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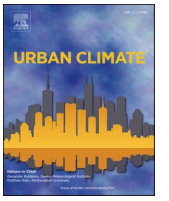

Systematic review of the climatic and non-climatic benefits of green roofs in urban areas

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ABSTRACT

The concentration of human activity and buildings in cities, combined with the general lack of green spaces, give rise to multiple sustainability challenges. At the same time, cities have become important arenas for decarbonization efforts. Green roofs have emerged as a promising option to alleviate this multitude of sustainability challenges though the diverse benefits they can provide. This study systematically reviews 386 peer-reviewed studies across eleven benefit categories, spanning climatic benefits (e.g. energy and greenhouse gases emissions savings, carbon sequestration and storage), as well as non-climatic benefits such as noise and air pollution mitigation, stormwater retention, and improved biodiversity and human wellbeing. The literature shows that green roofs can provide all of these benefits through different mechanisms, but that the actual magnitude of benefits depends on various factors. Although intensive green roofs generally perform better across almost all benefit categories, the available evidence is currently dominated by literature on extensive green roofs (80 % of reviewed articles). Similarly, for most benefit categories the bulk of the evidence comes from modeling and simulations, rather than experimental studies in real-world conditions. There are notable research gaps in terms of long-term studies that explore benefit delivery over long periods of time, and case studies from the global South.

1. Introduction

Urban areas are typically characterized by concentrated human activity, high proportions of impermeable surfaces, and low green space coverage (Bevilacqua et al., 2017). Decades of intense urbanization have catalyzed adverse environmental impacts across different spatial and temporal scales globally. For example, while cities occupy only 0.2–2.7 % of the global land surface, they account for the bulk of global resource consumption (IRP, 2018) and produce roughly 70 % of global greenhouse gas (GHG) emissions (IPCC, 2023).

Buildings are responsible for the largest proportion of urban energy consumption and GHG emissions, accounting for 67 % of urban energy use and 28 % of urban energy-related GHG emissions (Fichera et al., 2017; Röck et al., 2020). Although these figures can vary substantially between cities and geographical contexts (Dhakal, 2010), such high levels of energy consumption and emissions mean

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that decarbonizing the residential and commercial building sectors would be crucial for the ongoing urban climate change mitigation efforts (Ke et al., 2024).

At the same time, the heat-absorbing properties of buildings' mass and the impervious surfaces in (and around) them, combine with the generally low green space coverage to generate very diverse urban sustainability challenges. These include Urban Heat Island (UHI) effects (Sharma et al., 2016), local microclimate changes (Alexandri and Jones, 2008; Santamouris et al., 2018), reduced indoor thermal comfort (Santamouris et al., 2018; Mutani and Todeschi, 2020), reduced urban air quality (Grimmond, 2007; Kumar et al., 2016), reduced water runoff quality (Li and Babcock, 2014), urban flooding (Miller et al., 2023; Huang et al., 2020), biodiversity loss (Lepczyk et al., 2017; IPBES, 2019 Murray et al., 2019; Kaiser et al., 2016), noise pollution (Dzhambov and Dimitrova, 2014; Van Renterghem, 2018), and overall decreases in the subjective wellbeing and mental health of urban residents (Aries et al., 2010).

Increasing urban green space coverage can ameliorate many of these challenges and enhance urban sustainability more broadly (Mihalakakou et al., 2023). However, several factors constrain the expansion of conventional green spaces in many cities, including locked-in infrastructure, limited space availability, and high costs (Haaland and van den Bosch, 2015). Such constraints have prompted alternative approaches to urban green spaces expansion, such as green roofs, considering that roofs constitute 20–30 % of urban surface space (Org et al., 2009; Langemeyer et al., 2020) and remain largely unused (Liberalesso et al., 2020).

Green roofs are defined as vertical vegetation systems on rooftops, which typically comprise various layers including a root barrier, drainage layer, filter fabric, growing media, and vegetation (Whittinghill and Rowe, 2012). Some green roofs may utilize pre-fabricated growing modules or vegetated mats (Ampim et al., 2010).

Green roofs are generally divided into three main types: extensive, semi-intensive, and intensive green roofs. Extensive roofs contain shallow substrates (<15 cm), which makes them lightweight, low-maintenance, cost-effective, and easily retrofitted onto existing buildings (Shafique et al., 2018a, 2018b). Extensive roofs often use hardy Sedum plants (Morakinyo et al., 2017). Semi-intensive roofs have deeper substrates, require irrigation, and are heavier (Cascone et al., 2018). They can support diverse plants ranging from grasses to shrubs, but generally require maintenance (Peng and Jim, 2013). Intensive roofs, resemble urban parks and support a wide range of plants, including trees (Zhang and He, 2021). They have deeper substrates (>15 cm) and require irrigation, which makes them the costliest and heaviest types of green roofs, needing rigorous building assessments for retrofitting (Bianchini and Hewage, 2012). Due to their favorable characteristics, extensive green roofs are currently the most commonly adopted type in practically all geographical contexts (Getter et al., 2007; Elliott et al., 2016).

Green roofs have been linked to many benefits for urban sustainability. For example, green roofs can contribute to urban climate change mitigation by reducing energy consumption in buildings (Susca, 2019), and storing carbon in their biomass and soil (Rowe and Getter, 2015). Green roofs can also regulate effectively temperatures in urban areas (reducing UHI effect) (Imran et al., 2018), around individual buildings (Yin et al., 2019), and inside individual buildings (Gagliano et al., 2015). Green roofs can also mitigate air and noise pollution by intercepting and filtering atmospheric pollutants (Yang et al., 2008; Currie and Bass, 2008; Speak et al., 2012; Nowak et al., 2014) and enhancing sound insulation (Van Renterghem, 2018). Green roofs can also reduce urban flood risks and improve water runoff quality by intercepting and storing runoff in soil, coupled with evapotranspiration (Stovin et al., 2012a, 2012b). Additionally, they can trap particulate matter, heavy metals, and nutrients in plant root systems and aboveground plant tissue (Li and Babcock, 2014; Gong et al., 2019). Green roofs also create pockets of habitat on rooftops for diverse plant species, which, in turn, attract insects, birds, and other wildlife, collectively benefiting urban biodiversity (Madre et al., 2014; Joimel et al., 2018; Yıldırım and Özden, 2018). Lastly, similar to urban green spaces, green roofs can reportedly contribute to the well-being of urban residents (Wang et al., 2016).

When looking critically at these very diverse green roof benefits, it becomes obvious that many are directly linked to the urban climate, either by mitigating climate change or by regulating urban micro-climates. These climatic benefits are mainly associated with temperature regulation (Cascone et al., 2019), reduction of energy consumption and GHG emissions (Gagliano et al., 2017), and carbon sequestration and storage (Kristin et al., 2009). By offering such climatic benefits, green roofs have the potential to support urban decarbonization efforts (Saadatian et al., 2013). However, green roofs also offer many non-climatic benefits, which are mostly associated with improving urban ecosystem quality (Wooster et al., 2022), enhancing human wellbeing (Lee et al., 2015), and mitigating air/water/noise pollution (Stovin et al., 2012a, 2012b; Van Renterghem and Botteldooren, 2014; Jayasooriya et al., 2017). These non-climatic benefits improve the quality of life in cities and contribute to urban sustainability, without directly impacting the climate. Arguably, the potential of green roofs to provide such diverse climatic and non-climatic benefits makes them a promising component of urban sustainability and decarbonization strategies.

Despite extensive research on green roof benefits in the past decades, there are some notable gaps in the academic literature. First, there is a dearth of comprehensive systematic reviews that synthesize the knowledge about all major green roof benefits, especially across the different dimensions of climatic and non-climatic benefits. Existing systematic reviews have focused on single benefits such as stormwater management (Czemiel Berndtsson, 2010), energy savings (Li and Babcock, 2014), biodiversity (Wang et al., 2022a, 2022b), or subsets of benefits (e.g. Francis and Jensen, 2017). More importantly, such syntheses often fail to differentiate clearly benefit delivery accross green roof type (e.g. intensive, extensive) and evidence type (e.g. experimental studies on real roofs, modeling/simulation studies). Second, despite the fact that some have studies identified the possible climatic benefits of green roofs (e.g. Shafique et al., 2020) there are still gaps about the potential contribution of green roofs to decarbonization efforts for the residential and commercial sectors. The need for this type of evidence has recently become particularly important considering the growing trend of urban policies that mandate green roofs in numerous cities (Liberalesso et al., 2020; Venter et al., 2021).

This study aims to address these knowledge gaps by synthesizing the current literature across the full scale of climatic and non-climatic benefits of green roofs, for different green roof types. In particular, we conduct a comprehensive systematic review of the peer-reviewed literature across eleven benefit categories. First, we outline the methodology of the systematic literature review (Section

2). Then, we present the main literature patterns for these climatic and non-climatic benefits, emphasizing the underlying mechanisms, extent of benefit provision, and comparisons between green roof typesand underlying methodologies where available (Section 3). Lastly, we distill the key findings about green roof benefits (Section 4.1), before critically discussing some of the challenges related to the study of green roof performance (Section 4.2), and the priority areas for future research (Section 4.3).

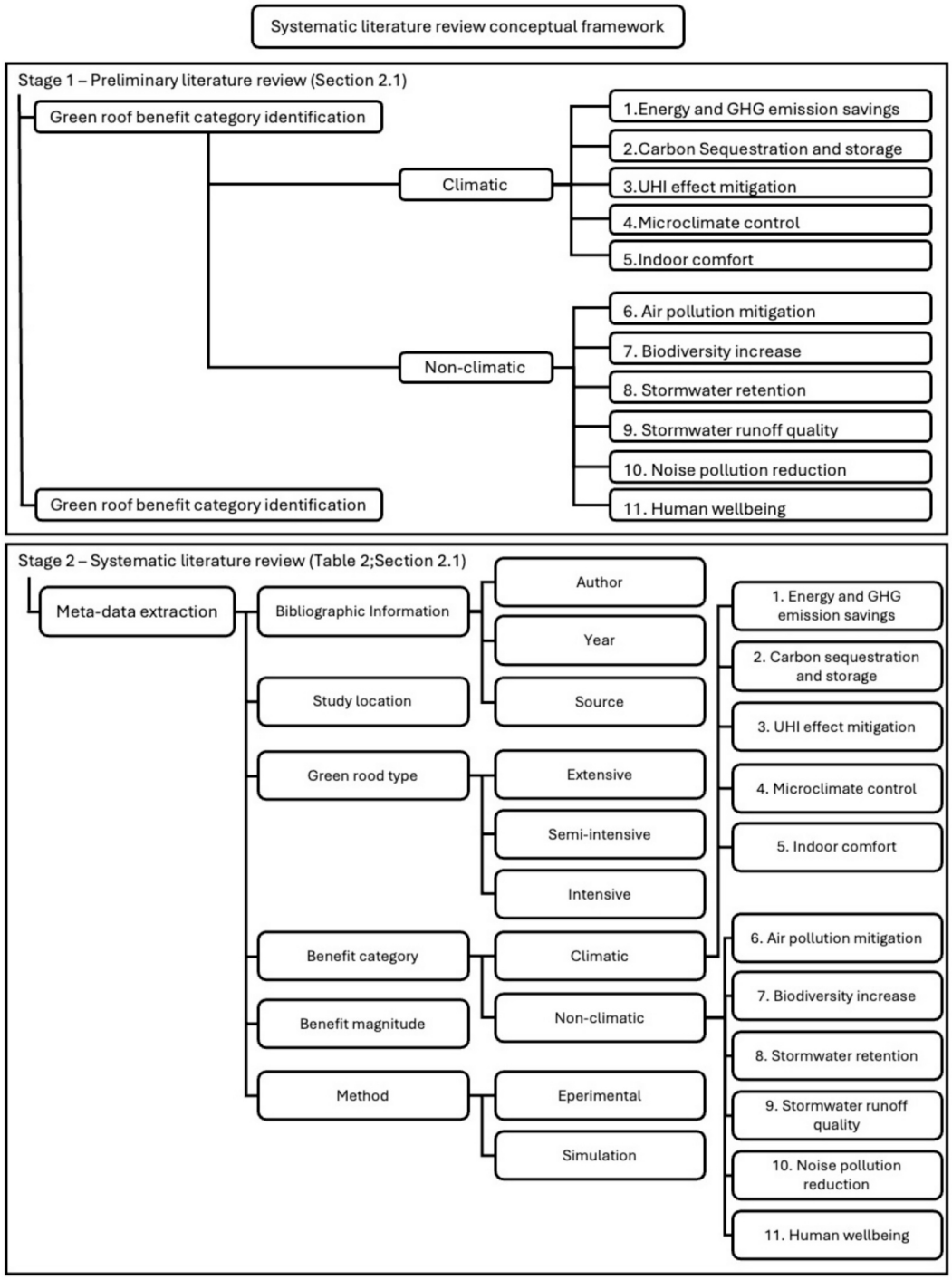

Fig. 1. Conceptual framework of the systematic literature review.

2. Methodology

Fig. 1 summarizes the conceptual framework of the systematic review, including the approach, tasks and the main type of elicited information. Overall, we employed a two-stage process for the systematic literature review.

The first stage entailed a preliminary review (Fig. 1) to (a) identify the pertinent climatic and non-climatic benefits offered by green roofs, and (b) to determine the keywords and search terms for the subsequent systematic literature search for each specific benefit. This preliminary review was conducted in December 2019 in Scopus, and in January 2020 in Web of Science. To capture the widest possible literature, the search terms were simply "green" and "roof" for the title and abstract of peer-reviewed articles. Based on the critical reading of this literature we consolidated the green roof benefits discussed in the literature into 11 benefit categories (see Fig. 1), which were the eventual focus of the systematic literature review. Through this process, it became apparent that these 11 benefit categories could be further categorized into benefits that are directly related to climate change mitigation (climatic), and benefits that contribute to other areas of urban sustainability (non-climatic).

The second stage entailed the formal systematic literature review and the elicitation of relevant information (Fig. 1). For this, we followed the process outlined in the PRISMA 2009 guidelines for literature identification and inclusion (Moher et al., 2009). Initially, we conducted in March 2020 a literature search in Scopus and Web of Science for each of the 11 individual climatic and non-climatic benefit categories, using the keywords and inclusion/exclusion criteria outlined in Tables 1 and 2 respectively. The literature search in Scopus returned 3387 manuscripts and in Web of Science 4353, for a total of 7740 manuscripts. After removing duplicates, we conducted the first screening by reading abstracts for relevance. This first screening resulted in 785 publications, which were fully read and filtered based on the set of specific inclusion and exclusion criteria during the second screening process. Three of these inclusion/exclusion criteria were the same for all studies, while some were specific for some benefit categories. Table 2 outlines the general and specific inclusion criteria. During this second screening process, we also identified an additional 71 publications in the references of the reviewed studies that were not identified during the search in Scopus and Web of Science. We fully reviewed these studies as they met the general and specific inclusion/exclusion criteria.

In February 2023 we conducted a second search in Scopus and Web of Science using the same keywords and inclusion/exclusion criteria to cover studies published since the first search. Upon concluding this second search and screening process following the same approach outlined above, we ended up with a total of 386 publications. The full list of studies included in the systematic review is included in the reference list of the supplementary material. The studies considered in each benefit category are included in the Supplementary Dataset, which outlines the meta-data extracted for each study. Fig. 2 contains the number of studies included and excluded at every stage of the systematic review.

From these 386 publications, we extracted six main meta-data categories (Fig. 1). The meta-data included the (a) bibliographic information (e.g. authors, year), (b) study location, (c) green roof type (i.e. extensive, semi-intensive, intensive, multiple), (d) benefit

Table 1
Keywords, sources and number of studies included in the final analysis for each benefit category.

Benefit category	Benefit	Keywords	Studies from initial search		Studies after duplicate removal and abstract screening	Studies identified from other sources	Studies included in final analysis
			Scopus	Web of Science			
Urban climatic benefits	Energy and GHG emissions savings	green AND roof AND energy AND reduction	1879	2221	134	21	69
	Carbon sequestration and storage	green AND roof AND carbon AND sequestration AND uptake	56	77	54	4	16
	UHI effect mitigation	green AND roof AND urban AND heat AND island AND effect AND UHI	191	161	70	7	45
	Microclimate regulation	green AND roof AND microclimate	201	262	29	1	11
	Indoor comfort	green AND roof AND indoor AND thermal AND comfort	148	525	53	0	24
	Air pollution mitigation	green AND roof AND air AND pollution AND quality	124	132	34	0	17
Non-climatic co-benefits	Biodiversity increase	green AND roof AND biodiversity AND habitat	296	346	112	12	35
	Stormwater retention	green AND roof AND rain AND retention AND stormwater	302	351	145	11	83
	Stormwater runoff quality	green AND roof AND rain AND quality AND stormwater AND pollution	69	121	74	3	38
	Noise pollution mitigation	green AND roof AND surface AND noise	88	94	88	1	17
	Human wellbeing	green AND roof AND health AND wellbeing	33	13	21	13	27

Table 2
General and specific inclusion and exclusion criteria for the systematic literature review.

Category of criterion	Type of criterion	Inclusion criteria	Exclusion criteria
General	Publication scope	Publication related only to green roofs benefits	Publications unrelated to green roofs benefits or using combined roof technologies
	Publication source	Peer-reviewed journals	Reports, books, conference proceedings
	Publication language	Publications in English	Publications in other languages
Specific	Carbon sequestration	CO_2 reduction based on air pollution	CO_2 reduction based on energy savings
	UHI mitigation	Discrete temperature reduction	Unclear temperature reduction results
	Air pollution mitigation	Discrete reduction of air pollutants	CO_2 reduction
	Biodiversity increase	Quantified species increase; studies on urban areas	No species quantification; Studies on urban areas
	Stormwater retention	Studies on green roof stormwater retention	Studies considering only substrate retention; unclear results
	Noise pollution reduction	Studies on green roofs	Studies on roof walls or roof vegetable gardens
	Indoor comfort	Studies on green roofs	Studies on bare roofs

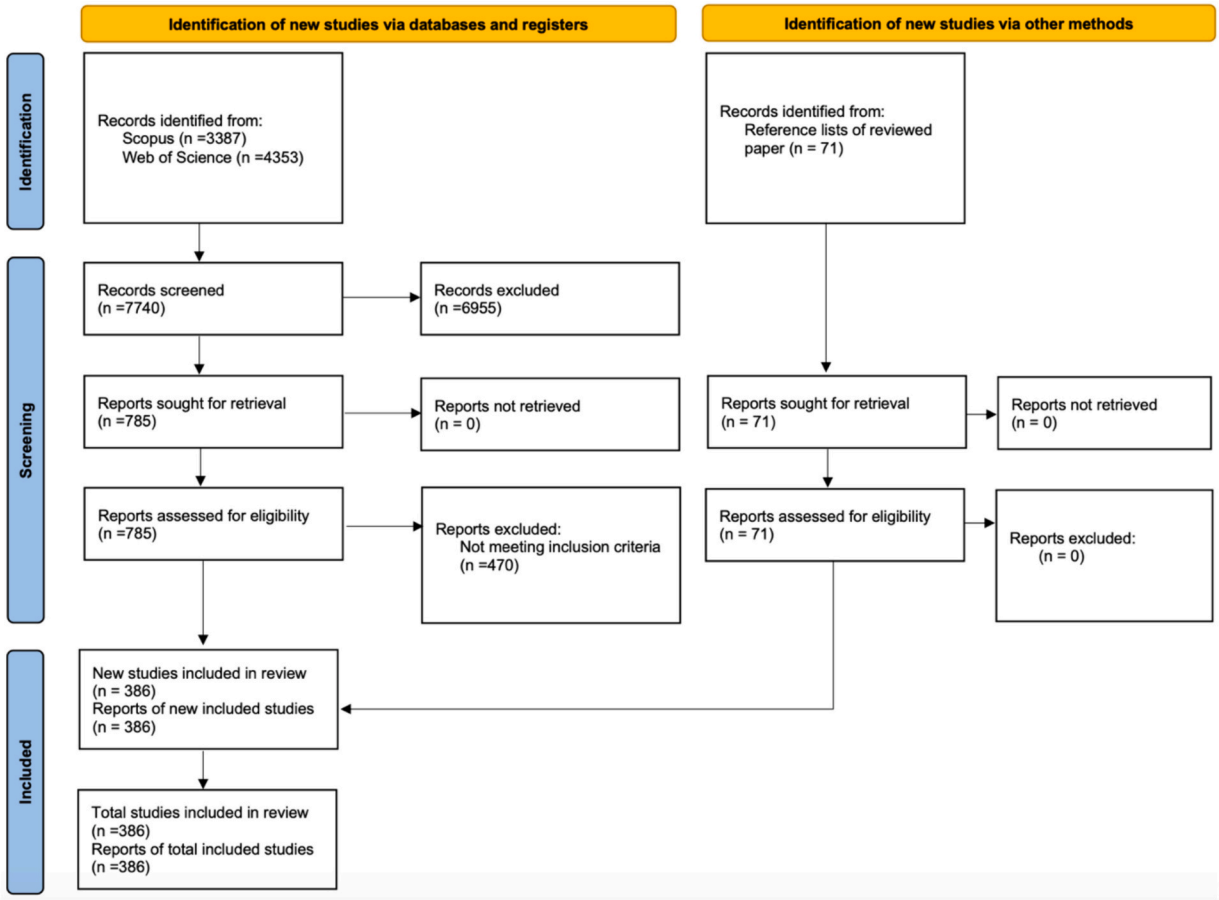

Fig. 2. PRISMA 2009 Flow diagram of the systematic literature review.

category, (e) benefit magnitude, and (f) type of methodology (e.g. experimental, modeling). For (e), if available, we elicited directly the numerical values of each benefit category as presented in the results of each reviewed study. However, whenever the results of studies were not directly available but were only presented in tables or figures, we used WebPlotDigitizer to extract the data for the benefit magnitude. The extracted meta-data for the benefit parameters varied between and within benefit categories and is included in Tables S.1-S.11 in the Supplementary Material.

The first author read the studies and did the meta-data extraction for all studies, following agreement between all authors about the

meta-data categories and elicitation procedure. For a few cases that meta-data extraction was not clear or straightforward, the first author consulted the other authors to obtain consensus on how the specific meta-data should be extracted, coded and analyzed.

3. Results

3.1. General characteristics of reviewed studies

The 386 studies considered here were published between 2000 and 2022 (Fig. 2) and represent very diverse geographical regions worldwide (Fig. 3). In these 22 years, green roof research has gradually become more sophisticated and has covered an ever-increasing number of parameters that affect the provision of the different benefits. These include, among others, the plant species and substrate layers of the green roofs, as well as different soil combinations and construction materials. More complex models are gradually used to simulate plants and their physicochemical properties in terms of thermal conductivity, evapotranspiration rates, moisture content and Leaf Area Index (LAI) (Table S.1 Supplementary Material). Among the 11 benefit categories considered here, the more studied have been temperature reduction (especially in regard to UHI effect mitigation) and energy savings. Stormwater retention has been the second most studied benefit category, considering that urban flooding is one of the major hazards that many cities face. The least studied benefit category is human wellbeing, with only four studies covering this aspect.

The mobilized research approaches and methods also vary substantially between benefit categories. For example, the vast majority of temperature- and energy-related studies rely heavily on modeling, while studies on carbon sequestration/storage and biodiversity mostly rely on real-world experiments and observations on experimental green roofs. Modeling approaches also dominate studies that extrapolate benefits to larger scales.

In terms of green roof types, approximately 80 % of the reviewed studies focused on extensive green roofs (e.g. sedum), whereas much fewer studies focused on semi-intensive (e.g grass) and intensive (e.g. shrubs, trees) green roofs. Finally, the reviewed research on green roofs disproportionally focused on the Global North (Fig. 4), specifically Western Europe ($n = 118$), the United States ($n = 73$), and the UK ($n = 20$). Focal countries from the global South include mainland China ($n = 49$) and Brazil ($n = 12$) (Fig. 3).

3.2. Urban climatic benefits

3.2.1. Energy and GHG emission savings

We reviewed 69 studies on the energy-saving potential of green roofs. Fig. S.1 (Supplementary Material) shows the geographic distribution of these studies, while Table S.2 (Supplementary Material) the actual studies and elicited meta-data. Among these, 56 % of the studies examine experimental green roofs, 30 % use modeling approaches, and 15 % combine experimental data with modeling. In addition, 72 % of the studies investigate extensive, 17 % intensive, and 11 % both extensive and intensive green roofs. The overwhelming majority of these studies demonstrated that green roofs can reduce the energy demand of buildings, with only a single exception that estimated a marginal (1 %) increase in demand (Kolokotroni et al., 2016).

The first mechanism through which green roofs contribute to energy savings is by providing an extra insulation layer and decreasing heat fluxes through the roof. Essentially, the layers of substrate and vegetation on the roof act as a thermal barrier, reducing heat transfer from the interior to the exterior environments and vice versa. This benefit is mostly observed in uninsulated roofs, typically found in older buildings (Castleton et al., 2010). The plant cover ratio of the roof plays an important role in this process, e.g. Teemusk and Mander (2009) estimate a minimal roof surface temperature decrease (by 9 %) to a low green roof cover (45 %).

The second mechanism is by decreasing roof surface temperature amplitudes through roof albedo effects, which are typically higher than conventional roofs. Saadatian et al. (2013) estimate higher albedos from green roofs (0.7–0.85) compared to bitumen and

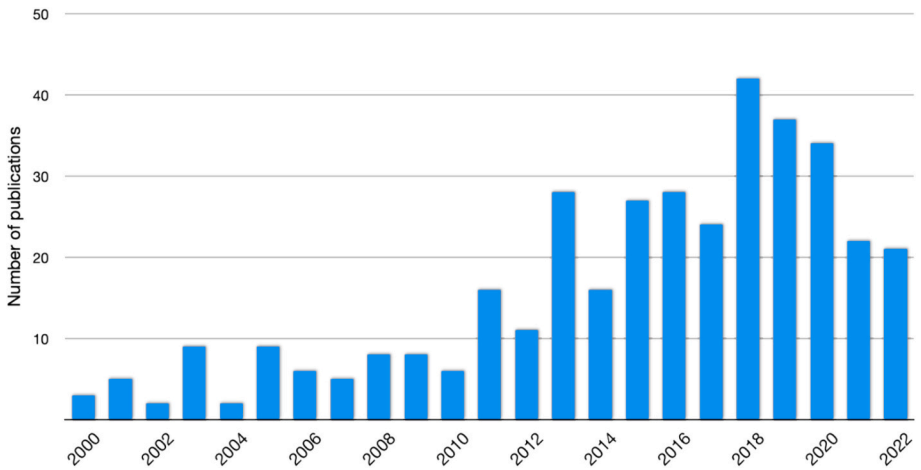

Fig. 3. Number of reviewed studies per year of publication (2000−2022).

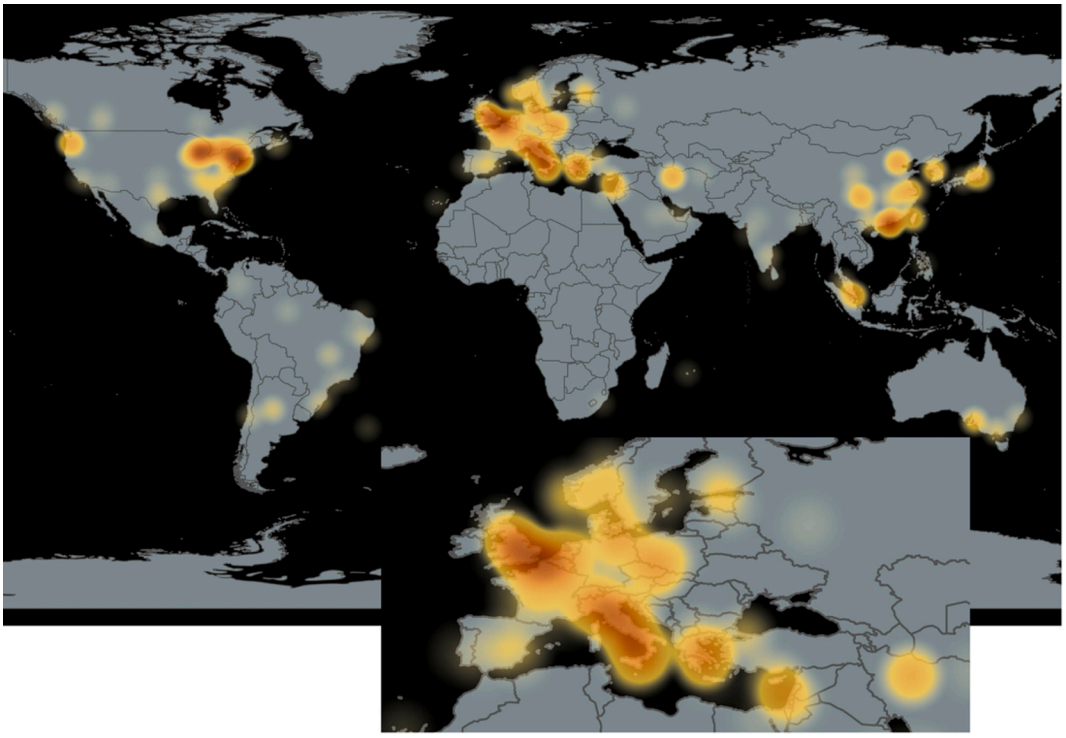

Fig. 4. Heatmap of the global distribution of reviewed studies.

gravel roofs (0.1–0.2). Among the numerous studies showing the considerable decrease in surface temperatures on green roofs due to albedo effects, D'Orazio et al. (2012) found a maximum surface temperature reduction of 50 °C compared to a conventional roof.

The local climate also seems to play an important role in green roofs' ability to reduce energy demand. For example, Berardi (2016) modeled the performance of an extensive Sedum-type green roof in Toronto (Canada) estimating a small reduction in building energy demand (by 3 %), compared to a more significant reduction (47 %) in the hotter climate of Sicily (Gagliano et al., 2017).

The average reduction in building energy demand in the reviewed literature was 22 % (Table 3). However, we should note the great variability depending on the building and roof construction parameters, the climate zone and even the research approaches. Regarding the latter, experimental studies estimate an average energy demand reduction of 2.25 % for extensive and 14 % for intensive green roofs, while modeling studies estimate respective decreases of 25.5 % and 10 %.

3.2.2. Carbon sequestration and storage

We reviewed 16 articles on the carbon sequestration potential of green roofs, of which 82 % focused only on extensive green roofs. This was the only benefit category where all studies were conducted on experimental green roofs. Fig. S.2 (Supplementary Material) shows the geographic distribution of these studies, while Table S.3 (Supplementary Material) the actual studies and elicited meta-data.

The main mechanism through which green roofs directly mitigate CO_2 emissions is through sequestering and storing carbon in both plants and soil (Kristin et al., 2009). Carbon dioxide is removed from the air through photosynthesis and is then stored in the plant biomass and soil.

Sedum-type vegetation is most commonly used in extensive green roofs due to its high resistance to drought conditions (Yamori et al., 2014). This type of vegetation has evolved to open its stomata at night when the environment is cooler (Herrera, 2009), and as a result, its photosynthetic capacity is limited to nighttime (Durhman et al., 2006). These plants have developed a succulent morphology characterized by larger photosynthetic cells with extensive vacuoles to store more carbon to overcome this limitation (Starry et al., 2014). Sedum plants sequester carbon through Crassulacean Acid Metabolism (CAM) photosynthetic pathways; however, CAM-type plants sequester far less carbon, half to 1/3 that of non-CAM type vegetation (Kristin et al., 2009). This is one of the reasons why

Table 3
Average energy demand reduction potential by green roofs in the reviewed literature.

Energy demand reduction	Experimental studies		Modeling studies	
	Extensive	Intensive	Extensive	Intensive
Average	2.25 %	14 %	25.50 %	10 %
Average among all studies	22 %			

Sedum-type extensive green roofs perform worse than intensive green roofs.

The timeframe of the majority of studies on sedum ranges from two months to two years. One exception is a five-year study by Konopka et al. (2021), which reveals variable sequestration rates depending on yearly rainfall and ranging between 95 g C m^2 /y and 189 g C m^2 /y. On average, sedum-type green roofs sequestrate 1.819 kg of $CO_2/m^2/y$.

In contrast, the limited number of studies on semi-intensive and intensive green roof types shows a much higher average potential for sequestration of 11.566 and 20.038$kgCO_2/m^2/y$ respectively.

3.2.3. UHI effect mitigation

The literature review for UHI mitigation covered 45 studies. Fig. S.3 (Supplementary Material) shows the geographic distribution of these studies, while Table S.4 (Supplementary Material) the actual studies and elicited meta-data. Among these, 71 % used a modeling research approach, 20 % utilized small-scale experimental green roofs, and the remaining 9 % a combination of the two.

One of the mechanisms through which green roofs mitigate the surface UHI effect is evapotranspiration in which plants absorb significant energy which is then released into the atmosphere as water vapor (Cascone et al., 2019). Additionally, green roofs provide added shading and insulation to building rooftops, hence reducing the amount of solar radiation absorbed, and consequently re-released by buildings (Jaffal et al., 2012). This is further enhanced by their higher albedo compared to conventional roofing materials (Chen and Zhang, 2018). Most studies indicate that green roofs can reduce roof surface temperature and that this effect extends beyond the roof surface area hence contributing to lowering the ambient temperatures at a wider scale (Imran et al., 2018).

The maximum roof surface temperature reduction can be up to 66 % compared to conventional roofs (Liu and Baskaran, 2003; Jaffal et al., 2012). Reductions scale up linearly depending on the roof coverage percentage, however, there seems to be a required minimum of 40 % for extensive, 30 % for semi-intensive, and 20 % for intensive roof coverage in order to get any ambient temperature reduction on a wider scale that goes beyond the roofs (Li et al., 2014; Žuvela-Aloise et al., 2018; Imran et al., 2018).

Two studies by Djedjig et al. (2015) and Morakinyo et al. (2017), indicate an opposite, slight warming effect by green roofs during nighttime, potentially contributing to the worsening effect of surface-level UHI considering it is more pronounced during nighttime. However, other studies showed that this nighttime temperature increase can be avoided by irrigating the green roofs (Huttner et al., 2008; Yang and Bou-Zeid, 2019; Wang et al., 2022a, 2022b).

While the results between modeling, experimental, and mixed studies show variance in roof surface temperature reductions, it does not seem to be significant. In addition, it does not seem to vary based on the climate of the research area, as is the case with other temperature-related benefits (e.g. energy reduction). For example, Klein and Coffman (2015), found a 1 °C ambient temperature reduction on an experimental extensive green roof in Norman Oklahoma. Peng and Jim (2013) modeled intensive and extensive green roofs in Hong Kong, showing a respective 0.7 and 1.7 °C ambient temperature decrease around the green roof. More recently, Tewari et al. (2019), used a single-layer urban canopy model in Phoenix, Arizona, and New York City, USA, and found that irrigated green roofs can essentially cancel out the surface-layer UHI effect with respective 1.5 and 2.5 °C roof-level temperature decreases.

On average, the reviewed studies show that retrofitted green roofs with a coverage of 80–100 %, can mitigate surface-layer UHI by 0.96 °C if they are extensive, and by 1.06 °C if they are intensive.

3.2.4. Microclimate control

In total 11 studies were included in the literature review, indicating that research on this benefit is somewhat limited. Fig. S.4 (Supplementary Material) shows the geographic distribution of these studies, while Table S.5 (Supplementary Material) the actual studies and elicited meta-data. Of these 10 % were experimental and 90 % used modeling approaches. 64 % focused on extensive type green roofs, and 36 % on the intensive roof type.

The main mechanism here relates to the ability of a green roof to reduce temperatures in the surrounding areas of the building they are installed (Peng and Jim, 2013). Usually, these studies have focused on temperature effects at the pedestrian level, and despite the comparatively small number of studies, the results indicate that green roofs have a limited ability to reduce pedestrian-level temperatures.

Yin et al. (2019) found that a Sedum-type green roof in Nanjing, China, reduced pedestrian level temperatures by 0.09 °C during the day, and by 0.15 °C at night. In the same study, an intensive green roof achieved a reduction of 1.1 °C. Smalls-Mantey and Montalto (2021) found a similar reduction of 0.91 °C by a similar green roof in New York, USA. Taleghani et al. (2016) studied a semi-intensive green roof in El Monte, California, USA, and recorded pedestrian-level daytime temperatures reduced by 0.2 °C.

The average temperature reduction at the pedestrian levels among all studies was 0.4 °C for extensive and 0.56 for intensive green roofs. While the number of studies is limited, all of them showed the potential for a small improvement in microclimate control, with intensive green roofs achieving the highest numbers.

3.2.5. Indoor comfort

We identified 24 studies related to the indoor comfort benefit category, out of which 9 were on extensive, 14 on semi-intensive, and 7 on intensive green roofs. Table S.6 (Supplementary Material) shows the actual studies and elicited meta-data.

The potential of green roofs to reduce temperatures is among the most researched aspects of the literature. Indoor comfort refers to green roof temperature reductions achieved in the inside spaces of buildings and specifically the floors directly under a green roof. Cooling effects can be felt up to two floors under a green roof retrofit (Berardi, 2016).

Similarly to the previous climatic benefits, the mechanisms through which green roofs enhance indoor comfort are decreasing roof surface temperature amplitudes and acting as an additional insulation layer, effectively reducing heat transfer through the roof thereby improving overall thermal comfort within the adjacent space (Jim et al., 2022).

The indoor cooling effect of green roofs appears to depend on the insulation of the roof of the building. Gagliano et al. (2015) investigated the indoor comfort provision potential of an extensive, Sedum-type green roof in three cases of a non-insulated, averagely insulated, and well-insulated roof. According to the studies, the roof provided an indoor temperature reduction of 3.2 °C in the room directly below the non-insulated roof, 3.1 °C in the room below the averagely insulated one, and 3 °C in the room below the well-insulated roof.

One of the major focuses of research for green roof indoor comfort is climate change. For example, Kaboré et al. (2020) simulated the climate conditions for the year 2080 in Marseille and Paris, France. In their study, a Sedum-type green roof retrofit resulted in a 4.6 % temperature reduction for the current and 4.3 % for the 2080 climate conditions in Marseille. Paris showed much higher values with 14.6 % for the current and 8.1 % for the 2080 simulated climate conditions. Guattari et al. (2020) recorded indoor temperatures lower by 4.13 °C in indoor temperatures under a semi-intensive grass-type green roof compared to the reference roof. Interestingly, this study also investigated winter, finding indoor temperatures higher than 5.19 °C compared to the reference roof. In Klang Valley, Malaysia, Rahman et al. (2022) found a semi-intensive grass-type green roof to achieve indoor ceiling temperatures of 19.1 °C, while the reference roof recorded 49.4 °C. Pandey et al. (2013) recorded an average of 4 °C lower indoor temperatures in an intensive roof retrofit study, with outside air temperatures as high as 40.9 °C.

Among all climates included in the reviewed studies, on average, extensive Sedum-type green roofs can reduce inside air temperatures by 1.95 °C, semi-intensive by 3.85 °C, and intensive by 1.6 °C. Results seem inconsistent and might be attributed to the limited research on intensive green roofs. These averages show the potential for green roofs to offer benefits of indoor comfort during warm temperatures, however, given the limited number of studies the values of indoor temperature reduction remain somewhat inconclusive for intensive green roofs.

3.3. Non-climatic co-benefits

3.3.1. Air pollution mitigation

We reviewed 17 articles related to air pollution mitigation. Among the reviewed studies, 56 % are experimental, 31 % use modeling, and 13 % use mixed research approaches. In addition, 75 % focus on extensive, 19 % on intensive, and the remaining 6 % on both types of green roofs. Fig. S.5 (Supplementary Material) shows the geographic distribution of these studies, while Table S.7 (Supplementary Material) the actual studies and elicited meta-data.

One of the mechanisms mediating this benefit category is that plants absorb gaseous pollutants through their leaf stomata where they are diffused, and a portion of gaseous pollutants can be permanently removed through metabolic pathways (Nowak, 2006; Nowak et al., 2014). A second mechanism relates to the ability of plants to intercept pollutants, such as particulate matter, through dry deposition (Petroff et al., 2008; Nowak et al., 2013; Salmond et al., 2016). In the reviewed literature, green roofs were shown to have the ability to reduce five types of pollutants namely NO_2, O_3, PM10, SO_2, and PM2.5. However, not all studies investigate all of these pollutant types.

For Sedum-type green roofs, Speak et al. (2012) conducted an experimental study in Manchester, UK, which found that a Sedum-type green roof removed 0.42 g of PM10 per m^2 of green roof per year. More recently, Arbid et al. (2021) found that an extensive Sedum-type green roof in Paris, France, reduced air pollution by 0.9 g of NO_2 and 1.36 g of O_3 per m^2 per year in their experimental study.

Concerning grass-type green roofs, Currie and Bass (2008) used a modeling approach that revealed that 360 g of PM10, 520 g of O_3, 260 g of NO_2, and 100 g of SO_2 of pollutants per m^2 per year could be removed from grass green roofs in Toronto, Canada. A short grass green roof study in Chicago, USA, by Yang et al. (2008) found a much lower pollution mitigation potential of 4.49 g of O_3, 2.33 g of NO_2, 0.65 g of SO_2, and 1.12 g of PM10 per m^2 per year.

As for intensive green roofs, they seem to have a similar ability to remove air pollutants to the other types. Jayasooriya et al. (2017) quantified the ability of an extensive green roof in Melbourne, Australia, to mitigate air pollution, resulting in a reduction of 0.377 g of NO_2, 0.10 g of SO_2, 1.53 g of PM10, 0.05 g of PM2.5, and 1.24 g of O_3 per m^2 per year. Banirazi Motlagh et al. (2021) modeled an intensive type of green roof which showed a reduction of 10.52 g of PM10 per m^2 of green roof per year.

Table 4 summarizes the average pollution mitigation potential per type of pollutant and green roof. As described earlier, the results between experimental, modeling, and mixed studies are somewhat inconsistent. However, all studies indicate that semi-intensive and intensive green roofs have a higher ability to remove air pollutants than extensive green roofs do. As indicated in the results, however, O_3 reduction for the intensive roofs is considerably lower which can be attributed to the limited number of studies. Therefore, caution should be exercised in generalizing these results as more research is needed.

3.3.2. Biodiversity increase

We reviewed 35 articles associated with the biodiversity benefit category. All studies were performed on experimental green roofs, out of which 70 % were on extensive, 7.5 % semi-intensive, and 22.5 % intensive roofs. Fig. S.6 (Supplementary Material) shows the geographic distribution of these studies, while Table S.8 (Supplementary Material) the actual studies and elicited meta-data.

The main mechanism reflects the ability of green roofs to essentially provide habitat for different plant species, insects, birds, and other wildlife, considering that cities are generally characterized by low green space coverage and a high proportion of paved areas (Madre et al., 2014; Joimel et al., 2018). A related mechanism is the ability of green roofs to connect fragmented habitats, and thus create habitats and corridors for the movement of insects, birds, and other species (Braaker et al., 2014).

Studies have compared green roofs with different comparative bases (e.g. green spaces, empty roofs) and for different species and environments. Overall, the reviewed literature indicates that urban biodiversity gains from green roofs can depend upon several

Table 4
Average air pollution mitigation potential by green roof type.

Type of roof	NO_2 reduction (g m^2y^{-1})	O_3 reduction (g m^2y^{-1})	PM10 reduction (g m^2y^{-1})	SO_2 reduction (g m^2y^{-1})	PM2.5 reduction (g m^2y^{-1})
Extensive	1.13	1.36	0.42	N/A	N/A
Semi-Intensive	440.8	262.2	62.1	50.3	N/A
Intensive	420.8	3.52	370.6	53.6	0.785

factors such as distance to green spaces, habitat quality and roof size.

When comparing green roofs with actual urban green spaces on the ground level, the biodiversity outcomes are somewhat mixed. Two main variables are usually investigated: (a) species density (i.e. population sizes of the same species), and (b) species richness (i.e. number of different species). Schrader and Böning (2006) reported that collembolan species densities and richness in extensive green roofs in Hannover (Germany) were within the range reported for urban soils at ground level. MacIvor and Lundholm (2011a, 2011b) compared insect diversity between an intensive green roof and ground-level grassy patches with trees, finding no significant difference in species density and richness. Braaker et al. (2017) compared extensively managed green roofs with extensively managed ground-level sites, finding significantly higher species richness on ground sites, but no significant difference in functional density. Bergeron et al. (2018) compared several Sedum-type and grass-type green roof designs, finding on average two times higher carabid densities on ground sites, but no significant differences in species richness.

When comparing green roofs with conventional empty roofs, the results show overwhelming biodiversity gains. Wooster et al. (2022) found that their studied green roof supported significantly higher avian, arthropod, and gastropod diversity, compared to an equivalent conventional roof (even attracting even some locally rare species). Partridge and Clark (2018) investigated the density and richness of birds and arthropods between several sedum-type green roofs and an equivalent concrete roof, finding not only higher species density and richness, but also offering habitats to birds during migration seasons. Deng and Jim (2017) studied the potential of all three major green roof types in attracting resident and migrant species and for spontaneous plant species colonization, finding that all three roof types support plant and bird communities compared to empty roofs. Interestingly, in this study, extensive and semi-intensive roofs attracted two times more bird species than intensive roofs (Deng and Jim, 2017).

Habitat fragmentation is one of the major barriers to urban biodiversity proliferation. Green roofs can become part of this fragmented green infrastructure and therefore provide minimum potential for biodiversity increase (Hanski et al., 2004). However, distance to existing green areas plays an important role a green roof's ability to do so. Aloisio et al. (2020) in a study on green roofs in New York City, found that for plant diversity as much as 80 % of the variation in species richness was due to the proximity to green areas within 100 to 200 m of the green roofs. Verticality also seems to have a similar effect. Fabián et al. (2021) suggest that both horizontal and vertical isolation negatively affects arthropod richness in green roofs. MacIvor and Ksiazek (2015) indicate that the height of a building could potentially be another barrier contributing to fragmentation as some species are unable to reach certain heights despite the green roof being on a building adjacent to a park. In the same study mentioned earlier, Wooster et al. (2022) concluded that in their studied green roof on a six-story building, the establishment of species could have been greater if the green roof was located on a building with fewer floors.

Another factor affecting a green roof's ability to contribute to urban biodiversity increase is poor habitat quality (Tscharntke et al., 2002). Gonsalves et al. (2022) investigated the effect of green roof design on beetle biodiversity. Their results showed higher species richness on a roof with a more diverse design, having varying substrate depths and varying layers of vegetation compared to a simpler green roof design. Ksiazek-Mikenas et al. (2019) concluded in their study that the commercially propagated green roof plants offer poor habitat for genetic diversity and long-term population stability of plant species (Ksiazek-Mikenas et al., 2019).

Finally, as is the case with other benefits, the size of a green roof is an important factor of habitat provision for biodiversity increase (MacIvor and Ksiazek, 2015). In the previously described study of Fabián et al. (2021) in Argentina, species density and richness were considerably greater on bigger green roofs. Kyrö et al. (2020) conclude that their studied green roof failed to establish a grasshopper population because it was isolated from other green spaces and more importantly, it was not of large enough size.

3.3.3. Stormwater retention

We reviewed 83 studies on stormwater retention, of which 72 % are experimental, 2.5 % use modeling, and 20.5 % use a combination of modeling based on smaller-scale experiments. Overall, 86.2 % are on extensive roofs, 11.5 % on intensive roofs, and only 2.3 %, on semi-intensive green roofs. Fig. S.7 (Supplementary Material) shows the geographic distribution of these studies, while Table S.9 (Supplementary Material) the actual studies and elicited meta-data.

The literature suggests that green roofs mitigate urban flood hazard through two main mechanisms. First, they can reduce runoff volume by either completely retaining rainfall during smaller precipitation events, or by reducing runoff volume through considerable rainfall retention during heavier precipitation events (Carson et al., 2013; Kuoppamäki, 2021). Second, during heavier precipitation events green roofs reduce peak flow rates delaying overflow, and hence, not overburdening urban drainage systems (Moran, 2005; Johannessen et al., 2018).

The characteristics of a green roof as well as the intensity of rainfall affect its potential to retain rainwater. Green roofs reduce runoff through interception by plants, evapotranspiration, and infiltration and storage in soil (Stovin et al., 2012a, 2012b). Older roofs have been found to retain a greater amount of runoff (Getter et al., 2007) making them a long-term investment for urban stormwater management. An overreaching consensus throughout the literature is that green roofs are indeed effective in attenuating runoff, with

retention of 100 % in cases of lighter rain events or preceding dry weather (Moran, 2005; Carter and Rasmussen, 2006; Mentens et al., 2006; Villarreal, 2007). Getter et al. (2007) recorded a water retention of 94.2 % during light rain events, and 63.3 % during heavier rain events. In contrast, Zhang et al. (2015) found an average retention of 3.69 % on an asphalt roof.

The climate in the region where a green roof is located also affects its water retention ability. They appear to work best in summer or hotter climates providing higher water retention due to higher evapotranspiration rates in warmer temperatures (Moran, 2005). Among the literature, the Köppen classification Csa climate, characterized by hot, dry summers or the Mediterranean climate, has the highest average potential of 73 % rainwater retention. The second best performance is for Dwa climate, characterized by warm to hot summers and cold winters, or the Humid Continental climate, with an average retention of 69.6 %. The lowest recorded retention rate had an average of 56.8 % in Dfb climate zones which are characterized by warm summers and cold winters. See Table S.10 in the supplementary material for the rainwater retention rate per publication and climate zone.

On average, extensive green roofs retain 59.9 % of rainwater, while 68.8 % is retained by intensive green roofs. While there are variations depending on the intensity of the rain event, or the climate zone at the roof`s location, they do not exceed 10 %. This shows that both extensive and intensive green roofs can contribute to rainwater retention and hence have the potential to mitigate urban fluvial flooding and alleviate the strain on urban water systems.

3.3.4. Stormwater runoff quality

We reviewed 38 studies regarding the ability of green roofs to mitigate rainwater pollution. Fig. S.8 (Supplementary Material) shows the geographic distribution of these studies, while Table S.9 (Supplementary Material) the actual studies and elicited meta-data.

The main mechanism here is that green roofs mitigate stormwater runoff pollution by acting as a physical barrier, trapping and retaining particulate matter, heavy metals, and nutrients from the vegetation and the substrate layers (Gong et al., 2019). However, the effectiveness of green roofs in reducing pollutants in rainwater runoff is variable. Certain studies have shown that green roofs reduce pollutants and others show that they can increase certain pollutants. This depends on several factors, including the type of pollutant. The reviewed literature focused on three main pollutants, namely phosphorus, nitrogen, and heavy metals.

When it comes to phosphorus, its concentrations can be significant in rainfall, but also in the green roof substrate for the fertilization of plants. In this sense, green roofs can act as a source of phosphorus pollution (Czemiel Berndtsson, 2010). Green roofs are commonly installed with commercial soil and plants, both of which are fertilized to ensure plant survival and optimal coverage (Li and Babcock, 2014). Older green roofs have been shown to leach lower phosphorus amounts due to the gradual washing of initial fertilizers over time (van Seters et al., 2009). According to Carpenter et al. (2016), some extensive Sedum-type green roofs can have almost double the total phosphorus concentration in runoff compared to precipitation and an 84 % retention capacity compared to a reference roof (97.6 % mean retention capacity during the non-growing season, and 74.5 % during the growing season). Speak et al. (2014) found an intensive green roof to have half the concentration of Phosphorous compared to a reference roof. Ferrans et al. (2018), on the other hand, found that an extensive Sedum-type green roof had a substantially higher concentration of total Phosphorus of 4.06 mg/l, compared to the 0.08 mg/l of the control case.

Similar findings are also observed for nitrogen concentration in runoff, which usually presents as ammonium nitrogen and nitrate nitrogen (Li and Babcock, 2014). Carpenter et al. (2016) compared the total nitrogen concentration from the green roof discharge with rainwater. They found a concentration of 168.8 μmol/l, several times higher than the concentration in the precipitation of 52.6 μmol/l. Gong et al. (2019) found that in several Sedum-type roofs in Beijing China, concentrations of Nitrogen ranged from 8.4 to 13.6 mg/l in the green roof, and 7.1 mg/l to 5.3 mg/l in the reference roof, depending on the volume of rainfall. In contrast, Setters et al. found a 15 % decrease in total Nitrogen concentration when comparing a semi-intensive green roof to a reference roof. Speak et al. (2014) found that an intensive green roof reduced the concentrations of total Nitrogen by up to 64.4 % in rainwater. The reference roof in the same study had up to 142.4 % increased concentration compared to rainfall.

When it comes to heavy metals, the majority of studies favor green roofs, suggesting that they serve as a sink for heavy metals and suspended solids. Green roofs absorb significant quantities of heavy metals by assimilating them in both their root systems and aboveground plant tissue (Li and Babcock, 2014). Linden and Stone (2009) found a Sedum-type extensive green roof to have lower concentrations of suspended solids, averaging 5.6 mg/l compared to the 8.3 mg/l in the reference roof. Okita et al. (2018) studied an extensive Sedum-type green roof and found that it retained more than 3 times as much Zinc compared to the reference roof, as well as lower concentrations of Copper. In their study, Gnecco et al. (2013) observed that a Semi-intensive Grass-type green roof served as a sink, retaining roughly 60 % of Zinc and about 10 % for suspended solids. van Seters et al. (2009) identified lower concentrations of 69.5 % for Zinc and 53 % for Lead, in the runoff of a semi-intensive grass-type green roof compared to that of a reference roof. Speak et al. (2014) compared an intensive green roof to a reference roof finding significantly lower concentrations in Iron (40 %), Lead (76 %), and Zinc (93 %) in the green roof.

Overall, the retention of pollutants in stormwater by green roofs is unclear in the reviewed literature when it comes to Phosphorus and Nitrogen. Estimating any average reduction or increase would be of no substantial use. However, when it comes to the reduction of heavy metals, the majority of studies clearly show that green roofs can serve as sinks for several of these elements.

3.3.5. Noise pollution reduction

The systematic review included 14 publications on green roofs' ability to mitigate noise pollution. The number of studies is limited, but it is noteworthy that 5 of these studies were conducted by the same researchers in the same location. Of these, 45.4 % of studies were experiments on existing green roofs, 27.3 % used a modeling approach, and 27.3 % used a mixed approach. The overwhelming majority of green roofs investigated were extensive (91.6 %), and only 8.4 % were intensive. Fig. S.9 (Supplementary Material) shows the geographic distribution of these studies, while Table S.11 (Supplementary Material) the actual studies and elicited meta-data.

The main mechanism mediating noise pollution mitigation relates to the fact that green roofs essentially alter urban surfaces and act as sound-absorbing materials, reducing substantially urban noise pollution[1] levels in some cases (Dzhambov and Dimitrova, 2014).

Van Renterghem conducted several studies on the ability of green roofs to reduce noise pollution. In their 2018 study, they found that an extensive green roof can reduce the noise from traffic by 3 dBA compared to a reference roof. Yang et al. (2012) had previously found a 4dBA reduction by a semi-intensive grass-type green roof. In 2009, Van Renterghem suggested no significant difference in noise attenuation between extensive and intensive green roofs, or their different substrate depths when it comes to smaller green roof sizes. However, Galbrun and Scerri (2017) found that in a lightweight building, a Sedum-type green roof reduced the sound infiltration by 3 dBA, while a semi-intensive grass-type green roof by 7 dBA. Van Renterghem and Botteldooren (2014) found that there was a correlation between noise level reduction and the proportion of green roofs in the area, hinting at potentially larger reductions with larger roof sizes.

In the reviewed literature, there is a potentially positive contribution to noise pollution reduction by green roofs. On average, extensive green roofs decrease the noise propagation in a surrounding area by 3.4 dBA, semi-intensive roofs by 8.9 dBA, and intensive roofs by 8.9 dBA.

3.3.6. Human wellbeing

Although the preliminary literature review identified that this benefit category is often mentioned in the green roof literature, the deeper screening of the literature indicated rather minimal deep research on the topic. In fact, following the screening, we identified only 4 publications exploring in depth the wellbeing benefits of green roofs after engagement or use. These publications solely focused on the direct exposure, visual or physical, or use of green roofs and did not include the health benefits (hypothesized or observed) that can potentially stem from temperature and pollution reduction (e.g. Clark et al., 2008; He et al., 2020).

The underlying mechanisms here can be very diverse and context-specific, but always reflect to some degree the ability of greenery to contribute positively to some aspect of human wellbeing after exposure and/or use during everyday activities.

For example, Loder (2014) found that: (a) green roofs that break the monotony of concrete roofs provide work-related stress relief to study participants, (b) green roofs in closer proximity and at eye level have a more significant impact on stress relief, (c) grass-type green roofs had betters stress-relief effects than more popular Sedum-type roofs. Williams et al. (2019) similarly found that study participants preferred semi-intensive and intensive green roofs to Sedum in terms of psychological effects. Rezaei et al. (2021) associated green roof visits with stress alleviation and tension relief to study participants, who also indicated a higher interest in the wellbeing benefits of green roofs compared to other benefits such as biodiversity increase, water management, and noise and air pollution mitigation. A study by Lee et al. (2015) investigated the influence of views of green roofs compared to the concrete roof on office workers. They found that even 40-s breaks with the views on green roofs had a positive effect on the ability of workers to sustain attention.

4. Discussion

4.1. Knowledge synthesis about green roof benefits

4.1.1. Superior performance of intensive green roofs across most benefit categories

The findings of the systematic review indicate that intensive green roofs perform better than extensive roofs across most of the benefit categories considered here, both climatic and non-climatic.

Notable examples include energy and GHG emission savings, UHI effect mitigation, air pollution mitigation, rainwater retention, microclimate control, noise pollution reduction, and indoor comfort improvement. For instance, semi-intensive and intensive green roof systems, on average, sequester 11.57 and 20.04 kg of $CO_2/m^2/y$, respectively (Section 3.2.2), significantly outperforming extensive Sedum-type green roofs, which, on average, sequester 1.82 kg of $CO_2/m^2/y$. Similarly intensive green roofs on average reduce the surface-layer UHI effect by 1.06 °C when retrofitting 80–100 % of roofs in a given area (Section 3.2.3), while for the same extent of deployment, extensive green roofs reduce the surface-layer UHI effect by an average of 0.96 °C. Furthermore, semi-intensive and intensive green roofs have a greater potential for air pollution mitigation. Semi-intensive roofs remove on average per square meter per year, 440.8 g NO_2, 262.2 g O_3, 62.1 g PM10 and 50.3 g SO_2 (Section 3.3.4), while Sedum-type extensive green roofs remove on average 1.13 g NO_2, 1.36 g O_3, and 0.42 g PM10 per square meter of roof per year.

The factors seemingly influencing this better performance primarily relate to substrate depth and the Leaf Area Index (LAI)[2] of plants (Chan and Chow, 2013; Gomes et al., 2019; Jamei et al., 2021). Deeper substrates tend to provide better insulation properties and more storage capacity (Zhang et al., 2019; He et al., 2020), while higher LAI is associated with wider plant cover and therefore better cooling properties of foliage (Pérez et al., 2022).

On the one hand, intensive roofs are characterized by deeper substrates (Section 1), and thus naturally offer superior benefits. Such

[1] There are different sources of urban noise pollution. First, the most prevalent construction materials in cities (e.g. glass, concrete, steel), are rigid and more reflective, therefore amplifying ambient noise levels (Van Renterghem, 2018). Second, the high proportions of densely built-up areas in cities, and the abundance of high-rise buildings, further exacerbate noise reflectivity (Van Renterghem, 2018). Third, increases in urban population and high concentration of traffic in cities, has increased levels of noise pollution (Van Renterghem and Botteldooren, 2009).

[2] The Leaf Area Index (LAI) is defined as leaf density within a land surface or canopy area. Generally, higher LAI is associated with wider plant cover and less exposed soil (Mahmoodzadeh et al., 2019), and better cooling properties of greenery (Pérez et al., 2022).

an example is stormwater retention, as the volume of retained water is directly correlated with the storage capacity of soil (Speak et al., 2013; Zhang et al., 2019). Moreover, it is also important for the carbon sequestration benefit as increased substrate depths facilitate more extensive root growth, directly correlating with a higher capacity for carbon storage (Wan Ismail et al., 2019).

On the other hand, intensive green roofs can accommodate a wider variety of plants in terms of species and size and thus tend to have generally higher LAI (Gomes et al., 2019). Here, a higher LAI essentially implies a larger surface area for the interception and storage of air pollutants (Bianchini and Hewage, 2012; Shafique et al., 2018a, 2018b).

For some benefits, it is the combined effect of deeper substrates and higher LAI that contributes to higher benefit delivery. One such example is the energy reduction of buildings where deeper substrates provide higher insulation resulting in reduced energy consumption for heating and cooling (Jaffal et al., 2012). Furthermore, a higher total leaf area per unit of the ground surface further improves roof thermal performance through shading (Gomes et al., 2019).

A notable exception is stormwater quality, in that the current findings for this benefit category are mixed. Here water runoff quality highly depends on the initial nutrient concentration in the green roof soil (Czemiel Berndtsson, 2010). Intensive green roofs require higher fertilization levels to sustain the growth of their diverse range of plants and ensure their survival (Green Roofs | Soil Science Society of America, 2024). By virtue of their deeper substrates and wider plant variety as discussed above, intensive green roofs generally exhibit less favorable outcomes for rainwater runoff quality compared to extensive roofs (Marín et al., 2023). However, recent research increasingly explores various substrate materials and soil compositions to mitigate this issue (Vijayaraghavan and Raja, 2014; Kuoppamäki et al., 2016).

Another notable exception relates to biodiversity increase. Here, connectivity to other green areas, both in terms of distance and verticality (Tonietto et al., 2011), is the primary factor influencing green roof performance in terms of urban biodiversity improvement. In general, more isolated green roofs have a lower number and diversity of visiting species such as insects or birds (Partridge and Clark, 2018), regardless of the type of roof itself and the plants it harbors. For instance, Tonietto et al. (2011) found a positive correlation between bee abundance and species richness, and the extent of green space in the vicinity. They noted a greater abundance of bees and species richness in areas with higher proportions of the surrounding greenery, while isolated roofs exhibited lower counts.

Despite the apparent advantages of intensive green roofs for most benefit categories, much less research has been conducted for this type of green roof compared to extensive roofs. This is mainly because intensive green roof implementation has sometimes prohibitively high costs (Sailor, 2008; Theodoridou et al., 2017) and more stringent structural requirements (Kristin et al., 2009; Berardi), which makes it more complex and thus less prevalent. In this sense, although lower, the evidence of the benefits of extensive green roofs can be arguably seen as more robust due to its broader representation both in research and real-world implementation.

4.1.2. Incomplete evidence for human wellbeing benefits

Green roofs are sometimes presented as a possible alternative and/or complement to conventional urban green spaces (Shafique et al., 2018a, 2018b; Shin and Kim, 2019). This is often argued across the lines of the challenges of green space expansion within some cities and the potential of green roofs to provide wellbeing and health benefits (Manso et al., 2021; Ode Sang et al., 2022; Rahman et al., 2023). For instance, green roofs can offer retreats from the bustling city (Rezaei et al., 2021), or create spaces that enhance social cohesion (Jennings and Bamkole, 2019; Green Roof Policy - Copenhagen, 2023). As a result, many cities have included green roofs in their urban policies, citing such possible wellbeing benefits as one of the justifications (Green Roof Policy - Copenhagen, 2023; Up on the roof - Eurocities, 2023).

During the preliminary literature review to identify benefit categories and keywords (Section 2), well-being emerged as a frequently used term to describe the benefits of green roofs. However, we could only identify four studies that delved deeper into the wellbeing benefits of green roofs (Loder, 2014; Lee et al., 2015; Williams et al., 2019; Rezaei et al., 2021). These studies identify different mechanisms through which exposure and use of green roofs can have positive outcomes on human wellbeing, including through stress relief (Loder, 2014; Rezaei et al., 2021) or restorative health outcomes (Loder, 2014). Interestingly, these benefits do not seem to only emerge through the actual use of green roofs (e.g. Rezaei et al., 2021), but also through visual exposure (Williams et al., 2019). These reflect several of the mechanisms mediating the positive human wellbeing outcomes of exposure and use of urban green spaces identified in the considerable literature on the topic (Dzhambov and Dimitrova, 2014; Jabbar et al., 2022; Nieuwenhuijsen, 2021).

Although it is likely that such human wellbeing benefits might manifest through exposure and use of green roofs, the fact remains that the current evidence base is rather incomplete and fragmented. It is not uncommon for the existing arguments about the possible health and human wellbeing benefits of green roofs to be extrapolated from studies from conventional green areas or urban parks (e.g. see Manso et al., 2021 arguing for such potential benefits drawing from (Kabisch et al., 2017) or (Hedblom et al., 2019).

4.1.3. Possible contribution for urban decarbonization

Our findings suggest that green roofs can play some role in urban decarbonization efforts, particularly by improving building performance. Leibowicz et al. (2018) identify three main pathways to urban building decarbonization: (a) enhancing construction efficiency through sustainable materials and practices, (b) improving appliance efficiency, and (c) enhancing thermal efficiency.

Green roofs can be particularly valuable for the latter pathway through three distinct mechanisms. First, green roofs can improve the thermal properties of buildings by providing an extra insulation layer that acts as a thermal barrier, diminishes heat transfer by reducing the heat flux through the roof, and ultimately creates energy savings from reduced space heating and cooling (Castleton et al., 2010; Gagliano et al., 2017). Second, and related to the first mechanism, by creating this insulation layer and minimizing heat transfer through the roof, green roofs can enhance overall indoor thermal comfort, again reducing the need for space cooling and heating (Moghbel and Erfanian Salim, 2017). Third, green roofs can affect urban microclimates, effectively lowering temperatures around the

buildings where they are installed through multiple mechanisms such as cooling through evapotranspiration (Susca et al., 2011) and considerably lowering roof surface temperatures (Liu and Baskaran, 2003; Jaffal et al., 2012). If employed on a large scale, through these mechanisms green roofs can contribute to the UHI effect mitigation, again having important mitigating effects on building energy use for space cooling and heating (Li et al., 2014; Imran et al., 2018). A fourth mechanism through which green roofs can contribute directly to urban decarbonization is by sequestering and storing atmospheric carbon in plants and soil (Heusinger and Weber, 2017) (see Section 3.2.2).

As outlined throughout this review and in Section 4.1.1, intensive and semi-intensive green roofs tend to have the highest positive outcomes for all these mechanisms (direct sequestration/storage, UHI effect mitigation, reduced energy demand and GHG emissions, and increased thermal comfort), and thus hold the greatest potential for urban decarbonization.

4.2. Challenges for performance validation

Despite the likely benefits of different green roof types and designs across the diverse benefit categories explored here, there are substantial challenges hindering their on-the-ground performance assessment and large-scale implementation. This is true not only for the generally costlier and more complex intensive green roofs, but oftentimes also for the simpler extensive green roofs that have accounted for the bulk of studies reviewed here.

Most studies on intensive green roofs and a considerable fraction of studies on extensive green roofs tend to be limited to small-scale experimental modules (e.g. Ismail et al., 2012; Agra et al., 2017) rather than established full-scale installations on buildings. However, there are some notable examples for real-life implementation studies for extensive roofs (e.g. MacIvor and Lundholm, 2011a, 2011b; Madre et al., 2014; Squier-Babcock and Davidson, 2020), and intensive roofs (Wei Wang et al., 2017; Belcher et al., 2019). Considering this limited real-world availability of intensive green roofs, most studies have explored their performance through simulations and modeling instead rather than experimental studies (e.g. Jayasooriya et al., 2017; Knaus and Haase, 2020). For instance, energy performance assessments of green roofs involve aspects such as the physics of heat flux through buildings (Kolokotsa et al., 2013; Costanzo et al., 2015), which has contributed to the higher prevalence of modeling studies (e.g. Ascione et al., 2013; Battista et al., 2016). In particular, of the studies reviewed here, 51 % of studies on energy savings, 80 % of studies on UHI mitigation, and 90 % of studies on microclimate regulation employed either pure modeling or modeling based on some field measurements. A notable outlier is the microclimate control benefit category (Section 3.2.4), where 90 % of the reviewed studies used an experimental approach.

Overreliance on modeling studies might end up in overestimating the performance of green roofs for some benefit categories. For example, there is a discrepancy between experimental and modeling studies for energy demand decrease (Section 3.2.1), with the former estimating an average reduction of 2.25 % for extensive and 14.5 % for intensive green roofs, and the latter a respective reduction of 24 % and 10 %.

Aligned with the above points, numerous modeling studies have suggested that the benefits of green roofs would likely increase with large-scale implementation and upscaling (Imran et al., 2018; Žuvela-Aloise et al., 2018). However, it is arguably challenging (if not impossible) to validate such recommendations through large-scale experimental studies. For example, mitigating the UHI effect through the large-scale implementation of green roofs cannot be feasibly tested experimentally on a large scale due to the extensive resources and logistical challenges it would entail. In this sense, there is a need to be both cautious and convey the inherent uncertainties when discussing the performance of large-scale green roof implementation, as well as (at least some) green roof types and designs.

4.3. Knowledge gaps and future research

The previous sub-sections have outlined some major knowledge gaps, and particularly the (a) unclear performance of intensive green roofs (Section 4.1.1), (b) unclear evidence about the mechanisms and magnitude of human wellbeing benefits (Section 4.1.2), (c) unclear understanding of their urban decarbonization potential (Section 4.1.3), (d) overreliance on simulation and modeling (Section 4.2), and (e) inability to predict properly the benefits of large-scale green roof implementation (Section 4.2).

Robust empirical research should seek to fill these gaps to establish better the actual potential of green roofs for urban sustainability. Furthermore, studies should adopt a much broader and comparative mindset. For example, research on decarbonization potential should not only consider the direct effects of green roofs on emission mitigation through carbon storage and energy demand decrease, but should consider the full life cycle assessment of green roofs (see Shafique et al., 2020 for a review of life cycle assessment of green roofs) and compare them with other building decarbonization options such as solar photovoltaic panels.

Beyond the above, a more pervasive knowledge gap that underlies practically every green roof type/design and benefit category is the lack of long-term studies evaluating the survivability of green roofs over extended periods, as well as their sustained effectiveness and performance in delivering long-term benefits. Green roofs are essentially a living organism, and their performance might be affected not only by the weather conditions but also by their age. However, most research reviewed here spans from several days (e.g. Molineux et al., 2015; Joimel et al., 2018) to up to three years (e.g. Whittinghill et al., 2014). Among the reviewed studies, the longest monitoring period for a green roof benefit was five years, and concerned carbon sequestration and storage (Konopka et al., 2021). Another relevant knowledge gap associated with this lack of long-term monitoring is our lack of good understanding regarding the performance of green roofs during winter periods when the plants die off or undergo dormancy (Du et al., 2019). Considering, that plants contribute significantly to the overall performance of green roofs across all benefit categories, their seasonality should be understood much better in future research.

Finally, we must point out the relatively limited geographical distribution of green roof studies, with most studies focusing on the

global North (Section 3.1) (see also Blank et al., 2013; Zhang and He, 2021). In tandem, green roofs have gained much more policy attention and traction in the global North considering their promotion and policy integration in cities such as Venice, Tokyo, Hamburg, Hannover, Toronto, and others (e.g. Liberalesso et al., 2020; Jim et al., 2022). However, it is mostly the global South that experiences rapid urbanization and its negative consequences, implying that it is in such developing contexts where green roofs can have major opportunities to enhance urban sustainability if implemented properly. Considering that benefit delivery and the underlying mechanisms can be affected by the prevailing climate, we urgently need studies about green roof benefits and performance from the global South, and especially from areas that experience rapid urbanization and/or extreme climatic conditions.

4.4. Limitations

Despite the large number of studies included in this systematic review and the comprehensive information elicited, there are some limitations that the readers should be aware of when generalizing the findings of the study.

First, we relied only on peer-reviewed literature from academic repositories, despite the fact that information on green roof applications can also be found in grey literature such as government/policy reports, construction and consultancy reports, theses, and other non-peer-reviewed documents. We decided to avoid including grey literature in the systematic review, as there is no central repository where we can systematically identify such studies in a replicable manner. Furthermore, we were concerned about possible biases as many of these reports are written by entities that design and/or implement green roofs. Although we acknowledge that by excluding these studies we do not include some of the current evidence base about green roof benefits, we believe that ultimately this decision enhances the robustness of the underlying evidence and the replicability of the overall protocol.

Second, this systematic literature review relied only on papers published in the English Language. However, green roof studies are also published in other languages including Japanese, Chinese, and Spanish, considering the large number of studies from these countries (Section 3.1). This possibly can lead to the green roof research results not being included, especially those concerning local climates, not being reflected in the results of this study.

Finally, green roof research, as reflected by the results of this analysis, spans a multitude of parameters with a plethora of variables concerning different natural properties. As such, in many instances, it is not possible to normalize the results of reviewed studies in the same units of measurement, complicating the conduction of a proper meta-analysis. This is exacerbated by the existence of studies that do not clearly state the parameters of their experiments, such as green roof substrate depth, plant species, reference roof parameters, and more, making meta-data extraction a challenge and further limiting comparisons between studies. For the same reason, it is not possible to conduct a formal bias analysis.

To overcome such limitations, future comprehensive reviews could potentially capitalize on the advancements in A.I. to incorporate non-English language documents. In addition, future reviews could include findings from non-academic reports and grey literature and compare them with the academic literature. This is because most research on green roofs tends to use unique designs tailored to context-specific conditions, making it difficult to compare results across different studies. This lack of standardization highlights the need for utilizing technical reports of commercially available green roofs in order to get any meaningful comparisons. However, this must be done very carefully to avoid the possible biases mentioned above. Finally, considering the rapid expansion of the relevant literature, future studies should attempt to do proper meta-analyses for all or a subset of the benefit categories, once there is a critical number of publications with consistent and complete parameters.

5. Conclusions

Here, we systematically reviewed 386 peer-reviewed studies to systematize the mechanisms mediating the delivery of eleven climatic and non-climatic benefits provided by green roofs, the extent of benefit delivery, and the factors affecting it. We focused on five climatic benefits (namely energy and GHG emissions savings, carbon sequestration and storage, UHI effect mitigation, microclimate control, and indoor comfort) and six non-climatic benefit categories (namely air pollution mitigation, stormwater retention, stormwater runoff quality, noise pollution mitigation, biodiversity, and human wellbeing).

Approximately 80 % of the reviewed studies focused on extensive green roofs, indicating the strong need for additional research on intensive green roofs. This is further underscored by the (as yet) limited but promising findings that intensive green roofs have generally superior benefit delivery across most benefit categories.

Despite this expanding literature, our study identified several knowledge gaps, and specifically the: (a) lower knowledge base about intensive green roof performance, (b) overreliance on simulations and modeling, (c) unclear understanding of human wellbeing benefits, (d) unclear understanding of urban decarbonization potential (e) inability to predict accurately the benefits of large-scale green roof implementation, (f) lack of long-term studies about green roof effectiveness, performance, and survivability, and (g) lack of studies from the global South and/or areas with extreme climatic conditions.

Overall, our systematic review provided a comprehensive overview of green roof benefits (including some of the less-represented benefits). It offered a holistic perspective to assist policymakers and practitioners in decision-making, offering insights into the full range of benefits and facilitating the selection of effective green roof types for implementation.

CRediT authorship contribution statement

Jelena Aleksejeva: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gerasimos Voulgaris:** Writing – review & editing, Formal analysis, Data curation. **Alexandros Gasparatos:**

Writing – review & editing, Supervision, Resources, Funding acquisition.

Declaration of competing interest

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

Data availability

The meta-data is included in the Supplementary Electronic Material

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Appendix A. Supplementary data

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