020; Chen et al., 2015; Sæbø et al., 2012). As for the optimal height of hedges, Li et al. (2016) identified 1.1 m as the ideal height for street canyons with aspect ratios between 0.3 and 1.67, while 0.9–2.5 m are optimal for canyons with lower aspect ratios. Kumar et al. (2019) suggested that, for street canyons with aspect ratios greater than 0.5, hedges should have a minimum thickness of 1.5 m and a minimum height of 2 m and be placed continuously near the road for maximum efficacy.

Some studies suggested that trees may promote air quality in the urban streets (Baek et al., 2024; Miao et al., 2021; Vos et al., 2013). For example, Baek et al. (2024) found that trees could reduce PM_{10} concentration in CFD simulations, with minor improvements when hedges were added to the scenario. This result can be explained by the deposition of pollutants by green infrastructure, which can outweigh the negative aerodynamic effects that reduce air ventilation. However, current research generally indicates that street trees are more likely to degrade air quality in street canyons. Meanwhile, hedges may improve it, but their configuration needs to be carefully designed and requires site-specific testing.

4.3. Green roofs and vertical greenery

Both green roofs and vertical greenery show potential for pollutant removal. Viecco et al. (2021) suggested that the combined use of green roofs and vertical greenery can remove up to 7.3% of $PM_{2.5}$ in an urban neighbourhood of Santiago, Chile by ENVI-met simulations. In terms of green roofs, Speak et al. (2012) estimated that green roofs with species *F. rubra* could remove PM_{10} by up to 3.21 g/m^2 per year under the maximum green roof scenario. Similarly, Irga et al. (2022) estimated that the green roof studied in Sydney, Australia could remove 0.5 kg of $PM_{2.5}$, 6.9 kg of O_3 and 2.3 kg of NO_2 annually. Pugh et al. (2012) also reported that vertical greenery could reduce the concentrations of PM_{10} and NO_2 by up to 50% and 35%, respectively. Green roofs can also influence the microclimate by introducing cooler air into street canyons, therefore, strengthening wind flow to enhance pollutant dispersion near roads (Baik et al., 2012). Simulation results indicated a 30–57% reduction of pollutant concentration due to green roofs, correlating with the cooling intensity (Baik et al., 2012). However, some studies noted that pollution at the pedestrian level might increase with intense green roof coverage, potentially attributed to reduced vertical air fluxes (Moradpour et al., 2018; Rafael et al., 2018). Tomson et al. (2021) found that the existence of green roofs posed challenges to pollutant removal in some circumstances. It is recommended that contextual design considerations, such as site conditions, plant species and dry deposition velocities, are the key to maximizing the pollutant removal potential of green roofs (Speak et al., 2012; Vera et al., 2021; Yang et al., 2008).

Vertical greenery is different from other green infrastructure in terms of influencing UPI effects because they do not significantly alter prevailing ventilation in urban streets (Ysebaert et al., 2021). Studies suggested a positive effect of vertical greenery on pollution reduction (Joshi and Ghosh, 2014; Liu et al., 2022; Pugh et al., 2012; Qin et al., 2018). Moreover, benefiting from their cooling effect, vertical greenery can reduce the photochemical reaction rate to limit the generation of O_3 and in turn improve the air quality in street canyons (Liu et al., 2022). The effectiveness of vertical greenery in PM deposition is correlated with specific plant species and the residence time of PM in the street environment (Ysebaert et al., 2021). Certain species can also absorb ultrafine particles such as $PM_{0.1}$ through their stomata (Lovett, 1994). Plants with hairy, smaller, rougher-surfaced and more complex-shaped leaves tend to have a higher ability for PM accumulation due to their significant edge effect (higher perimeter to surface area ratio) and ability to increase turbulence (Perini et al., 2017; Weerakkody et al., 2018). However, it is worth mentioning that many findings about plant traits and PM deposition traits are primarily derived from laboratory experiments at the individual leaf scale (Hellebaut et al., 2022), while some field experiments indicate limited differencesin PM reduction across different species (Paull et al., 2020a; Paull et al., 2020b). The future challenge and opportunity lie in confirming their effectiveness through *in-situ* air quality experiments.

5. Synergies, conflicts and outlook

Heat waves can be accompanied by heavier air pollution in urban areas (Bao et al., 2023; Lin et al., 2020). In general, numerous studies have confirmed the cooling effects of green infrastructure, which vary depending on their configuration, vegetation type, coverage and local climate. However, their effectiveness in reducing air pollution varies, with certain scenarios showing that some types of greenery might exacerbate pollution levels (Fig. 4).

5.1. Synergies

From the synergy perspective, larger UGS with extensive canopy cover and low bVOC-emitting species can facilitate both cooling and pollutant deposition, as presented in Fig. 4. However, the complex dynamics between UGS size and their cooling and purification efficacy can be influenced by the heterogeneity of the landscape. Our findings suggest that, due to the diminishing marginal cooling benefit with a larger scale of UGS, small to medium-sized UGS ($\leq$16 ha) are optimal for urban planning (as a comparison, the size of Central Park in New York, US is approximately 341 ha). In densely populated urban cores, smaller UGS interlace directly with human activity, offering more immediate and perceptible cleaner air. Identifying the most appropriate size of UGS depends on the urban context since the threshold value of efficiency on UHI and UPI mitigation varies across different areas. In large, low-density cities, it is generally more beneficial to preserve existing UGS, or restore and create new ones, to maximize environmental benefits. However, policymakers should ensure that expanding UGS does not increase travel distances and car dependency, which could lead to higher greenhouse gas and pollutant emissions (Nieuwenhuijsen, 2020). In compact cities, strategies such as incorporating micro-gardens can be effective. Moreover, UGS planning should address accessibility and equitable distribution to promote environmental justice (Iungman et al., 2024). The impact of different UGS morphologies has not been fully established. More studies should be conducted to explain not only the scale dependence of UGS but also the complex interactions between landscapes, urban spatial structure and geoclimatic settings (Geng et al., 2022; Lei et al., 2021).

The benefits of street hedges for roadside air quality are well-established. Species with larger leaf area and higher leaf area index, for instances *E.* × *ebbingei* and *P.* × *fraseri*, are preferred in Mediterranean regions (Mori et al., 2015). In contrast, their cooling effect remains inconclusive. In fact, hedges, often exceeding 1 m in height with continuous layouts, are pervasive in urban settings, suggesting a

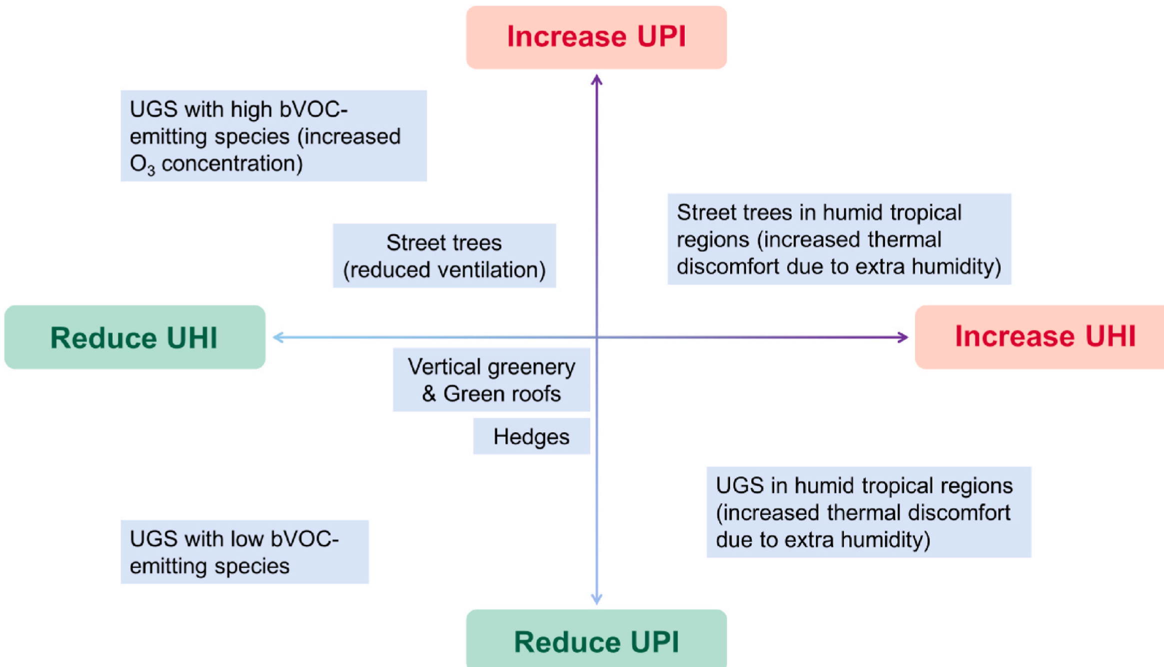

Fig. 4. Typology of green infrastructure impact on UPI and UHI. Different types of green infrastructure are divided into quadrants according to their level of impact on UHI and UPI. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

significant, yet under-researched potential to influence the local thermal environment.

Green roofs and vertical greenery generally benefit both cooling and pollution reduction although they may have a less significant cooling effect than street trees do (de Quadros and Mizgier, 2023), as shown in Fig. 4. Due to their more challenging planting locations, the species selection should prioritize drought resilience, lower soil nutrition requirements and minimal maintenance (Tomson et al., 2021). UHI mitigation effect of these two relies not just on density, leaf area index and coverage but also on substrate composition with topsoil often reaching the highest temperatures. Adding a water retention layer can enhance moisture conservation and evapotranspiration cooling (Ode Sang et al., 2022). In terms of UPI, mosses can be a precious supplement to green roof installations. They may trap more particles than leaves of common vascular species in Australia (Haynes et al., 2019). For vertical greenery installations, further quantitative research is required to identify optimal species that can withstand high winds, prolong exposure to pollutants and minimize wash-off during rain, thus enhancing pollutant capture (Hunter et al., 2014; Ysebaert et al., 2021).

5.2. *Conflicts*

A significant consideration of UGS is their potential to raise bVOC emissions, thereby intensifying O_3 pollution levels (Fig. 4). The emission rate and the total output of bVOCs from plants increase with air temperature, as highlighted by Janyasuthiwong et al. (2022). For example, the contribution of bVOCs to O_3 formation increased to 60% during the heat wave period in Berlin, Germany (Churkina et al., 2017). If species with high bVOC emissions were implemented prevalently, the negative health impacts of O_3 pollution might even outweigh the cooling advantages. Therefore, prioritizing tree species that maintain extensive canopy cover but minimize bVOC emissions is crucial in UGS planning. Deciduous species generally outperform conifers in this respect (Bao et al., 2023). Some high isoprene-emitting species, such as *Populus* and *Salix*, may release over 90 μg/g-h, and thus are not recommended for large-scale planting in UGS (Bao et al., 2023).

Street trees present a complex challenge in balancing UHI mitigation with UPI management. They can enhance shading and evapotranspiration during the daytime while hindering pollution dispersion by limiting airflow because their aerodynamic impacts are more significant than the deposition of pollutants. Their potential to increase the pollution level and reduce thermal comfort in humid regions cannot be ignored (Fig. 4). Current research shows that higher tree cover leads to higher air pollution concentration but reduced urban heat (Li et al., 2023b; Yang et al., 2023). Optimizing tree selection based on traits such as leaf area index and canopy density is crucial for preserving cooling effects and minimizing the negative impact on air quality. Moreover, street canyon morphology may determine the impact of trees on the UPI effect. Trees on a street canyon with low aspect ratio may help to reduce PM concentration (Miao et al., 2021; Wang et al., 2020). As evidenced by Guo et al. (2023), appropriate street tree implementation could reduce their impact on PM_{10} concentration with an increase as low as 0.9%. Roughly speaking, species with better shading, low resistance to airflow and better environmental tolerance are recommended (Barwise and Kumar, 2020). Species choice of street trees should also consider geographic factors, to avoid humidity induced by species with a high evapotranspiration rate during summer days in tropical regions. Given the complexity of tree-canyon interactions, there is no one-size-fits-all answer. Therefore, the concept of the right tree for the right street becomes important in urban planning decision-making (Buccolieri et al., 2018). This approach accounts for the impact of street trees on pollutant dispersion when planning to increase their number to mitigate high outdoor air temperatures and enhance other socio-economic benefits (Morakinyo et al., 2020).

5.3. *Research challenges and future outlooks*

UHI and UPI effects are increasingly recognized for their significant impacts on public health, with green infrastructure emerging as a solution for mitigating both issues. Despite its potential, challenges remain in quantifying the relationships between the cooling and air purification benefits due to the lack of synergistic investigations. This review analyzed the impact of green infrastructure on UHI and UPI, identifying important synergies. However, the key conflict - where green infrastructure reduces UHI but exacerbates UPI - presents substantial opportunities for future research. This area is largely underexplored, particularly when both effects are considered simultaneously, making it a critical direction for future investigation.

The multidisciplinary nature of investigating the influence of green infrastructure on UHI and UPI leads to variability in results across different approaches, such as on-site experiments, remote sensing, wind tunnel tests, and numerical simulations. Each method has its strengths and limitations. For example, on-site experiments can provide high temporal resolution at the site scale, but the spatial continuity of the data is often limited (Razzaghmanesh et al., 2016; Zhang, 2020). Moreover, the accuracy of sensors, data logging frequency, and replicability of tests can affect the robustness of the results. Remote sensing offers the widest spatial coverage with lower expense, but typically has lower spatial resolution and only captures instantaneous observations at the time of satellite transit, limiting temporal continuity (Zhou et al., 2023). Wind tunnel experiments show high accuracy and are often used for validating numerical simulations, but are time-consuming and expensive (Buccolieri et al., 2018). Simulation approaches can bypass spatial and temporal constraints, and allow for investigation of various factors affecting UHI and UPI. However, the accuracy of results can be compromised by oversimplified model assumptions required to manage the complexity and computational costs of the modelling process. Therefore, these challenges often result in discrepancies in findings, such as the noticeable differences in the surface temperature reduction of UGS between on-site and remote sensing approaches (Wong et al., 2021). Moreover, using the same methods to measure different indices for evaluating green infrastructure's impact on UHI and UPI can lead to varying outcomes. Such variations underscore the need for researchers to be cautious when comparing results across methodologies and highlight the importance of developing a unified framework to evaluate the true effectiveness of green infrastructure.

To bridge research findings with practical application, creating a database of plant functional traits can guide the selection of species based on characteristics including cooling efficiency, the capacity of air pollution mitigation, growth rate and drought tolerance, therefore reducing redundancy of repeating tests of species that have been investigated in previous studies. Such resources can serve dual purposes. First, it can refine numerical modelling by providing more accurate input information such as vegetation coverage, leaf area index and evapotranspiration rate (Chen et al., 2019b). Second, integrated with other research outcomes on benefits such as enhancing biodiversity and improving psychological well-being, these findings can further guide urban designers in choosing plants that maximize ecosystem service functions of urban green infrastructure (Twohig-Bennett and Jones, 2018).

Based on our current findings, we suggest that integrating UGS planted with low bVOC-emitting species, green roofs, vertical greenery, street hedges, and restricted, well-designed street trees can provide greater environmental benefits in mitigating UHI and UPI effects. However, the collective impact and interactions of different types of green infrastructure on UHI and UPI remain to be further investigated. Understanding these interactions is crucial, as these types of green infrastructure can potentially complement or counterbalance each other's effects on urban heat and air pollution mitigation. Investigating these combinations would require the manipulation of scenarios with various configurations of green infrastructure, which may be easier to achieve by numerical approaches. Future research should explore the optimal height and placement of street greenery, green roofs, and vertical greenery within street canyons to maximize cooling effects while minimizing their contribution to UPI. Also, the interaction of green infrastructure and building features, such as surface materials and building orientations, and the urban geographical environment, requires further investigation with different approaches.

Finally, future research should consider the distinct challenges and needs that different cities/regions face regarding urban green infrastructure. Some regions are experiencing a rapid decline in green spaces due to expanding built-up areas, while others are exploring efficient ways to expand green infrastructure and enhance ecological benefits (Das et al., 2022; Li et al., 2023a). This highlights the varying stages of urban green infrastructure development, which must be tailored to local conditions. Furthermore, regardless of whether regions are developed or developing, access to green infrastructure and the average green space per person commonly lack equity (Aamodt et al., 2023; Tian et al., 2024). Addressing these issues is crucial for ensuring that green infrastructure not only delivers enhanced ecological services but also promotes social equity by providing fair access to these benefits for more urban populations to bridge the gap between environmental sustainability and social justice. Our study offers a perspective for selecting optimal solutions for mitigating UHI and UPI, but additional ecosystem services, such as flood control and biodiversity support, were not covered (Zhang and MacKenzie, 2024). Future research and policymaking may consider our perspectives, incorporating a broader range of ecosystem services to develop comprehensive, systemic solutions that maximize the utility of urban green infrastructure.

6. Conclusions

Urban green infrastructure is a nature-based solution that can alleviate urban heat, enhance air quality and promote sustainability. Until now, limited research or review has investigated their combined effect on UHI and UPI mitigation, with research often isolating the impact of various green infrastructures. This review offers a comprehensive synthesis of the effectiveness of UGS, street trees, street hedges, green roofs and vertical greenery in mitigating UHI and UPI simultaneously. Key findings indicate that UGS with low bVOC-emitting species can effectively mitigate these two effects. Medium-sized UGS are recommended for heat mitigation since they can balance efficiency and cost, while city-specific factors need to be considered. Moreover, green roofs and vertical greenery generally promote the mitigation of both effects. However, street trees present a dilemma since they improve thermal comfort yet potentially reduce air quality, necessitating strategic species selection and tree planning that optimizes UHI mitigation without exacerbating UPI. Species selection needs to consider the potential of inducing extra humidity that decreases thermal comfort in tropical regions. Future studies should prioritize a deeper exploration of species-specific impacts on UHI and UPI and integrate broader building features to equip policymakers with a holistic guide for mitigating both UHI and UPI effects in urban settings.

CRediT authorship contribution statement

Qingyun Wu: Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis. **Yuhan Huang:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Peter Irga:** Writing – review & editing. **Prashant Kumar:** Writing – review & editing. **Wengui Li:** Writing – review & editing. **Wei Wei:** Writing – review & editing. **Ho Kyong Shon:** Writing – review & editing. **Chengwang Lei:** Writing – review & editing. **John L. Zhou:** Writing – review & editing.

Declaration of generative AI in scientific writing

The authors declare that they did not use any Generative AI and AI-assisted technologies during the preparation of this work.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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