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REVIEW ARTICLE

Benefits and co-benefits of urban green infrastructure for sustainable cities: six current and emerging themes

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Abstract

Integrating urban green infrastructure (UGI) into cities is receiving increasing attention owing to its potential to provide various urban ecosystem services (UES). This review assesses the multifaceted services of UGI as benefits and co-benefits. By combining systematic and narrative review processes, we aim to synthesise existing knowledge along six current themes and identify research gaps. A total of 690 peer-reviewed articles published during 2000–2020 from Web of Science were selected, followed by bibliometric and full-text analysis. Based on the frequency of appearance in the network visualisation of keywords, six themes of current trends were identified, namely: (1) benefits of UGI as UES; (2) mitigating climate and urban climate impacts by UGI; (3) UGI contribution to sustainable development goals; (4) reconceptualising greenspaces as 'safe havens'; (5) public acknowledgement and supportive governance for UGI; and (6) rethinking the operationalisability of UGI. The first two themes represent existing focus on categories of ecosystem services, the next two encompass broader emerging co-benefits and the last two focus on how to operationalise UGI and support widespread adoption and implementation. Within Theme 2, the most frequently discussed service with the largest number of research, we conducted a detailed analysis of the methods and content focus in the existing literature. Through a narrative review, we identified 15 research gaps throughout these 6 themes. This review provides a comprehensive overview for urban researchers and practitioners to inform the integration of urban green infrastructure into urban planning and management.

Keywords Urban blue–green infrastructure · Urban ecosystem services · Climate change mitigation · Sustainable development goals · Clustering analysis · Urban planning

Introduction

Over half of the world's population lives in cities, and this number is estimated to increase to 68% by 2050 (UN DESA 2018). Rapid urbanisation has been linked with various environmental, social, and economic impacts on a local and global scale (Bai et al. 2017; Grimm et al. 2008). For example, urbanisation-induced land-use change, mainly through replacing vegetated land with impervious and heat-absorbing surfaces, alters the urban energy and water balance (ADB 2015; Jiang et al. 2018). Such alterations lead to unique conditions in urban climates, such as the urban heat island (UHI) effect, while intensifying the impact of extreme heat events (Patricola and Wehner 2018; Shi et al. 2017; Zhang et al. 2018), decreasing thermal comfort in urban areas, driving energy demand for cooling and heating (Li et al. 2019b; Lundgren and Kjellstrom 2013; Waite et al. 2017), and contributing to increased health issues and mortality due to heat stress (Lam et al. 2018; Lemonsu et al. 2015).

Cities are actively searching for climate mitigation and adaptation interventions using concepts, such as climate proofing, low- and zero-carbon urban development, and other sustainable city initiatives (Albers et al. 2015; Bai et al. 2018; DTI 2003; Kamal-chaoui and Robert 2009; Lam et al. 2018; Lemonsu et al. 2015; OECD 2020; Revi et al. 2014; Satterthwaite 2010; UN 2013). Urban green infrastructure (UGI), such as public parks, forests, green spaces, private gardens, urban wetlands, agricultural lands, ponds, streams, and single green elements (vertical greenery, green roofs, and street trees), has recently gained increasing attention

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from research communities, local governments, and the general public (UN 2013). As defined by ClimateADAPT (2023), UGI planning is a strategic approach which involves developing interconnected and multifunctional networks of blue and green spaces to offer a diverse array of advantages across environmental, social, and economic domains. Building UGI has the potential to simultaneously enhance the liveability and climate resilience of cities (Climate ADAPT 2023). Hence, UGI is increasingly becoming an essential component of the urban fabric (Meerow and Newell 2017; Mell 2013).

An increasing number of studies have focused on the benefits of UGI from the perspective of ecosystem services. Ecosystem services are a subset of ecological functions and the benefits people receive from physical, chemical, and biological processes in the ecosystem (MEA 2005; Haase et al. 2014). There are many reviews focusing on the ecosystem services of UGI. Yet, several key gaps can be identified, including a limited scope that focuses on only one of the urban ecosystem services (UES) or benefits, such as temperature regulation (Bowler et al. 2010; Yu et al. 2020), air quality regulation (Abhijith et al. 2017), climate change adaptation (Ramyar et al. 2021), and human well-being [30], or on only a single UES category, such as cultural UES (La Rosa et al. 2016) and provisioning UES (Haase et al. 2014). Some reviews focused on a single UGI type (Roy et al. 2012), or on UES in indoor environments (Wang et al. 2014), while some reviews had limited geographic cover (Amorim et al. 2021; DasGupta et al. 2019; Lindley et al. 2018). Veerkamp et al. (2021) focused on multiple UES, but stopped at six (Veerkamp et al. 2021).

In light of these considerations, this review aims to investigate comprehensive, multifaceted benefits and co-benefits offered by UGI. An ecosystem service framework is adopted to identify and categorise these benefits and co-benefits. The review aims to consolidate and synthesise an often fragmented body of knowledge by casting a wide net to encompass the full spectrum of UGI benefits and co-benefits. Combining a systematic and narrative review, it identifies current and emerging hot topics and remaining gaps through in-depth qualitative analysis. The findings may inform researchers, policymakers, and practitioners seeking to integrate UGI into urban planning and management.

Methods

Systematic literature reviews have been recognised as the standard for accessing, appraising, and synthesising scientific information (Collaboration for Environmental Evidence 2013). This review combines a systematic review in literature search, filtering, and bibliometric analysis to identify key themes, following guidelines from Collaboration for Environmental Evidence (2013), and a narrative review within each theme to synthesise and identify gaps. We used a set of keywords related to urban and green infrastructure and their role in environmental, economic, and social benefits and ecosystem services. Keywords for green infrastructure appeared in literature in multiple terminologies, including (but not limited to) urban green infrastructure (UGI), nature-based solutions (NbS), ecosystem-based adaptation (EbA), and blue-green infrastructure (BGI). These terms have similarities and disparities with their functional variance. For instance, NbS acts as an umbrella for all the other concepts. EbA includes adaptations with respect to biodiversity and ecosystem services, whereas UGI focuses on various interconnected green spaces in urban areas (Pauleit et al. 2017). BGI is defined as a network of interconnected natural and designed landscape components, including water bodies and green and open spaces (Ghofrani et al. 2017). In this study, we use the general term UGI to refer to both urban vegetation and water structures. Accordingly, all of these related keywords were combined in the Web of Science (WOS) core collection using Booleans AND OR, as necessary (search query is presented in the appendix). The expanded search across 22 years rendered 5812 publications, which were filtered through the framework presented in Fig. 1.

In Tier 1, we screened articles published in English from 2000 to 2022 using the Science Citation Index-Expanded (SCI-E) and Social Science Citation Index (SSCI), which included in-scope keywords. Furthermore, quick filtering assisted in screening reviews and conference proceedings to focus on original and peer-reviewed publications. This step yielded 3144 articles, and they were directed to Tier 2 for title and abstract screening. Tier 2 screening facilitated filtering out duplicates and identifying studies that focus on the benefits of UGI in cities. This step filtered 706 articles and subjected them to full-text screening in Tier 3. The full texts of 706 articles were carefully assessed to identify case studies that presented empirical evidence. The filtered articles at this tier accounted for 690 original articles with individual and comparative case studies discussing the benefits of UGI from an environmental, social, and economic perspective. Those selected articles were then subjected to bibliometric and content analysis, and the keywords were visualised to represent the networks and co-occurrence in data extraction and synthesis. Based on the frequency of appearance in the network visualisation of keywords in all the 690 articles in VOSviewer, we identified the key areas which have co-occurred frequently with spotlight attention, which were later reorganised as six key themes. Content was extracted regarding UGI intervention, key benefits, other co-benefits, quantified modelling outcomes, etc. A narrative review of the six key themes highlighted current trends and identified knowledge gaps in research on the benefits and

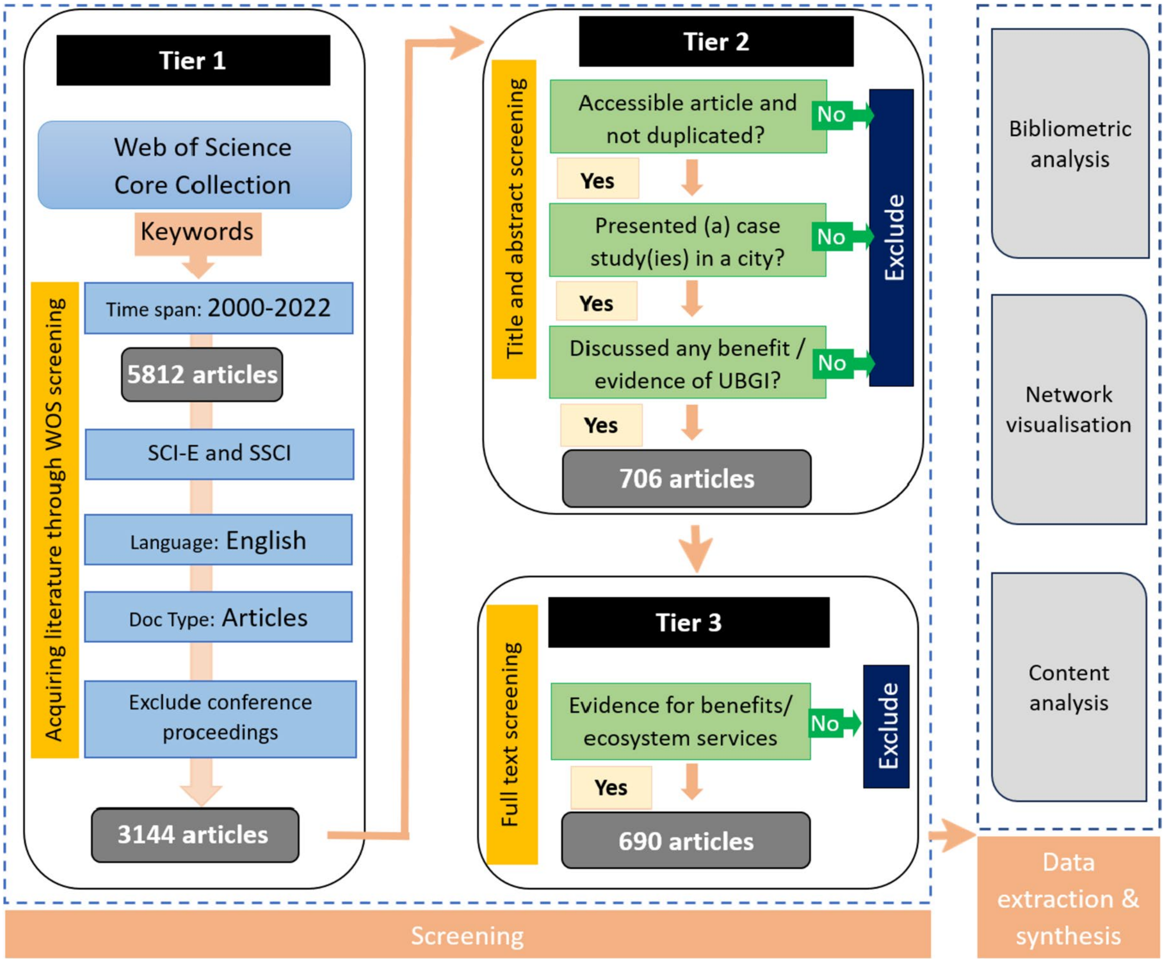


Fig. 1 3-Tier screening framework for the review. After the full-text screening in Tier 3, the selected 690 articles were subjected to data extraction and synthesis through a comprehensive content and bibliometric analysis and network visualisation

co-benefits of UGI. These findings are detailed in "Results and discussion".

Results and discussion

Identifying key themes

Through the screening process, we identified 690 articles on UGI that discuss different UES. These selected articles represent a wide range of research areas, including environmental sciences, ecology, urban studies, forestry, engineering, water resources, geography, and green sustainable science technology. This spectrum of research areas demonstrates the diverse functionality and applicability of UGI in different environmental, economic, and social domains.

The geographic distribution patterns of published articles agree well with previous literature findings—two-thirds of the reviewed studies were from the Global North, consistent with existing deficiencies in, and biases against, urban research in the Global South (Nagendra et al. 2018). Europe had the highest share of publications (38.6%), followed by Asia (29.3%) and North America (19.5%). Studies from Oceania, Africa, and South America exhibited the lowest shares of 5.5%, 3.9%, and 3.2%, respectively. China had the highest number of case studies (18.2%) across all categories, followed by the USA (17.3%). Over 90% of studies in Oceania had been conducted in Australia.

The increasing number of articles published since 2015 indicates a growing recognition of the benefits of UGI (see Fig. 2a). The observation of a low number of articles from 2000 to 2013 agrees with the findings of Escobedo et al. (2019) (Escobedo et al. 2019) about the appearance of each term with time: ES in 2006, green infrastructure in 2007, and NbS in 2015. Figure 2b shows the fifteen most frequently discussed UGI types in the reviewed studies; the most frequently mentioned types comprised *green roofs* (10%), *green spaces* (7.5%), and trees (in terms of *street trees*: 5.8%, and *urban trees*: 5.3%), indicating their popularity in urban areas.

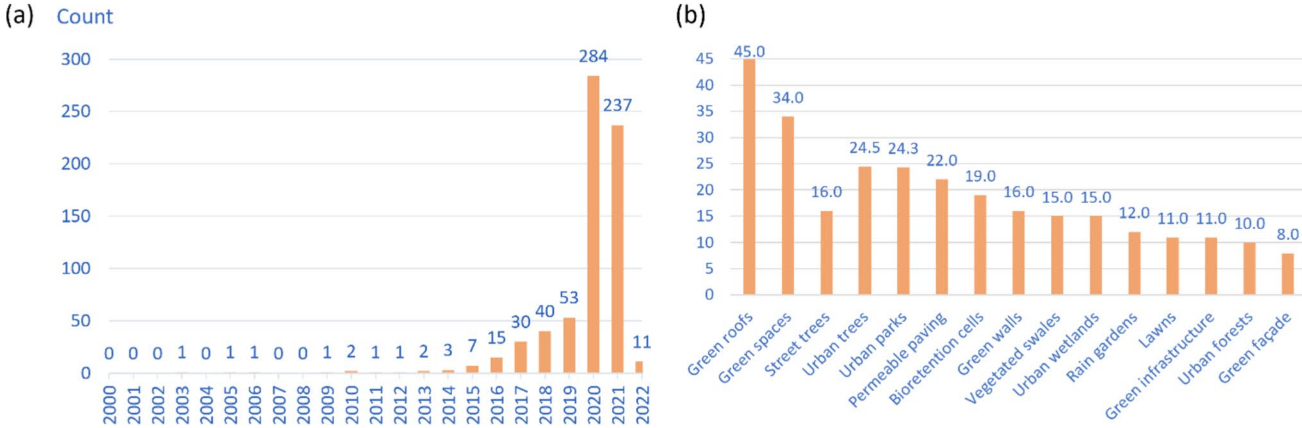


Fig. 2 **a** Number of articles that discuss UGI and ecosystem services between 2000 and 2022; **b** the top 15 most frequent terms for UGI types discussed in articles (the articles with more than one UGI type are counted as fractions)

However, half of these types were discussed only once, whereas certain UGI types, such as rooftop farming and urban agricultural land, appeared to garner less attention.

Figure 3 illustrates the network visualisation of the co-occurrence of all keywords assembled by VOSviewer using network-analytic methods. Since the circle size shows the frequency of co-occurrence, this illustration helped us to identify hot research topics/areas with spotlight attention in the existing literature. By observing the frequency, links, and cluster arrangement of keywords, six key areas were identified. Those were reorganised as key research themes of current trends, namely: (1) benefits of UGI as urban ecosystem services; (2) mitigating climate and urban climate impacts by UGI; (3) UGI contribution to sustainable development goals (SDGs); (4) reconceptualising greenspaces as 'safe havens'; (5) public acknowledgement and supportive governance for UGI, and (6) rethinking the operationalisability of UGI. The first two themes represent the 'categories of ecosystem services of UGI and the most prominent focus', the following two themes encompass 'broader and emerging co-benefits of UGI', and the last two themes focus on 'how to operationalise UGI and support widespread adoption and implementation in cities' (Fig. 4). For each of the six key themes, an in-depth content analysis was performed to identify the current trends and knowledge gaps in the related research area. Within Theme 2, which was the most frequently discussed category and, therefore, with the largest number of research, we further analysed the methods used and the content focus of existing literature.

State of the art and remaining gaps within each theme

Theme 1: Benefits of UGI as urban ecosystem services

The possibility of reassessing the benefits of UGI under the purview of ecosystems has been implied during the last decade (Bai 2018; Di Marino et al. 2019; Giedych and Maksymiuk 2017); however, it has been limited to specific areas. Di Marino et al. (2019) discussed integrating the concepts of UGI and ES into land-use policy and planning strategies. To identify all interconnections between nature and cities, adopting the categorisation of ES in the Millennium Ecosystem Assessment (MEA) is possible (Alcamo et al. 2005; MEA 2005), which entails provisioning, regulatory, cultural, and supporting services. Giedych and Maksymiuk (2017) studied the benefits of urban parks, although the study was limited to regulatory and cultural ES. Therefore, in this theme we explored the comprehensive benefits of UGI by linking them to MEA categorisation. The empirical data extracted from all 690 articles were categorised into the traditional MEA ecosystem categories using a treemap (Fig. 5). The treemap represents the number of cases discussing each UES to support the investigation on how different UES categories have been covered in the literature.

Through this visualisation, we identified uneven coverage of UES categories[1] as the first research gap in the literature (Table 1). Regulatory services provided by urban ecosystems were the most frequently discussed category, appearing in

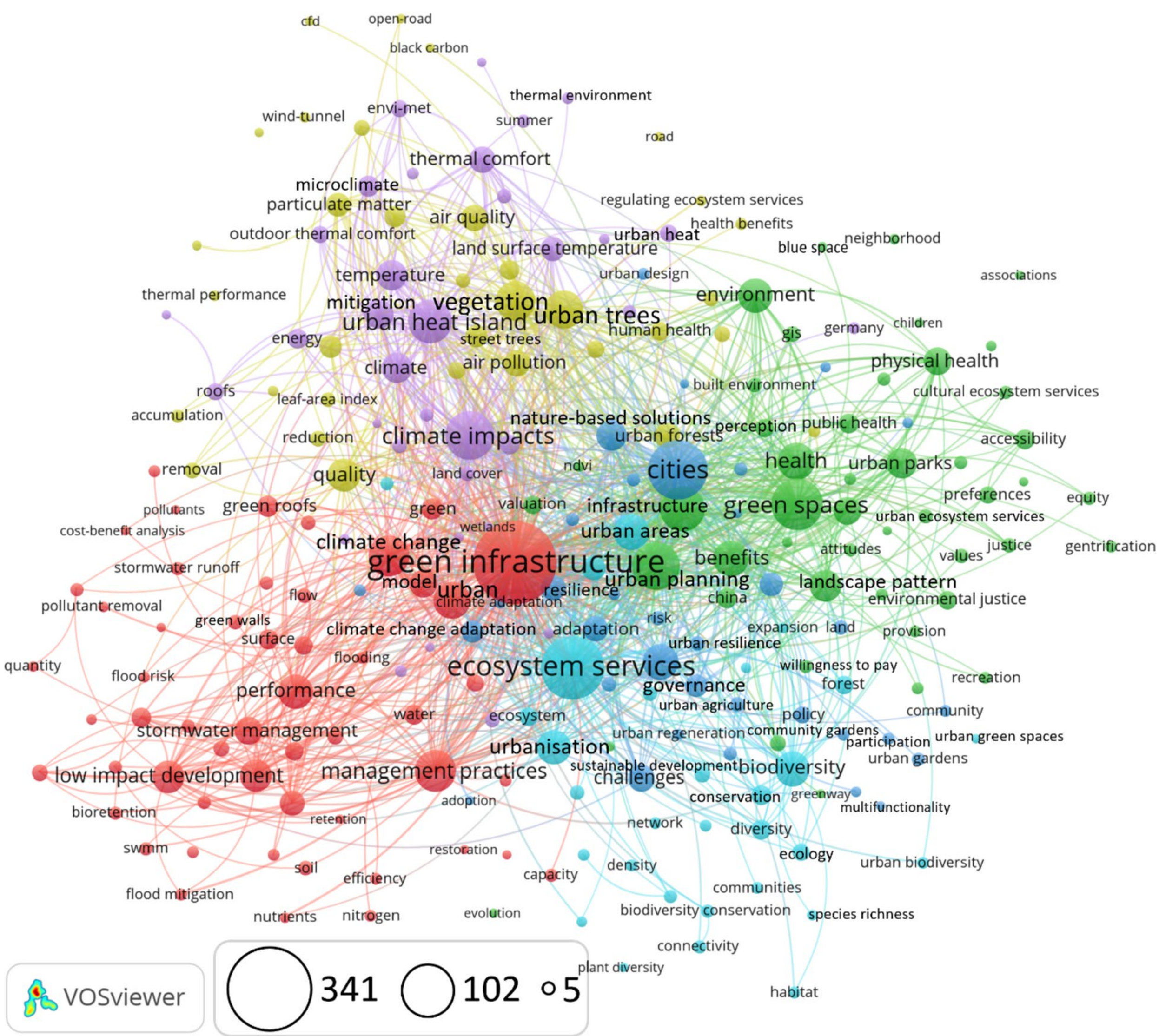


Fig. 3 Network visualisation of the co-occurrence of all keywords. Keywords appear on circles, and the circle's size is related to the frequency of occurrence. The assorted colours of each circle and links refer to the different clusters of the keywords. The width of the link between two keywords represents the strength of the link between them, such as bibliographic coupling links, co-authorship links, and co-occurrence links. The minimum number of occurrences of a keyword is 5 (234 out of 3359 keywords meet this threshold) and represents the smallest circle size in the scale

77.5% of the selected publications. Support for UES was present in 7.8% of the cases as the second-highest category. Provisioning and cultural UES accounted for 7.4% of all cases. Studies that focused on more than one UES within the same category were counted multiple times.

Regulatory services delivered by UGI play an essential role in human health and well-being in cities. As shown in Fig. 5, regulating urban microclimate impacts was the most frequently discussed UES, accounting for 20% of the total cases and has been separately discussed in Theme 2. Much research shows an increasing use of UGI in regulating floods and urban stormwater quantity (16.5%) and stormwater quality (9.1%), with various terms, including stormwater harvesting, integrated water management (IWM), water-sensitive urban design (WSUD), drained cities, and water-sensitive cities. This regulatory service directly addresses essential aspects of flood hazard reduction and the sustainable management of water resources (Green et al. 2021; Khodadad et al. 2023). Another important service is the regulation of air quality, including the reduction of pollutants, such as NO_2, CO_2, CO, SO_2, O_3, particulate matter, $PM_{2.5}$, and PM_{10} from traffic emissions (Capotorti et al. 2019; Santiago et al. 2019; Simon et al. 2019) and carbon offsetting (Chen 2015). Regulation of human well-being through facilitating thermal comfort, waste management, water storage, and energy savings is

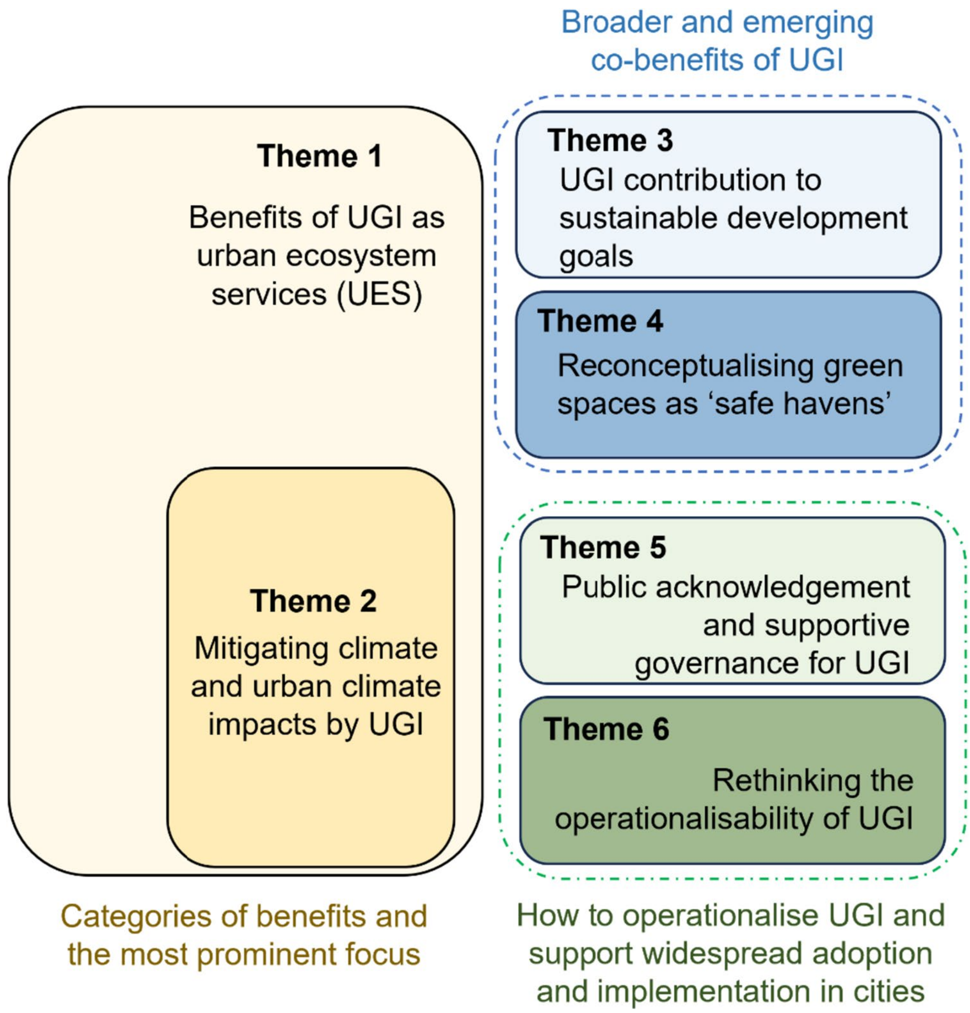


Fig. 4 Six key research areas with spotlight attention (based on the frequency, links, and cluster arrangement in keywords visualisation), which are rearranged as the six themes, and the three thematic domains as clusters to show the possible interrelations between themes

another benefit described as regulatory services (Ghazalli et al. 2018, 2019; Santiago et al. 2019; Simon et al. 2019). Moreover, most UGI types, such as urban trees, green walls, green facades, green roofs, and other urban landscapes, support carbon sequestration as a 'soft engineering' strategy, which can be defined as supporting greenhouse gas (GHG) emission mitigation because CO_2 is recognised as a primary GHG (Kim and Coseo 2018). In addition, natural vegetation in cities is known to improve the health and well-being of communities (Simon et al. 2019; Chen 2015), and improve life expectancy (Jonker et al. 2014). The high water retention ability of urban wetlands, water bodies, urban forests, rain gardens, and urban parks supports stormwater regulation, storage, flood resilience, water conservation, and filtering of polluted water (Herslund et al. 2018; Hettiarachchi et al. 2022; Liquete et al. 2016; Rodríguez-Rojas et al. 2018). Hybrid and fabricated UGI types (vegetated swales, bioretention cells, and rain barrels) mimic natural hydrological processes. They can increase surface permeability (Chen et al. 2019; Miller and Montalto 2019; Pierre et al. 2019) to promote infiltration and eventually reduce disaster risk by controlling urban flash floods (Fei et al. 2019; Gunnell et al. 2019; Kim and Kim 2017; Maragno et al. 2018; Shifflett et al. 2019; Tavakol-Davani et al. 2019). Additionally, we observed limited discussions on important regulatory UES, such as the improvement of soil quality, by retaining sediments and accumulating organic matter within urban landscapes.

The second category consisted of supporting UES (7.8%). UGI provides habitats for urban flora and fauna (animals, insects, bats, native birds, beetles, bugs, and plants) (Threlfall et al. 2017). Urban green areas enhance biological processes while supporting the biodiversity of cities (Fattorini and Galassi 2016; Gopal et al. 2019; Lopez et al. 2021; Riley et al. 2018). For example, insects promote pollination even though urban habitats are highly heterogeneous and occur in isolated patches (Lewis et al. 2019). Empirical evidence from Berlin highlighted the promotion of biodiversity and cultural heritage in its green landscape (Kowarik 2019). The presence of urban flora and fauna in cities, in turn, helps increase citizens' awareness of efforts towards biodiversity conservation (Landor-Yamagata et al. 2018).

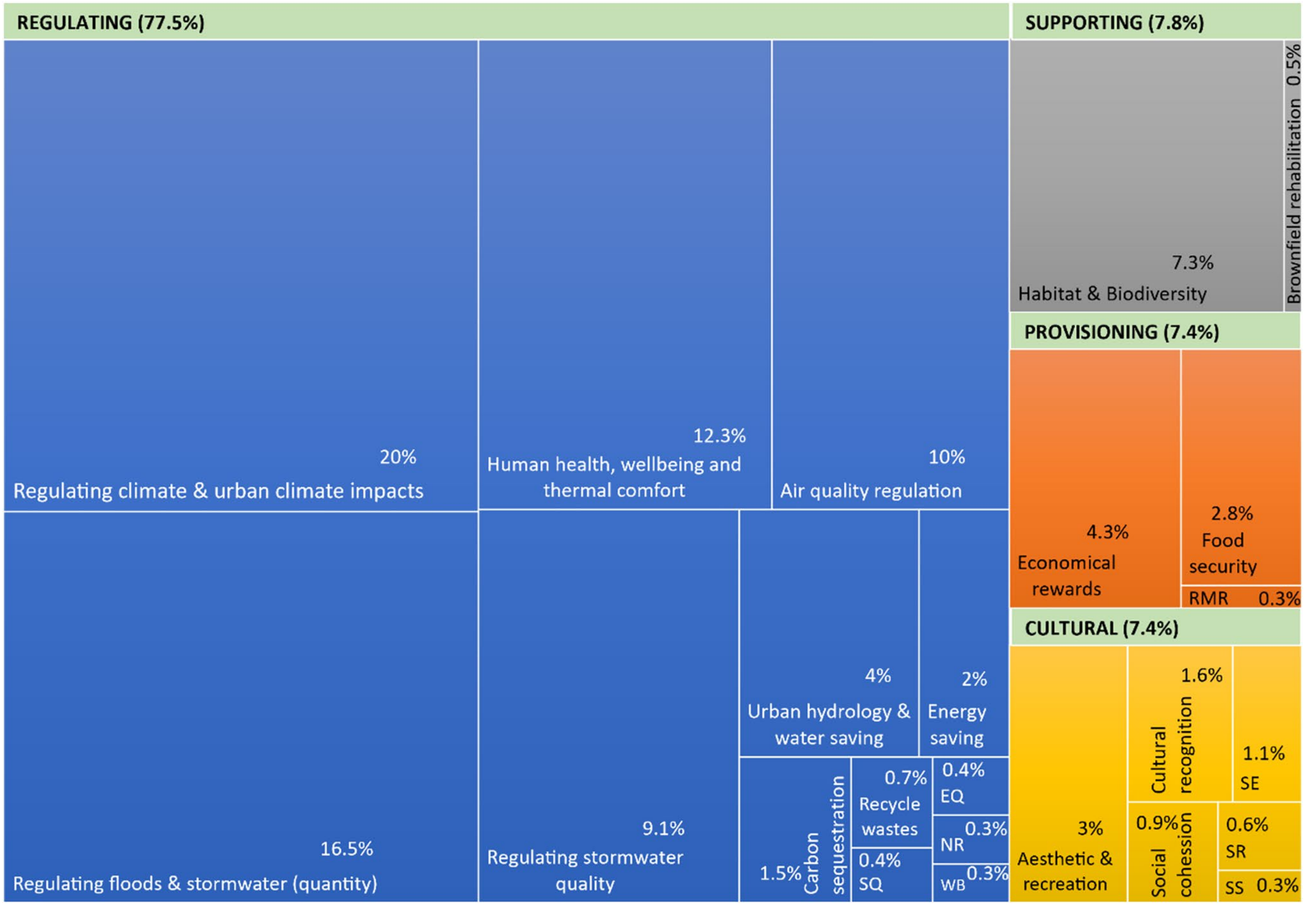


Fig. 5 Treemap for types of UES analysed in the 690 selected articles. The dimension of the nodule indicates the number of studies (percentage values are mentioned within the nodule). Multiple UES mentioned in one case study have been directed to each category (double-counted in some cases). *SQ* soil quality regulation, *EQ* environmental quality, *WB* windbreaks, *NR* noise reduction, *SS* social sustainability, *SR* spiritual rewards, *RMR* raw materials and resources, *SE* social equity

However, negative impacts on health and well-being, such as ecosystem disservices, have also been identified (Azmy et al. 2016; Lyytimäki et al. 2008), as these sites can be habitats for harmful insects, mosquitoes, and fruit flies. By providing habitats for soil microorganisms, UGI promotes soil quality, which is also considered a regulatory UES. With fewer reports in the existing literature, an understanding of the ability of UGI to enhance the nutrient cycle by storing, processing, acquiring, and recycling soil nutrients in urban systems remains a knowledge gap.

Provisioning UES accounts for 7.4%, which covers the consumptive use of urban greenery. These services involve the provision of firewood, medicinal plants, craft materials, timber, and peat. Providing food sources, including leafy vegetables, mushrooms, and edible insects often cultivated through rooftop farming, urban agricultural lands, community gardens, and allotments, is considered a significant provisioning UES. Provisioning UES extends beyond tangible resources to encompass sustainable provisioning of water, nutrient cycling, and genetic resources (Alves et al. 2019; Grard et al. 2018; Kim and Coseo 2018; Matos Silva et al. 2019; Säumel et al. 2019; Shackleton et al. 2018; Zhang and Dong 2018). Furthermore, this category considers the direct and indirect impacts of these services on commercial activities and local economy. For instance, green spaces have demonstrated their ability to boost the business volumes and revenues of retail companies, attracting residents and shop owners to locations near green spaces due to the enhanced sense of space usability (Koppelaar et al. 2021). Some literature suggests that higher property values are associated with proximity to green spaces as economic rewards (Combrinck et al. 2020; Yang et al. 2021). Moreover, the provision of fruits, seeds, blossoms, and leaves has been documented in research, and discussions have been conducted on equity in distribution and accessibility among different communities (Feng et al. 2019b; Lin et al. 2017; Orsini et al. 2020; Shi et al. 2020). Cities provide 'green collar jobs' for skilled and unskilled employees, which are rarely examined as

Table 1 List of identified research gaps via narrative review of each theme

#	Associated theme	Identified research gap
1	Theme 1: Benefits of UGI as urban ecosystem services	Uneven coverage of urban ecosystem services (UES) categories
2	Theme 2: Mitigation of climate and urban climate changes by UGI—the most frequently discussed function	Diverse effectiveness of UGI plans over different climate zones
3		Limited availability of measured data due to the lack of field measurements from on-ground implementations
4		Existing research primarily remains in the experimental or modelling stages
5		Lack of large-scale modelling assessments of UGI for climate adaptation and overall effectiveness
6		Insufficiency of multi-year analysis studies in the literature
7		Inadequacy of assessments focusing on the co-benefits approach
8		Limited investigations of UGI performance during extreme heat conditions
9	Theme 3: UGI contribution to sustainable development goals	Limited understanding of mechanisms for investing in UGI plans while addressing existing inequalities
10	Theme 4: Reconceptualising green spaces as 'safe havens'	Under-exploration of potential misuse of public green spaces beyond idealistic uses
11	Theme 5: Public acknowledgement and supportive governance for UGI	Lack of clear pathways towards financing green infrastructure
12	Theme 6: Rethinking the operationalisability of UGI	Insufficiency of a broader empirical basis to understand the effectiveness and co-benefits brought by hybrid infrastructure solutions
13		Lack of a comprehensive evaluation and assessment of UGI effectiveness
14		Insufficient exploration of the spatial configuration versus UGI efficiency
15		Lack of research on context-specific, multi-year analyses in different climatic regions

provisioning UES. King and Shackleton (2020) identified 17,429 jobs related to the maintenance of UGI in Eastern Cape towns, South Africa, generating approximately US$37 million per year (King and Shackleton 2020).

The final category was cultural UES, the "intangible and non-material benefits that people enjoy from ecosystems" (MEA 2005). Among the four main categories, cultural UES has been inadequately identified and under-studied in the literature (Cabana et al. 2020). We found that 7.4% of publications reported evidence for this category. Well-managed greening strategies in urban settings provide aesthetic and recreational value to a city by improving regular visits and tourism, and facilitating picnics, outings, non-commercial hunting and fishing, water sports, and other activities. These strategies can considerably increase the outdoor time of city occupants by enhancing the perception of walking and cycling and, ultimately, the quality of life (Douglas et al. 2019). Developing UGI in urban areas can enhance the cultural heritage of a site. For example, the Berlin Belt adds value to a cultural site and increases people's engagement and visits to the area (Kowarik 2019). Some studies have discussed how green spaces support people's religious beliefs, providing spiritual rewards and inspiration as a result of the quietness. In Bulawayo, Zimbabwe, several visitors from religious gatherings in urban green spaces said that outdoor worship is part of their religious practices, as the majority (79%) pray in public green spaces 1–4 times per week (Ngulani and Shackleton 2019).

The mapping of existing empirical literature into the four MEA categories of UES clearly showed the multivarious benefits that UGI provides for cities. A comprehensive assessment for valuation and appraisal of UES is always necessary to transfer the knowledge of UES into practice, to address the gaps associated with methodological inadequacy and inconsistency among approaches and to overcome less institutional support (Cabana et al. 2020; Saarikoski et al. 2018). However, we identified overlaps between categories, as most services are interconnected with direct and indirect benefits. At times, it was debatable to distinguish and place some services in the targeted UES category. For instance, in the case of air temperature reduction, it directly aligns with climate and urban climate regulation, while also contributing to human health and well-being and economic rewards. Assessing the monetary values through tangible indices, such as replacement costs, carbon taxes, afforestation costs, and market price methods (Xu and Zhao 2021), can overlap provisioning UES with other categories. While a cascade approach (Potschin-Young et al. 2018; Zhang et al. 2022) could be suitable for capturing these gaps, there are ongoing debates about this approach, as it simultaneously oversimplifies the complex reality and introduces unnecessary complexity to straightforward definitions (Costanza et al. 2017). Moreover, an evidence-based assessment of the effectiveness of UGI in comparison with that of traditional infrastructure is still required (Bai et al. 2018). Such a study would also be important for understanding the necessity, places, and people for whom UGI is required (Lopez et al. 2021).

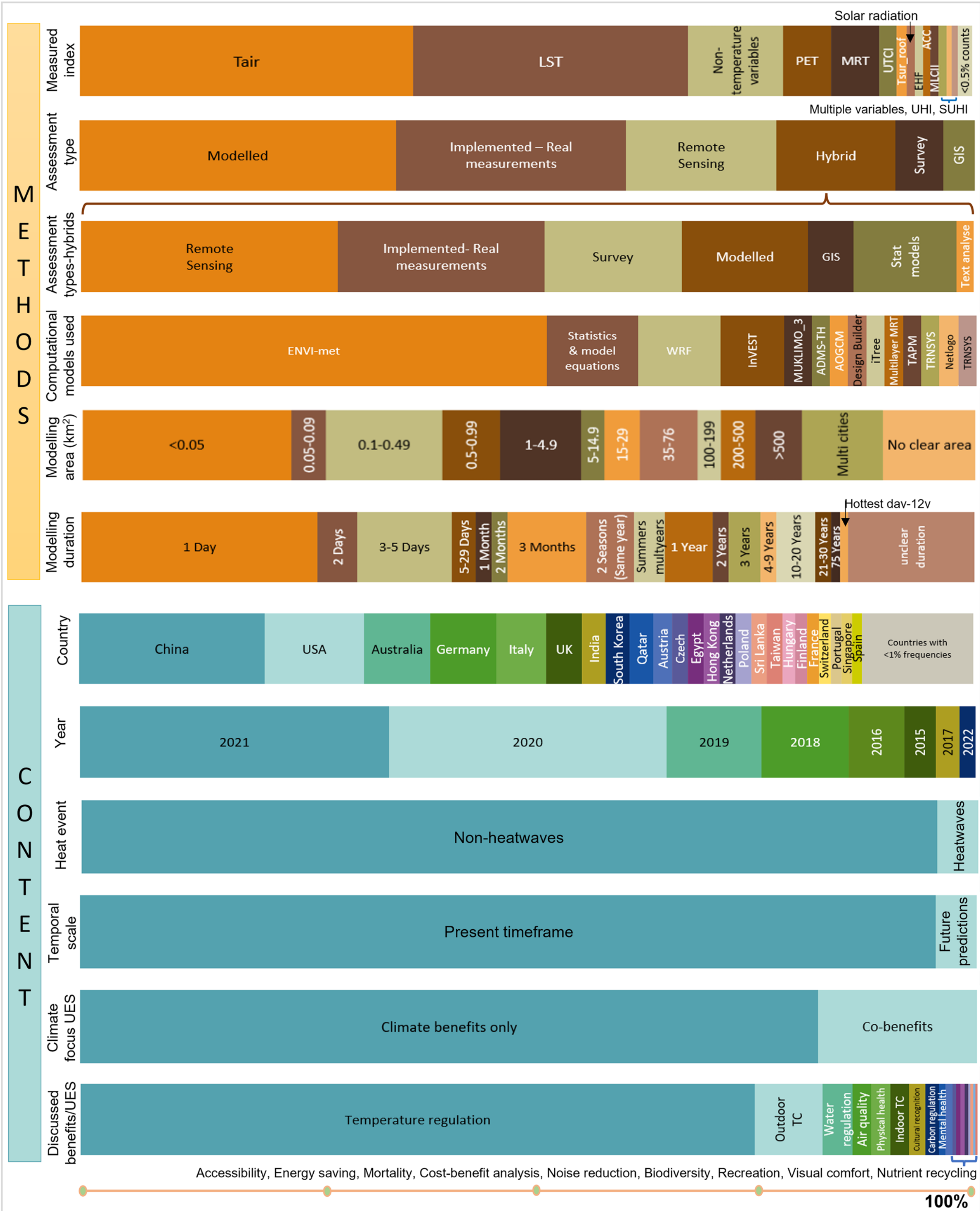
Theme 2: Mitigation of climate and urban climate changes by UGI—the most frequently discussed function

Impacts from climate change challenge urban resilience, liveability, and justice; hence, cities require effective adaptation and mitigation planning. The existing literature identifies UGI as a climate change adaptation tool, environmental and land management planning tool, ecosystem-based planning tool, and nature-based solution to bridge the existing gaps in climate change mitigation and adaptation actions (Anderson and Gough 2021; Salata and Yiannakou 2020). UGI systems ensure sustainable, less vulnerable, and more resilient communities by delivering critical UES and climatic benefits.

Among regulatory services, nearly half of UES (44%) have focused on climate and urban climate regulating benefits. The most common expectations for urban greenery are the regulation of urban temperature and the provision of thermal comfort and air quality (Duan et al. 2018; Masoudi et al. 2019; Wong et al. 2017). Moreover, a well-planned UGI can provide UES related to climate adaptation and mitigation, including stormwater regulation and water storage (Salata and Yiannakou 2020), GHG emissions (Kim and Coseo 2018), and carbon storage and sequestration (Ariluoma et al. 2021). Heat-regulatory services dominate climate benefits as the most discussed service, with 108 articles. In Fig. 6, the methods and contents are summarised to illustrate the diversity of those studies across 12 dimensions. By following the discussion trends, we assessed the heat-regulatory climate benefits of UGI (from 108 heat-related case studies) at greater depths. Hereafter, we present an overview of Fig. 6 with a subsequent discussion while identifying key research gaps and limitations regarding both content and methods in the most frequently discussed UES or function in the literature.

By observing the methodological approaches of the selected literature with attention to assessment type, measured index, modelling area, duration, and used models, several research gaps were identified. Various indices and terms, such as urban heat island (UHI) mitigation, urban cooling, indoor and outdoor thermal comfort, and human health and well-being across diverse climatic conditions and geographical locations, presented the association between urban green and urban heat. Urban green spaces regulate urban heat via evaporative cooling from transpiration and shading (Oke et al. 1989; Oliveira et al. 2011) and provide a land-use mix that improves the turbulence of the area. The vast majority of studies have analysed the association and impact of the behaviour of the air (T_{air}) or land surface temperature (LST) (or the UHI) with urban growth, the urbanisation gradient, or land-use changes (Masoudi et al. 2019; Wang et al. 2019a, b; Yang and Bou-Zeid 2019). Different primary indices, including T_{air} (mostly within the sensible heights for humans, 1.4–5 m layer) and land surface temperature (LST), and derivative indices, including UHI, mean radiant temperature (MRT), and surface urban heat island (SUHI), were used to study the temperature (see Fig. 6 for other indices) (Arnfield 2003; Grimmond 2007; Howard 1833). Thermal comfort is measured through indices, including physiological equivalent temperature (PET), predicted mean vote (PMV), universal thermal climate index (UTCI), and MRT, for which the temperate region has the highest discussion frequency of all indices. These universal thermal comfort indices are calculated based on primary heat indices, including T_{air}, radiation, humidity, wind, and personal factors (clothing and activity level) (Bröde et al. 2012; Höppe 1999). Our review shows that a wide array of methods were employed, from implemented UGI interventions to modelling (including physical models, GIS and RS, and statistical models, etc.), surveys and hybrid approaches combining two or more of the aforementioned methods. The substantial and growing contribution of LST and remote sensing to the findings is concerning, particularly given the method's acknowledged limitations in drawing definitive conclusions regarding UGI cooling benefits. However, extracting quantified reduction values/ranges for different indices was difficult. Out of the 108 cases, 14 presented outcomes in the form of map-based figures, statistical data, solar radiation results, or survey data, making it challenging to derive precise values. Consequently, the analysis presented in Fig. 7 is based on case studies with extractable outcomes, which accounts for 87% of the cases.

The diverse effectiveness of UGI plans over different climate zones[2] is a broad and under-explored topic and was identified as the second research gap. Different UGI typologies have been observed to have different levels of effectiveness in different climatic zones (Fig. 7) and require further assessment. Urban green spaces (identified by the search terms of urban parks, blue-green spaces, green cover, urban vegetation, green area, allotments, and urban gardens) were the most popular (33.3%) UGI strategy in the temperate region for heat mitigation (average reduction of T_{air} and LST of 2 °C and 6.2 °C, respectively). Urban trees are the most



frequently discussed UGI intervention for the subtropics (30.2%). Despite shading and evapotranspiration, urban trees modify wind flow to facilitate heat transfer in urban canyons (Oke et al. 1989). Green roofs are the dominant UGI intervention for heat mitigation in the tropics (23.3%), reducing the average T_{air} by 1.4 °C (0.02–2.6 °C). After

◀**Fig. 6** Overview of the proportions of the different aspects of content and method sections for selected climate-related articles. Multiple mentions are counted as decimals to maintain the fractional values. Climate models: *WRF*: weather research and forecasting method, *MUKLIMO_3*: microscale urban climate model, *AOGCM*: atmospheric ocean global climate models, *TAPM*: the air pollution model, *UT&C*: urban Tethys–Chloris model. Heat indices: T_{air}: air temperature, *LST*: land surface temperature, *MRT*: mean radiant temperature, *UHI*: urban heat island, *SUHI*: surface urban heat island, *MLCII*: maximum local cool island intensity, *ACC*: average cooling capacity, *EHF*: excess heat factor. Thermal comfort indices: *PET*: physiological equivalent temperature, *PMV*: predicted mean vote, *UTCI*: universal thermal climate index, *TC*: thermal comfort

applying UGI mitigation strategies, tropical climates show the maximum average T_{air} reduction (2.9 °C), but the broadest range is observable in the temperate region (0.02–9.4 °C). In the subtropical region, mitigating scenarios reported a maximum LST reduction of 14 °C (1.4–30.9 °C), whereas in the tropics, the reduction was at a minimum.

Our observations revealed the third research gap—limited availability of measured data, primarily due to a smaller number of field measurements from on-the-ground implementations[3]. In Fig. 6, we grouped the studies into six categories based on their assessment methods: field measurements from implemented cases, modelled, surveyed, GIS based, remote sense based (RS), and hybrid studies that combined two or more methods. Approximately, one-third (25.7%) of the studies investigated UGI predominantly through direct observation. Field measurements provide actual on-ground evidence, yet acquiring field data is challenging with time constraints, resources and instrumental limitations (related to data quality limitations, missing data), finances, and labour limitations (Hunziker et al. 2017; Mirzaei and Haghighat 2010). In addition, field data can cause unpredictable instrument or human errors during replication and long-term observations. The rest of the direct observations came from surveying studies (5.3%), which can be used as the qualitative component; however, surveying studies can also be onerous and liable to errors because of possibly biased responses and non-representative samples.

Modelling and thermal mapping studies are advantageous for overcoming these limitations to some extent, after validation with ground measurements. As excess heat is a constant urban challenge with the predicted urbanisation rate and future population growth, preparing resilient and adaptive cities for future shocks is a part of urban planning, which requires modelling and forecasting. The *popularity* of UGI, evident through numerous modelling and GIS/RS-based studies, was observed to be limited *as a concept*. Most research primarily remains in the experimental or modelling stages[4], which was identified as the fourth research gap. Modelling-based studies that used physical and simulation models, statistical models, and GIS-based and remote sensing models represented the majority (55.8%) of the results. Additionally, 13.3% of the studies used hybrid approaches, among which GIS and RS methods accounted for the highest fraction (36.11%), whereas modelling approaches accounted for 10%. Remote sensing captures surface temperature responses only at the tree-top and rooftop levels, which is a major disadvantage of this method (Krayenhoff et al. 2020). Thermal data on pedestrian levels are essential for planning pedestrian thermal comfort in cities, which the above GIS/RS-based methods fail to provide. Climate models are useful tools that can provide a platform to investigate the response of climate systems to different forces (e.g. urban land use change) and evaluate potential mitigation plans based on past experiences and future predictions (Flato et al. 2013). In the case studies from our search (Fig. 6), mesoscale and microscale climate models were mainly used with various resolutions. The spatial scale is critical for providing accurate outputs from simulations and is essential for providing high-resolution temporal and spatial climate data to assess the effectiveness of mitigation plans (Hayes et al. 2022). Mesoscale climate models support regional-level planning with comparatively larger resolutions (downscaling with resolutions of 1 to several hundred kilometres) by capturing dynamic atmospheric processes under boundary conditions (Hayes et al. 2022; Herath et al. 2023). We observed that 20.4% of the studies used different mesoscale urban climate models, including the weather research and forecasting (WRF) and atmospheric ocean global climate models (AOGCM), coupled with urban canopy models (UCM) to represent urban characteristics (Imran et al. 2018; Yang and Bou-Zeid 2019; Žuvela-Aloise et al. 2016). Most microscale models simulate detailed flow around terrain by resolving fine-scale turbulence using computational fluid dynamic (CFD) equations on the surface layer at the neighbourhood scale (further downscaled to metre-scale resolutions of 1 m–1 km) (Haupt et al. 2019), (ENVI-met GmbH 2022). Microscale models can estimate detailed information at the local scale, and this ability is highly important for pedestrian-level urban planning and thermal comfort assessments. However, the high computational demand and time required could limit the use of microscale climate models at the regional or city level. From our results, 52% of the simulation studies have used ENVI-met, a computational, microscale climate model (Bruse and Fleer 1998).

The lack of macroscale modelling assessments of UGI for climate adaptation and overall effectiveness[5] was identified as the fifth research gap. Most studies have focused on microscale modelling with focusing on areas < 0.05 km^2 or exclusively within an experimental setting. In reality, comprehending the effectiveness of UGI at a macroscale, such as a city level, is also essential, alongside neighbourhood studies in urban planning. This broader

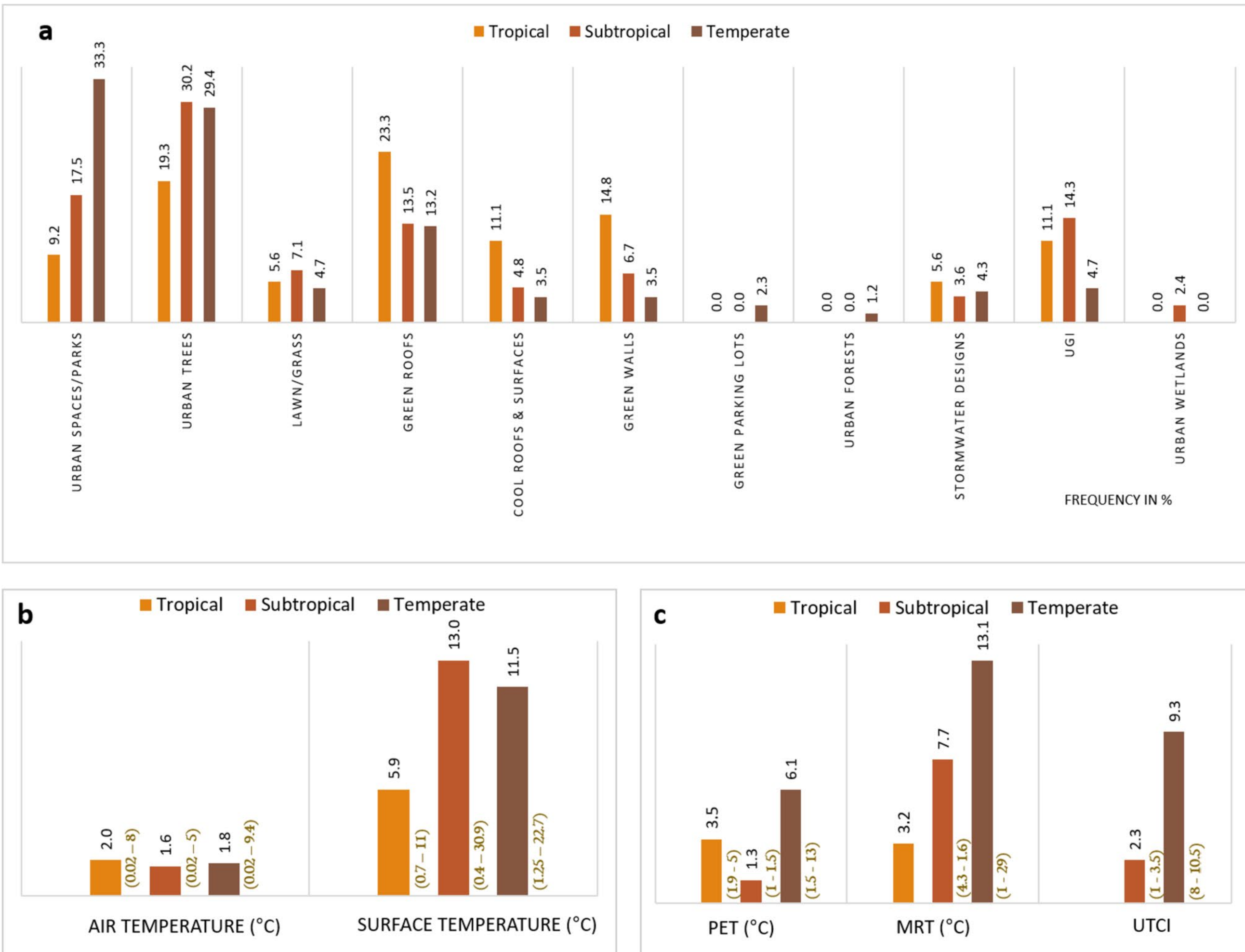


Fig. 7 **a** The number of case studies which mention UGI for urban heat mitigation in main climate zones in % (when the case studies discuss more than one UGI type, fractional values are counted); **b** The cooling effect (reduction) of different heat indices when considering the mitigation scenarios in different climate types; left panel: for air temperature (within 1.4–5 m layer in general, as identified in relevant case studies) and surface temperature; right panel: for thermal comfort indices. MRT: tropical ranges are not given as they represent a single value

perspective is crucial for city-scale planning, management, and understanding UGI interactions with other urban infrastructure. Therefore, the literature should be expanded towards the efficiency of UGI on a macroscale as well as its implementation beyond small-scale individual success stories (Bai 2018; Baró et al. 2015). In terms of modelling duration, most studies have presented short-term analyses (seasonal; e.g. for summer or across a year) (Fung and Jim 2019; Herath et al. 2021), for a duration below 20 years (> 80%). Only 4.6% of the studies represented long-term analyses that used durations longer than 20 years (Cai et al. 2019; Di Leo et al. 2016; Herath et al. 2023). The insufficient number of studies in the literature with multiyear analysis[6] was identified as the sixth research gap; hence, long-term and multiyear findings are critical for capturing the considerable year-to-year variability in the climate in the context of adaptation plans.

In terms of content, two research gaps were identified, which are discussed below. Considering the discussion frequencies, the inadequacy of assessments of the co-benefits approach[7] is highlighted as the seventh research gap. Most studies solely assessed heat reduction climate benefits, whereas only 17.7% of the cases considered co-benefits. Figure 6 suggests that most studies evaluated climate benefits considering the present (and past) timeframes of UGI, whereas only 4.4% of cases presented predictions from simulations with future timeframes (Emmanuel and Loconsole 2015; Fahmy et al. 2018). We highlight the limited number of assessments of UGI during extreme heat conditions[8] as the eighth research gap. Given the increasing frequency and severity of extreme events, the existing discussion frequency (only 4.4%) suggests a grey area with a lack of attention to UGI solutions for heatwave adaptation planning.

Theme 3: UGI contribution to sustainable development goals

Green areas are one of the seven essential factors determining urban carrying capacity in a sustainable city (Oh et al. 2005). Other UES from green spaces observed in this search also display direct and indirect benefits along with the other six factors, namely energy, roads, subway systems, water supply, sewage treatment, and waste treatment. Having functional green spaces in cities is directly compatible with Sustainable Development Goals (SDGs) targets. Target 11.7 is: 'to provide universal access to safe, inclusive, and accessible green and public spaces', and Target 11.6 is: 'to reduce the adverse per capita environmental impact of cities' under 'sustainable cities and communities' (United Nations 2018). As shown in Fig. 8, the literature shows that the UES delivered by UGI could contribute to most other SDGs as well. For example, climate-related regulatory services, including air quality regulation, temperature regulation, water storage, and disaster risk reduction, through stormwater management directly contribute to the 13th SDG and climate action strategies. The UES provided by urban wetlands, such as purification, retention, and water replenishment, contribute to the 6th SDG, which considers clean water and sanitation. Hence, a city can apply the concept of 'co-benefits' during sustainability planning with maximum effectiveness owing to the interlinked and multidisciplinary nature of UES.

Fig. 8 Contribution of urban green infrastructure (UGI) to sustainable development goals (SDG)s. References that substantiate the linkages a–k: **a** (Hurley & Emery 2018; Landor-Yamagata et al. 2018); **b** (Grard et al. 2018; Orsini et al. 2014); **c** (Battisti et al. 2019; Geary et al. 2021); **d** (Chan et al. 2018; Wong et al. 2018); **e** (Greenway 2017; Zölch et al. 2017); **f** (Capotorti et al. 2019; Threlfall et al. 2017; Herath et al. 2021, 2018b, 2018a); **g** (Viecco et al. 2018; Vojinovic et al. 2021); **h** (Grard et al. 2018; Mathey et al. 2015); **i** (Niu et al. 2010); **j** (Chou et al. 2017); **k** (Gelan & Girma 2021; Hurley & Emery 2018)

As identified in theme 3.2 (the 7th research gap under climate regulatory UES), our overall analysis confirms that there is room for enhanced recognition of the co-benefits of UGI. Most case studies (82.3%) included in our literature review focused on a single benefit/role of UGI, whereas 17.7% identified co-benefits. UGI often provides a golden payback, as it delivers several co-benefits beyond the initial planning. As proof of this, the green infrastructure plan, mainly intended to improve water quality and stormwater infiltration in New York, was found to 'inadvertently' deliver climate adaptation outcomes (Culligan 2019). Harnessing the many co-benefits delivered by UGI could be a strategic way to reduce the cost of addressing urban challenges (Raymond et al. 2017). For instance, planning for climate adaptation and mitigation with UGI could be more cost-effective considering the social co-benefits (European Commission 2013; Karlsson et al. 2020). However, in complex, interlinked systems, such as cities (Grimm et al. 2008; Ngulani and Shackleton 2019; Raymond et al. 2017; United Nations 2018), interventions often deliver intended benefits and co-benefits along with unintended consequences, such as potential trade-offs, limitations, and disservices. For example, planning urban forests in Australia to target the goals of carbon capture and water or pollutant regulation should consider potential fire risks. Planning for a co-benefit-focused, climate-responsive, multidisciplinary and inter-scaler design (Tomasi et al. 2021), local level planning (Yin et al. 2021), and cross-over concern to bridge several knowledge bases, such as urban climatology, landscape planning, and urban governance, can help overcome some limitations and disservices.

Urban green spaces play a vital role in social cohesion, promoting people's participation in community affairs and strengthening a community's social network and community care (Chou et al. 2017; Langemeyer et al. 2018). For example, establishing green spaces in urban settings promotes equitable sharing of urban spaces by urban communities (Quatrini et al. 2019). Urban agricultural efforts, rooftop farming, and community gardens improve active engagement, participation, cooperative work, mutual learning, and experience sharing. Edible city concepts are conducive, to an extent, to alleviating poverty and inequality in urban areas (Säumel et al. 2019).

The mechanisms behind investing in UGI plans while addressing inequalities (Herreros-Cantis and McPhearson 2021) remain unclear[9], which we identified as the ninth research gap. UGI draws attention to urban sustainability, but is often limited, particularly in underdeveloped, low-income areas (Cheshmehzangi et al. 2021). For example, environmental, economic, and social injustice and inequalities are reported in cities (regardless of city size) while distributing services of UGI (e.g. New York, USA, and smaller towns outside Wuhan, China) (Herreros-Cantis and McPhearson 2021; Dai et al. 2021). Several factors contribute to such inequalities, including supply and demand mismatch, income disparity, and racial factors (Herreros-Cantis and McPhearson 2021; Dai et al. 2021). Conversely, investing in UGI contributes to urban gentrification, potentially promoting social and racial inequalities and environmental injustices (Anguelovski et al. 2022).

Theme 4: Reconceptualising green spaces as 'safe havens'

A considerable number of recently published articles in our search results refer to COVID-19, with some of them specifically addressing the roles of UGI during the pandemic. As a result, we have identified this topic as one deserving separate attention. Urban parks, peri-urban forests, and protected areas are often used by local communities for exercise (walking, running, hiking, and cycling) and recreational purposes, thus supporting the physical and mental well-being of the community (Berdejo-Espinola et al. 2021; Liu and Wang 2021; Venter et al. 2020). During the recent COVID-19 outbreak, urban green spaces have garnered increasing attention and have had a higher demand as *places to escape* (Sugiyama et al. 2021; Venter et al. 2020). For instance, in a survey conducted in Brisbane, Australia, 36% of participants reported increased usage of their local green spaces, whereas 45% reported visiting a new green space for the first time (Berdejo-Espinola et al. 2021). In Oslo, Norway, outdoor recreational activities increased by 291% during the lockdown compared with the previous 3 years (Venter et al. 2020). Using green spaces during the pandemic has offered benefits to the physical and mental well-being of city dwellers. For example, studies in the USA and Australia have assessed the mental health factors of adults and young people, such as COVID-19-related worries, distress, anxiety, and depression, in relation to nearby green spaces. They found that green spaces facilitated relaxation, enjoyment of nature, and enhanced resilience with better physical and mental well-being during the pandemic, with confirmed negative associations between tree-rich green spaces and mental health-related variables (Astell-Burt and Feng 2019; Lopez et al. 2021; Oswald et al. 2021; Wortzel et al. 2021).

Addressing this urgent demand in some high-density localities while balancing social distancing measures and infection control has become increasingly challenging (Kleinschroth and Kowarik 2020). For instance, private gardens and backyards provided an alternative for some communities, such as the residents of Brisbane, Australia, during the pandemic (Berdejo-Espinola et al. 2021). Moreover, scattered tiny pocket parks in vacant property spaces could be another innovative alternative (Liu and Wang 2021).

However, public green spaces may not always provide safe spaces for the community. The possible misuses of public green spaces beyond idealistic uses are considerably under-explored in the existing literature[10] and were identified as the tenth research gap. When green spaces in city areas are poorly managed, they can be unsafe for park users and neighbourhood communities, especially at night, with threats of theft, violence, drugs, and other types of crime (Koskela and Pain 2000). Lyytimaki et al. (2008) discussed situations where nature appears to be a nuisance to urban lifestyles with disservices, including pollen health risks and safety concerns in dark parks (Lyytimäki et al. 2008). Such issues need proper attention while planning multiple green spaces in cities.

The implications of these findings are clear for future planning. Firstly, urban green spaces must be considered an integral part of response plans for future pandemics, especially as the COVID-19 pandemic may become the 'new normal'. Secondly, in addition to large public green spaces, strategic planning through the installation of smaller pocket-sized green spaces could be an effective and resilient way to prepare for future disasters (Herath et al. 2024). Thirdly, planning and policy must be in place to ensure equity and justice in access to, and the safety of, urban green spaces for all communities (Calderón-Argelich et al. 2021; Chen et al. 2022; Geary et al. 2021; Kleinschroth and Kowarik 2020).

Theme 5: Public acknowledgement and supportive governance for UGI

Our review shows a generally positive public perception and acceptance of UGI. In most cases, city residents and visitors appreciate the UGI and associate it with positive feelings, such as beauty, peace, joy, excitement, hope, relaxation, desire to explore the site, interestedness, and safety (Lee and Kim 2015; Mesimäki et al. 2019). Meanwhile, public acknowledgement of environmental and recreational UES, such as climate mitigation and adaptation (Lo et al. 2017), is very high owing to the straightforward, corrective, and preventive benefits with tangible evidence (Gashu and Gebre-Egziabher 2019). Conversely, communities acknowledge economic and social UES to a lesser extent because these impacts are long-term and intangible (Gashu and Gebre-Egziabher 2019). These public perceptions seem to be influenced by demographics, gender, and educational level. For instance, educated elders and females appear to be more sensitive to the environmental risks to human well-being in some communities, such as poor air quality and high temperatures (Culligan 2019; Duan et al. 2018).

While largely positive, UGI also acquires some negative public acknowledgement. The main reasons for this include impacts on land value, parking loss, and the accumulation of trash and non-preferred plants/species (Culligan 2019). Many of these negative public perceptions were mainly due to general dissatisfaction generated by a lack of public consultation before implementation (Culligan 2019; Säumel et al. 2019), suggesting the importance of better public engagement/ involvement and community consultation. The operationalisation of UGI planning is simple and straightforward, with higher public acknowledgement and positive attitudes. For example, educational programs can train people to detect exotic pests during park visits (Norman-Burgdolf and Rieske 2021). Such attempts help nature by reducing the risk of invasive species, whereas participants benefit in terms of their physical and mental health.

Institutional and policy support is essential for successful UGI planning and implementation. For instance, some European countries have policies to support mainstream UGI in spatial planning and terrestrial development (Pauleit et al. 2017). New York and Melbourne (Melbourne Green Plan) invested heavily on UGI to improve local environmental and social conditions (City of Melbourne 2017; Culligan 2019; Victoria State Government 2017). In Canada, urban green planning is well acknowledged in municipal plans; however, the concept of 'explicit use of the ecosystem' has not been considered (Thompson et al. 2019).

There are many concerns and doubts about financing green infrastructure in cities. The lack of clear pathways towards financing green infrastructure[11] was identified as the eleventh research gap in the UGI-related literature. We found very few supporting studies that sought to understand the involvement, perception, and agreements of different institutional and community stakeholder parties (politicians, planning administrations, citizens, and external service providers) in UGI planning, access to their services, and utilisation of public funds. One method to source funds for public infrastructure planning is through municipal revenues earned through local government taxes and fines (Lindfield and Teipelke 2017). Therefore, positive public perception could be advantageous in financing UGI as such an attitude could substantially aid the moral authority to utilise public funds for developing UGI. Another method of financing UGI planning is through indirect participation of the community, such as accounting for willingness to pay (WTP). For example, some communities express a WTP elevated rentals and mortgages (up to 2%), whereas others are interested in paying for the development and quality enhancement of adjacent green spaces to live beside nature (Derkzen et al. 2017; Mell et al. 2016; Zhou et al. 2021).

Theme 6: Rethinking the operationalisability of UGI

Several limitations often impede larger-scale UGI projects during the planning, implementation, design, and management stages (Gelan and Girma 2021; Mell 2021), and raise doubts about operationalisation. Critical factors such as funding, space availability, infrastructure maintenance, institutional collaboration, responsibility sharing, lack of supportive policy frameworks, resource availability (e.g. water and nutrients), and waste disposal are prevalent hurdles during different phases of an UGI life cycle (Herath et al. 2023).

The merits of innovative technologies can overcome some of the drawbacks during the maintenance and management phases. For example, novel technologies, such as wireless sensor networks (Le et al. 2019), real-time controls (Matasov et al. 2020), plant/tree-based sensors (Jones 2019), and satellite-based representative methods with vegetation indices (Ramyar et al. 2021; Raymond et al. 2017), are helpful in maintenance, monitoring of regular vegetation health, and evaluating the performance of large-scale urban forest planning in Melbourne, Australia, a city aspiring to become a forest city in the future (Fuentes et al. 2021). Guidelines, manuals, protocols, and training are essential for managing potential disservices and other challenges, such as weeds, water stress, invasive species, diseases, and flood risk (Reynolds et al. 2020).

Overcoming these limitations is essential to maximise the effectiveness of a UGI plan to enhance functionality and multifunctionality while being resource-efficient and cost-effective. For example, using recycled greywater for green walls and roofs has been a successful alternative to limit and reduce potable-water use (Fowdar et al. 2017; Prodanovic et al. 2017). Recycled aggregates and sludge from wastewater treatment have been investigated as substrates for green roofs and walls (Molineux et al. 2015) for improved plant cover and diversity (Molineux et al. 2015).

Rehabilitation of abandoned urban spaces, such as solid waste dumps, mines, disused transportation routes (tram lines), and brownfields, can help ease the limitations of urban space availability for UGI (Feng et al. 2019a; Mathey et al. 2015; Zhang et al. 2019). Combined or integrated UGI strategies are reasonable choices, considering the potential high costs of implementing citywide green roofing for heat mitigation (Herath et al. 2023). For instance, integrating green roofs with reflective cool roofs could be a more feasible operational strategy with reduced cost/resource requirements and more cooling benefits than green roofs alone for heat mitigation (Herath et al. 2021, 2023). Moreover, integrating green roofs with solar panels shows a higher efficiency in energy production (increasing energy gain by up to 16%) compared with using conventional solar roofs, as this combination eliminates pollutants in the air while maintaining the panel surface at an optimum temperature range via cooling (Barcelona City Council 2015; Cavadini and Cook 2021).

Planning a hybrid infrastructure that combines green with blue and grey infrastructure can help maximise overall effectiveness (Fowdar et al. 2017; Molineux et al. 2015; Prodanovic et al. 2017). Generating a broader empirical basis on the effectiveness of such hybrid infrastructure solutions is essential for identifying the kind of co-benefits they bring[12], which was recognised as the twelfth research gap. As examples of hybrid infrastructure planning, we found six case studies in our literature search; however, all studies on this topic have focused on stormwater management (Bakhshipour et al. 2019; De Sousa et al. 2012; Jeong et al. 2016; Mulligan et al. 2020; Taghizadeh et al. 2021; Vojinovic et al. 2021). Assessment of effectiveness by counting the target benefits along with all potential co-benefits would provide a complete picture of effectiveness.

The operationalisability of a planned UGI should be a key consideration when analysing its effectiveness. Hence, the lack of a comprehensive evaluation and assessment of the effectiveness of UGI[13] was identified as the thirteenth research gap. The current literature tends to discuss the effectiveness of UGI based on functional effectiveness, such as cooling/heating/pollution control or stormwater holding potential, without much evaluation of the operationalisability, ease of implementation, cost-effectiveness, or comparisons with conventional infrastructure. For example, applying 90% or 100% citywide green roofs is effective in terms of cooling, but is neither realistic nor operationalisable. Selecting the most suitable UGI plan for the given context is critical during the planning stage.

Finally, the devil is in the detail; the minor details should be considered when implementing UGI. We identified the insufficient exploration of the spatial configurational efficiency of UGI[14] as the fourteenth research gap in the existing literature. It is reasonable to assume that the differences in the configuration and spatial arrangement of UGI could lead to different outcomes. For example, some evidence suggests that street trees without appropriate spacing and with dense canopies could decrease MRT and increase air temperature (Meili et al. 2021; Park et al. 2019). Public open spaces benefit from a particular tree orientation for effective cooling (Privitera and La Rosa 2018). With current technological advancements, these outcomes can be easily and accurately assessed using various empirical efforts in future studies. Furthermore, each city requires context-specific green policies, as each has a unique microclimate depending on multiple factors, such as climate, solar radiation, aerodynamic properties of urban materials, urban–rural gradient, morphology, and green spaces (Bherwani et al. 2020; Giyasova 2021; Li et al. 2019a; Martilli et al. 2020; Patricola and Wehner 2018; Zhang et al. 2018). To inform practice at the city level, more research on context-specific, multi-year analyses in different climatic regions is needed[15], which we summarised as the final (fifteenth) research gap in this review.

Limitations of the review

As for the scope of our sample, we have restricted our literature selection to a single database, Web of Science, and have omitted articles published in languages other than English. Limiting the scope to academic publications may overlook valuable insights present in grey literature sources. Constraining the search period to 2000–2022 enabled us to focus on the most contemporary and novel literature. Although this approach may potentially omit significant papers published prior to this period, it is necessary to manage the volume of records and facilitate the screening process efficiently. Our comprehensive approach to UGI benefits involved a broad literature evaluation, but revealed challenges in categorising them within the traditional MEA framework. This highlights the need for more adaptable categorisation methods that acknowledge the interconnected nature of UES, encouraging a more holistic assessment. Future studies should prioritise large-scale, real-world implementations across diverse climatic zones, geographic regions, and urban settings to enhance our understanding of UGI's impact.

Conclusions and future work

This review offers a comprehensive overview of the ecosystem services provided by UGI. It combines systematic and narrative review approaches to assess the multifaceted benefits and co-benefits provided by UGI. The existing knowledge is synthesised into six current and emerging themes, namely, benefits of UGI as UES; mitigating climate and urban climate impacts by UGI; UGI contribution to sustainable development goals; reconceptualising greenspaces as 'safe havens'; public acknowledgement and supportive governance for UGI; and rethinking the operationalisability of UGI.

Within each theme, the state of the art and existing gaps are discussed in-depth. Categorising the existing empirical evidence from the literature sheds light on the various UES provided by UGI. The first theme accentuates the uneven coverage of UES categories, necessitating a more balanced exploration. More than 77% of UGI literature focuses on the regulatory function, highlighting UGI's robust capacity for urban climate adaptation and mitigation, particularly in heat regulation and stormwater management. Theme 2 explores the benefits of UGI for mitigating climate and urban climate impacts, revealing gaps such as diverse effectiveness across climate zones, limited field measurements, and reliance on experimental or modelling stages. Theme 3, UGI's contribution to sustainable development goals, underscores its significant impact on advancing 17 SDGs, notably SDG 11 (Sustainable Cities and Communities). The UES interconnects and simultaneously creates several linkages with the SDGs, demonstrating an intrinsic capacity to deliver cost-effective co-benefits beyond its primary functions across social, environmental, and economic domains. However, our analysis unveils the gap, a limited understanding of mechanisms for investing in UGI plans while addressing existing inequalities. Themes 4 and 5 draw attention to the positive public perception of UGI, amplified by the COVID-19 pandemic experience, positioning it as a potent tool and a powerful aid in designing, managing, and financing the UGI. Proactive planning before implementing UGI plans can be a cost-effective option to provide a safe space against shocks such as heatwaves and pandemics in the context of climate change and post-COVID-19 new normal. Despite these positives, gaps persist, particularly in Theme 4, which sheds light on the underexplored potential misuse of public green spaces beyond idealistic uses, and Theme 5, highlighting the absence of clear pathways for financing green infrastructure. Theme 6 explores the operational challenges of UGI plans, including the insufficiency of empirical data, comprehensive evaluations, and exploration of spatial configurations, while discussing the possible innovative approaches to overcome those limitations.

Overall, the review shows that notable knowledge gaps persist despite the abundant literature on UGI. Addressing these gaps is crucial for unlocking the full potential of UGI in creating resilient and sustainable urban environments.

Appendix

TS = ('*green infrastructure' OR 'nature*based solution*' OR 'blue*green infrastructure' OR 'ecosystem*based adaptat*') AND TS = (city OR cities OR urban OR metropolitan) AND TS = (role* OR advantage* OR function* OR capacit* OR mitigation OR modification OR adaptation OR control* OR adjust* OR service* OR impact* OR effective* OR improv* OR *climate OR "urban*island" OR "heat Island" OR "air pollut*" OR "air pollut* mitigation" OR "air quality" OR "ecolog*service" OR "eco*service" OR "environment*" OR "social" OR "societ*" OR "econom*" OR water).

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Data availability The search query is presented in the appendix, and all results from the data analysis are presented. Other than that, data is available on request.

Declarations

Conflict of interest The authors have no competing interests to declare that are relevant to the content of this article.

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