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Quantifying the influence of nature-based solutions on building cooling and heating energy demand: A climate specific review

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ABSTRACT

Implementing Nature-Based Solutions (NBS) is a promising way to reduce building energy demand and facilitates the achievement of United Nations Sustainable Development Goal 7, as they provide shading, evapotranspiration cooling and other influences on buildings. Although this field has attracted much attention, uncertainty persists regarding the potential of different NBS types to impact building energy demand in different climate conditions. To clarify this uncertainty, 101 papers were studied based on the Web of Science and Scopus databases. The current status analysis explored the development state of this field. Building energy performance analysis evaluated the potential reduction in cooling and heating energy in different climates by applying different NBS types at building scale. The review revealed that the cooling energy saving potential of NBS varies from 3% to 90%, while the potential reduction in heating energy demand ranges from 0.58% to 60%. The extent of the reduction in both cases is dependent on the NBS type and climate. Notably, some NBS types may lead to an increase in heating energy demand by between 5.9% and 25% in climates with short and mild winters. This review found that maximizing the energy-saving potential of NBS requires a comprehensive consideration of multiple factors rather than maximizing an individual factor. Further, most studies in this field have only concentrated on a few NBS types and climate zones, resulting in significant differences in research depth among different NBS categories. Future work should focus on neglected NBS types and climates to fully understand their energy-saving potential.

1. Introduction

The population of the world will reach 8.6 billion by 2030, of which 61% will live in the cities [1]. The continued growth of the urban population has inevitably driven the urban sprawl, leading to a series of complex problems, such as environmental degradation, increased energy demand, and increased anthropogenic climate change [2]. These issues bring significant challenges to the achievement of the United Nations Sustainable Development Goals (SDGs). However, Wendling [3] pointed out that the further concentration of population in urban areas can bring substantial potential for enhancing sustainability if urban development is carefully managed and resource utilization efficiency is improved.

The core concept of the SDGs is that environmental sustainability serves as a foundation for both economic and social dimensions of development [4,5]. Therefore, environmental sustainability is intertwined and mutually supportive of all 17 SDGs [4]. Nature-Based Solutions (NBS) involve working with nature and enhancing it to address

Abbreviations: NBS, Nature-Based Solutions; SDGs, United Nations Sustainable Development Goals; EU, European Union; HVAC, heating ventilation and air conditioning; LAI, Leaf Area Index; LAD, Leaf Area Density; Cfa, Humid subtropical climate; Csa, Hot-summer Mediterranean climate; BWh, Hot deserts climate; Cfb, Temperate oceanic climate; Dfa, Humid continental climate; Aw, Tropical savanna; Cwb, Subtropical highland climate; Csb, Warm-summer Mediterranean climate; Bsk, Cold semi-arid climate; Dfb, Warm-summer humid continental climate; BWk, Cold desert climate; Dwa, Monsoon-influenced hot-summer humid continental climate; BSh, Hot semi-arid climate; Am, Tropical monsoon climate; Dwc, Monsoon-influenced subarctic climate; Cwa, Monsoon-influenced humid subtropical climate.

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social challenges, which include broad action in protecting, restoring, or sustainably managing ecosystems [6]. NBS are considered an important measure to achieve the SDGs as they emphasize harmony between man and nature, and ecological development, thereby representing a comprehensive, human-centered response to climate change [7]. Increasing the global percentage of renewable energy and doubling the global rate of improvement in energy efficiency by 2030 are the specific goals of SDG 7 [8]. Although renewable energy already accounts for 22% of total energy consumed in European Union (EU) as of 2021, fossil fuels remain the largest energy source [9]. Against this backdrop, the International Energy Agency stressed that building sectors need to be ready for zero carbon by 2030 at the latest, as direct carbon emissions from buildings account for 8% of total emissions [10]. Improving energy efficiency could not only reduce greenhouse gas emissions but also increase the proportion of renewable energy in the energy system.

Over the past decades, an intensive analysis of how to adopt the best technology practices to reduce energy consumption has been conducted from the perspective of the building itself, such as appropriate site selection, rational building form, the design of building envelopes and use of materials with better thermal properties; etc. [11–14]. However, as stated by the International Energy Agency [10], energy efficiency investment incentives to improve building energy efficiency through materials are weakening in many countries as costs of building materials and technological solutions, such as highly efficient and smart system (e.g., HVAC, renewable energy systems) have reached all-time highs. In recent years, NBS has been recognized as an important alternative solution to improving building energy efficiency, as the transpiration, photosynthesis and shading impact of plants could change the thermal environment within a certain range; thereby, influencing building cooling and heating energy demand [14,15]. Moreover, they also provide conditions for the formation of forest-source winds, thereby reducing excess heat and modifying local microclimate [16]. Although a significant amount of papers on NBS can be found in the literature, the number of relevant papers on NBS and building energy demand is relatively small. Therefore, the question “How much building energy can different NBS types save?” is still not easy to answer.

This study aims to evaluate the extent to which different NBS types could reduce cooling and heating energy demand at the building scale in different climates. Based on scientific literature collection and analysis, there are two objectives of this research: (1) to examine the impact of different NBS types on building energy performance in different climate characteristics, and (2) to provide pathways for further research by identifying gaps in the application of NBS types in specific climatic zones.

1.1. The novelty of the current review

To prepare for our review, we looked for other reviews in same field. Table 1 compiles a list of recently published review papers on the themes of NBS and their application in the building sector. Most of these reviews included diverse topics, resulting in varying degrees of novelty. The topics covered in each paper are shown in the table. Although some studies have explored the impact on energy performance of NBS under different climate conditions, they only focus on one category of NBS or are restricted to climate zones in some specific countries or regions. As such, the energy performance of other NBS types under different climatic conditions remains unknown. Additionally, only one research quantitatively analyzes the energy performance of NBS in terms of percentage range, and it only concerns one NBS type. Studies that utilize geographic distribution analysis have also only performed superficial evaluations of the number of publications in each country. Compared to these collected review papers, the novelty aspects of our research could be summarized as follows:

(a) It critically evaluates the energy saving potential of different NBS categories on building energy demand at building scale under

Table 1
The recently published review articles on NBS and building fields.

Reference	Year	Topic covered	Novelty
[17]	2022	Green roofs and their energy, thermal and environmental benefits	• Reviewing the polices, regulations, and laws for green roofs and walls in Mexico • Evaluating the thermal and energy behavior of green roofs and walls in the different climates of Mexico according to the substrate, vegetation and systems configuration
[18]	2022	Green walls systems and building energy efficiency	• Exploring trends in the green walls field of research • Exploring the geographical distribution of studies (most productive countries and most relevant journals)
[19]	2023	Green roofs and their related sustainability (runoff control, urban noise reduction, carbon sequestration, energy conservation)	• Providing a comprehensive critical perspective of the thermal performance modeling of green roofs, and examining the effect of the configuration parameters of the main system on its energy performance and thermal fluxes • Outlining future scientific directions of system engineering applications, providing a comprehensive view of research advancements • Providing a critical presentation of the most important findings regarding the benefits of energy systems, mentioning concurrently the most significant problems, limitations, and assumptions.
[20]	2020	Green roofs and carbon sequestration	• Assessing the direct (storing air pollutants) and indirect (reducing building energy demand) impact of green roofs on carbon emission reduction
[21]	2021	Passive cooling methods and building energy efficiency	• Comparing and analyzing four different passive technologies in terms of economics (initial cost, maintenance cost, and operational cost) for their practicality and effectiveness under arid and warm climates.
[22]	2023	The benefits of vertical greenery technology	• Exploring the focus and key issues of current scholars’ attention on vertical greenery systems, and highlighting future research directions • Systematically analyzing the field of vertical greening, and highlighting the relevant technical and socio-economic benefits
[23]	2021	Green roofs and building energy efficiency in different climates	• Quantitative reports on the energy performance of roof greening under different climates were conducted based on different experimental methods

(continued on next page)

Table 1 (*continued*)

Reference	Year	Topic covered	Novelty
[24]	2021	Green roofs and heat stress mitigation	• Assessing the geographical distribution of studies (publications) • Assessing the cooling potential in three different climates • Investigating elements that affect energy performance of green roofs

different climatic conditions, and it elaborates the energy savings range of different NBS categories in the quantitative format.

(b) It identifies the factors that should be considered to maximize the energy saving potential of NBS.

(c) It provides an investigation on geographical distribution characteristics of current research (e.g., distribution of studies in different climate zones, cities that are frequently examined), and explores the reasons behind it.

(d) It introduces the progress in the field of NBS regarding building energy efficiency, and outlines the research gaps in this field.

2. Literature collection and survey

2.1. Publication collection

NBS was originally utilized to provide advice and suggestions to the field of agriculture, such as pest management [25]. Although the term was proposed in the early 2000s, it was only widely accepted by researchers and scholars after 2013 [26]. As such, this study restricted the time range of data collection from 2013 to 2022. The Web of Science and Scopus databases were used for data collection due to their coverage and because they provide functions to limit searches by search terms, time range; etc. In addition, to determine the appropriate search terms, the study employed the NBS categories that were mentioned and classified by the research of Langergraber [27]. Specifically, they divided NBS into several different functional units, in which the spatial and technological units contain many NBS categories that were significantly relevant to this research field, for example, the technological units have the categories of vertical greening systems and green roofs. Spatial units include green belts, parks, etc. As a result, eight categories under these two functional units, along with the terms of blue infrastructure, green infrastructure and NBS, were used as the search terms by combining each of them with building energy demand or consumption. Thus, the specific search terms were as follows:

• 'Vertical greenery system'	AND 'building energy demand'
• 'Street trees'	AND 'building energy consumption'
• 'Green roofs'	
• 'Gardens'	
• 'Water bodies'	
• 'Urban parks'	
• 'Urban farms'	
• 'Urban orchards'	
• 'Blue infrastructure'	
• 'Green infrastructure'	
• 'Nature-Based Solutions'	

The publications collected by utilizing the above search terms in the Web of Science and Scopus databases were not all entirely within the scope of this study. Therefore, the publications were filtered several times. Finally, the selected publications were analyzed with the help of the bibliographic analysis software VOSviewer.

2.2. Data analysis

Data analysis consisted of two parts. The first part used to explore the current state of the NBS research field. The second was to analyse building energy performance under different climate conditions.

2.2.1. The current state of the NBS research field

The main aim of this analysis was to investigate the current state of the research field, which contains two parts. The study first explored the status of publications in this field, including the annual number of scientific publications and the most relevant sources. The second part was dedicated to exploring the geographic distribution of the studies collected as well as the different climate zones involved in the analyses. According to the World Bank [28], NBS has scale flexibility in its application and could be used from single building to city-wide scales. It was vital to identify the specific types of NBS at the building scale as this study only focuses on building scale energy consumption. To do so, the NBS types used or mentioned by many studies were employed in this research, especially the research conducted by Refs. [28,29]. As such, the research categorized the NBS typologies into different specific types. In addition, so as to quantify the number of studies in each type, the number of each type involved in the collected publications were counted during the process of analysis. Then, the cumulative marks were calculated and visualized in a diagram.

Furthermore, the study also noted and counted the number of experimental or simulation sites and their affiliated countries and climate zones (based on Köppen-Geiger climate classifications) in each paper so as to collect the evidence for analysis of geographic distribution pattern.

2.2.2. Building energy performance analysis

The building energy performance analysis is dedicated to exploring how much energy could be reduced in different climates by applying different NBS types at building scale. The outcomes of each publication usually described a "percentage"; that is, how much energy consumption, sum of the heat fluxes, electricity intensity or energy loads reduced or increased by applying NBS types. Briefly, the changes of energy in these parameters reflect the influence of different NBS types on building energy performance. As noted by Ascione [30], research in this field presents a diverse range of evaluations of building energy performance, however, it would be valuable to study the performance of the whole building heating, HVAC system, or the performance of energy savings. As such, to avoid confusion, papers which only described the energy consumption-related percentage were highlighted and used as the main study objects in this research. Moreover, the saved or increased percentage of energy in each highlighted paper was collected. Then, their percentages were categorized and integrated based on the different climate zones and visualized in the diagrams.

3. Publication collection and overview

A total of 3188 publications were initially found on the Web of Science and Scopus by using the search terms described in Section 2.1. However, after checking the title and abstract of each paper, a significant number of papers concerned topics irrelevant to this research, such as UHI mitigation, HVAC systems, occupant behavior and energy use, etc. Only 116 papers were left after eliminating irrelevant and overlapping papers. In addition, 15 review papers were also eliminated as they could only partially help in the analysis of the geographic patterns or in the identification of the percentage of energy reductions in different climate zones. Finally, 101 papers remained and were studied in detail in this research.

4. Review results

In this section, we first analyse the chronological and thematic distribution of the relevant literature collected and selected from the Web of Science and Scopus. This result provides a first informative overview of the relevance of different NBS regarding geographical importance.

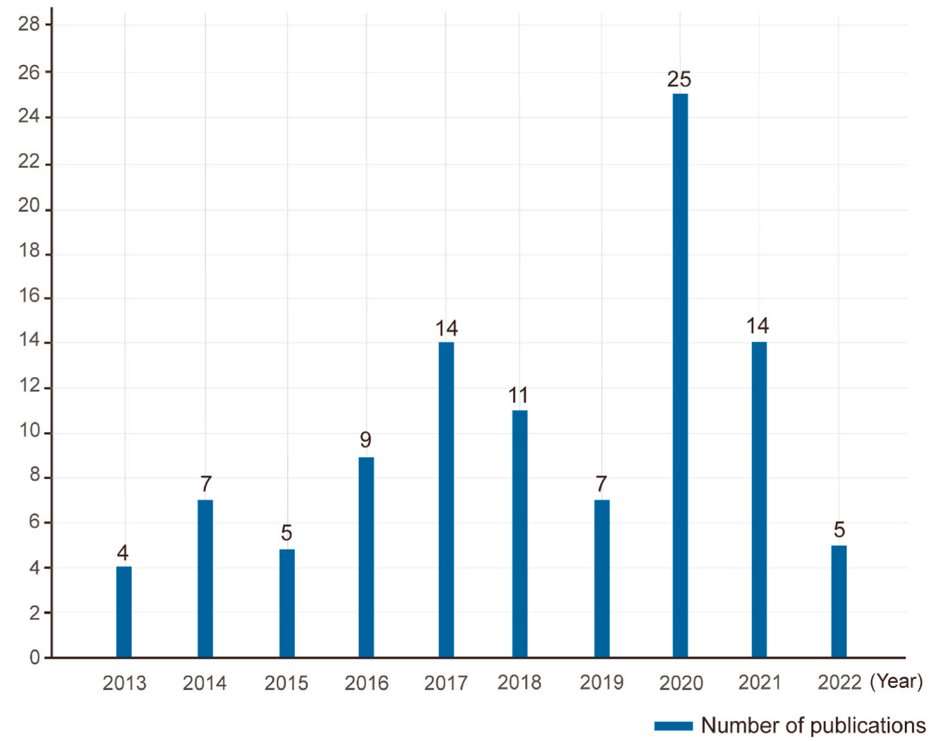

Fig. 1. Annual scientific production from 2013 to 2022.

More deeply, we connect the presented NBS to climatic zones based on geographical location. Finally, based on the detailed literature study, we explain the qualitative impact of NBS on building-scale cooling and heating energy demand in which climatic zone.

4.1. Chronological and thematic summary

Fig. 1 shows the chronological distribution of the identified publications. They fluctuated during the studied time period. The largest number of publications appeared in 2020, taking up over 24.8% of the total number of publications. This phenomenon may be relevant to the 25th UN Climate Change Conference held in December 2019 and the widespread acceptance of climate neutral initiatives around the world in early 2020. For example, in 25th UN Climate Change Conference, the decision 12/CP. 25 highlighted the importance of enhancing investment in "green projects" to reduce carbon emissions [31]. Moreover, the European Commission announced the "European Green Agreement" in early 2020, which emphasizes achieving climate neutrality through some measures, such as improving building energy efficiency, and using clean energy [32]. However, the number of annual publications declined rapidly after 2020. This may be largely related to the COVID-19 epidemic; for instance, some preventive policies or measures may cause inconvenience for extensive data collection and cross-regional cooperation.

As can be seen from Fig. 2, the number of documents varies significantly between different document types, with articles representing the majority of papers. The Journal of Energy and Buildings is most closely linked to this field of research.

Based on the description of Section 2.2.1, the research categorized the NBS typologies into seven different items according to the NBS typologies involved in the collected data, containing green walls, green roofs, trees, urban forests, green belts, mixture of trees, grasses and near the river, as well as water features. The study further divided water features into the types of bioswale, lake, stream, wetland, river and water fountain. Moreover, green roofs were further classified into the types of extensive green roof, semi-intensive and intensive green roof. Similarly, green walls were separated into the types of direct green façade, indirect green façade, living wall, perimeter flowerpots and movable green window system. There is no specific type for the remaining categories.

As for the distribution of publications under the different NBS types, it was found that there are two types of analysis among the collected

• Document types

ARTICLE	85
PROCEEDING PAPER	15
BOOK	1

• The top five most relevant journals

(Name of the Journal)	(Number)
1. ENERGY AND BUILDINGS	23
2. BUILDING AND ENVIRONMENT	12
3. JOURNAL OF CLEANER PRODUCTION	5
4. ENERGIES	4
5. APPLIED ENERGY	4

Fig. 2. Document types and the most relevant resources.

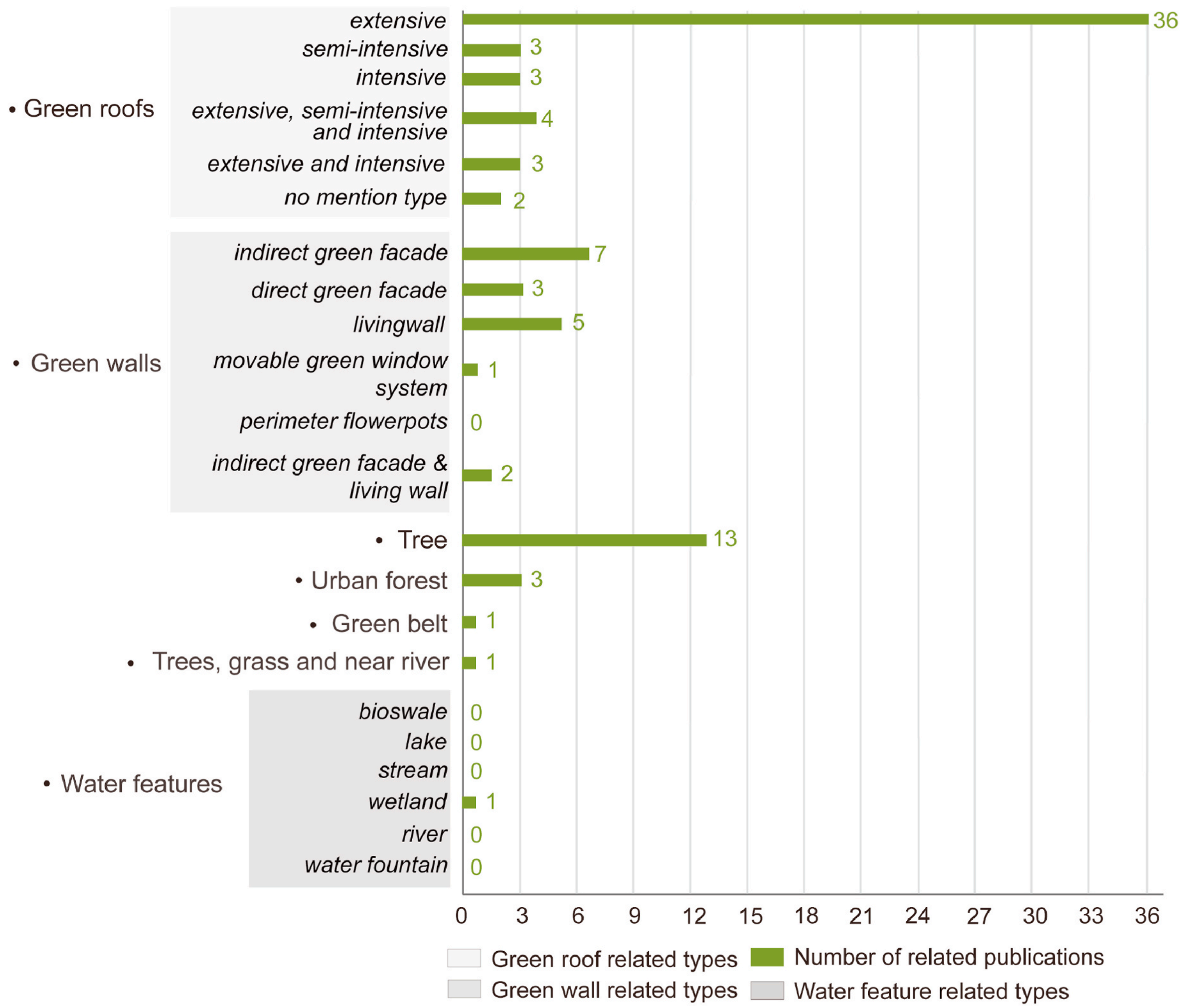

Fig. 3. The number of publications of different NBS types in single type analysis.

publications, including single type analysis (Fig. 3) and different types combination analysis (Fig. 4).

In terms of single type analysis (Fig. 3), it is evident that most of studies concentrated on green roofs and green walls, particularly green roofs. The research of green roofs relates to 51 publications, accounting for 50.5% of total number of collected papers. Among these publications, extensive green roof was frequently studied, featuring in 36 papers. In addition, green walls had 18 papers, of which indirect green façade, direct green façade and living wall represented 7, 3 and 5 papers, respectively. No study related to the type of perimeter flowerpots. 2 studies conducted comparative analysis between indirect green façades and living walls. Furthermore, trees featured in 13 papers, while urban forests only featured in 3. Green belt and the type of mixture of trees, grasses and near river both had only one publication. Notably, among the six specific types of water features, only wetland relevant to one research. This indicates that exploring the impact of blue infrastructure on building energy consumption has not yet attracted widespread attention from scholars.

As shown in Fig. 4, there were 5 types of combination analysis, involving 14 publications. 8 papers have conducted analysis by integrating green roofs with green walls. Among them, the study of combining extensive green roof and living wall had the largest number of publications. Two researches have assessed the influence of integrating green roofs, green walls and trees on building energy demand. However, they did not mention the specific types of green roofs and green walls. In addition, the combination analysis of green roofs and green belt represented 2 articles. The number of publications in the combination study of green roof, green wall, grass and trees was only one. Notably, the type of green roofs was involved in each of the combination analyses. Although the number of studies on combination analysis is limited, the way of integrating different NBS types to assess their impact on building energy demand has begun to attract the attention of scholars.

- Geographic distribution of the current research studies

In this section, the geographic distribution pattern of studies and the main examined climate zones are presented.

Fig. 5 shows that China and Italy rank as the top 2 countries in terms of the number of publications and total citations. The number of documents in these two countries accounts for 43% of the total number of publications (This part is further discussed in Section 5.1). Notably, although Canada published a few papers in this time period, the total citations are higher than in most countries.

Fig. 6 illustrates the geographic distribution of the study sites, in which the circles represent the location, and the size of the circle reflects the number of papers. Similarly, colors signify affiliated climate zones. It is obvious that the majority of studies correspond to the Northern Hemisphere, especially along the Mediterranean Sea, the western United States, the Asian Pacific coast and the Gulf of Mexico as well as the western United States. It is clear that these regions all inhabit large populations and have high building densities. In the continental based

Different types combination	Specific types	Number
Green roofs & green walls	• extensive green roof and living wall	4
	• extensive green roof and perimeter flowerpots	1
	• semi-intensive green roof and green wall (no mention green wall type)	1
	• extensive green roof and green wall (no mention green wall type)	1
	• green roof and living wall (no mention green roof type)	1
Green roofs, green walls & trees	• (no mention green wall and green roof type)	2
Green roofs & green belt	• extensive green roof and green belt	1
	• (no mention green wall type)	1
Green roofs, green walls, grass & trees	• (no mention green wall and green roof type)	1
Green roofs & trees	• extensive green roof and trees	1

Fig. 4. The number of publications in the combination analysis.

analysis, Asia had the largest number of studied sites; followed by Europe and North America. In the city-based analysis, Hong Kong has been frequently investigated, 6 times, ranking first. Cairo, Catania and Rome both have been used as experimental cities 5 times. 4 investigations relate to Nanning and Toronto.

Fig. 7 and Table 2 illustrate the number of study sites in each climate zone and the description of the characteristics of each climate, respectively. The research shows a strong preference toward the climate zones Cfa, Csa, BWh and Cfb. This reveals that scholars currently take cities located in temperate climate zones as the main exploration objects, and the examined climate zones also need to have the characteristics of hot summer. However, the tropical climate groups Aw (tropical savanna climate) and Am (tropical monsoon climate), which are characterized by high temperature throughout the year, have not attracted much attention from researchers.

To sum up, the study found that the research in this field is not only limited in quantity, but also shows an obvious characteristic of a narrow focus. In other words, most of the current studies have focused on certain types and climate zones. To some extent, this leads to a clear gap in research depth between the different NBS types. In addition, compared to the single type analysis, there is only a limited number of studies that conducted combination analysis of different types. This indicates that exploring the influence of different types of combinations on building energy demand has not attracted widespread attention from scholars.

4.2. The result of NBS on building energy performance in different climate zones

In this section, we analyse the selected publications, showing substantial footage regarding climate zone-related NBS impact on building scale energy demand. Moreover, after a detailed investigation of the literature, quantitative assumptions were made to show the overall effect of NBS on building energy performance depending on location. The comprehensive selection of studied publications is listed in Appendices.

Further, the experimental or simulation time and period was different in each research. For instance, most publications tended to assess the impact of trees on building energy performance based on the daily energy reduction analysis in a typical summer day. In contrast, the annual energy demand is often used by studies on extensive green roofs. Thus, it is necessary to differentiate the energy performance based on their widely utilized experimental and simulation time. As a result, the trees and green belts use daily cooling or heating energy demand. Correspondingly, urban forest and water feature use monthly cooling or heating energy use. The rest of types utilize annual cooling or heating demand.

- The impact of green roof on building energy performance

In Fig. 8, it is clear that effect of extensive green roofs on energy performance was explored in 15 climate zones. The number of climate zones examined is about 3 times more than the types of semi-intensive green roofs and intensive green roofs. In general, extensive green roofs show a positive impact on decreasing building cooling energy consumption in the majority of climate zones. Although they also have potential to increase cooling energy demand in three climate zones, the proportion is tiny, around 1%. The largest annual cooling saving appeared in Cwb climate, up to 90%; followed by Cfa, with a maximum reduction of 57.6%. The notable cooling energy reduction in the former climate far exceeds reductions in the other climate zones. As such, exploring the reasons behind this significant energy saving is necessary. This part is further discussed in Section 5.2. In addition, extensive green roofs also performed a significant cooling energy reduction in the climate zones of Csa (50%) and Cfb (57%). In the climates of BWh and Aw, extensive green roofs were associated with a reduction of 45% in cooling energy demand. These two climate zones are hot all year around, and buildings mainly need cooling energy. Extensive green roofs acting as an additional insulation layer have potential to reduce indoor and outdoor heat transfer and maintain indoor thermal comfort. In contrast, extensive green roofs were associated with 10% and 2.7% in cooling energy reduction in the Dfb and Dfa climate zones, respectively. As for heating energy demand, it is obvious that extensive green roofs had an unsatisfactory performance in reducing heating energy saving. Five climate zones revealed that extensive green roofs had a negative impact on reducing heating energy demand, especially in the climates of BWh and BSh. In these two climate zones, extensive green roofs may lead to an increase in heating energy use by up to 25%. In addition, the maximum reduction of heating energy use, up to 46.2%, occurred in climate zone Cfa. In contrast, it could only decrease heating energy demand by 0.56% in climate Csb. Extensive green roofs had similar heating energy saving performance in the climate zones of Dfb and Dfa, around 6%.

In addition, several studies have combined cooling and heating energy performance together to describe the impact of extensive green roofs on annual building energy demand. It is clear that except extensive green roofs have better energy-saving performance in the Dwc climate zone (saving more than 20%), the energy-saving effect of extensive green roofs in the remaining climate zones is not very prominent, for example 6.4% and 5.1% of energy reduction in climate zones of Cwa and DWa, respectively.

Regarding semi-intensive green roofs, it is only related to three

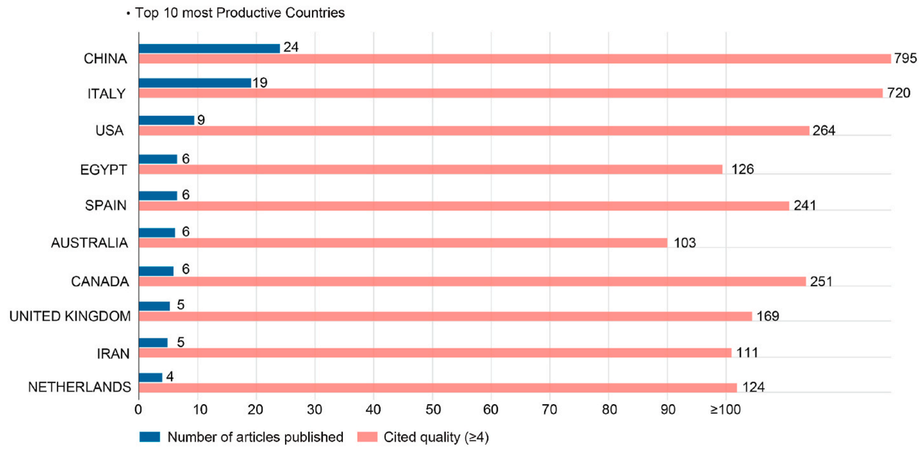

Fig. 5. The most productive countries and total citation per country.

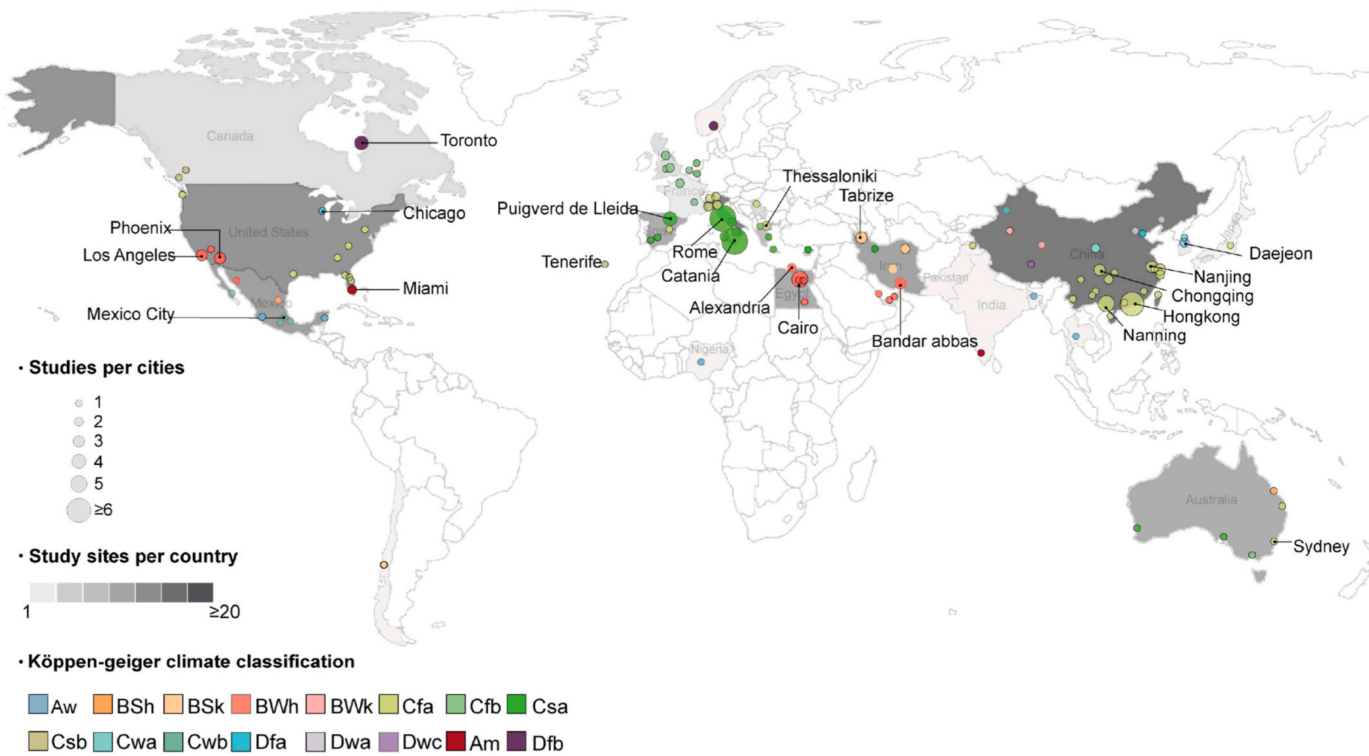

Fig. 6. Geographic distributions of study sites and affiliated countries or climate zones.

climate zones. Like extensive green roofs, semi-intensive green roofs have outstanding cooling energy saving performances in the Csa, Cfb and Cfa climate zones. Notably, they decreased more heating energy demand than extensive green roofs in these three climate zones.

Furthermore, intensive green roofs were associated with over 55% cooling energy reduction in the climate zones of Csa, Cfa, and Cfb. In addition, intensive green roofs were also associated with a 37% decrease in cooling energy needs in the Aw climate zone. However, only 4.1% cooling energy demand could be decreased in the Dfb climate zone. Besides, intensive green roofs also have a significant impact on heating energy reduction in the climate zones of Cfa and Cfb. Specifically, they were associated with a decrease in heating energy demand of 46.2% and 30.6% in these two climate zones.

Overall, these three types of green roofs had a positive influence on reducing building cooling energy demand, especially in the temperate climate zones, where they demonstrated significant cooling energy-saving performance. However, research results on reducing heating energy consumption are inconsistent. Further, some studies adopted annual energy consumption calculation methods by integrating cooling and heating energy consumption together. Nevertheless, the type of green roof still shows a positive effect in reducing building energy demand in most cases.

- The impact of green wall on building energy performance

The number of publications associated with green walls was relatively small compared to the literature about green roofs. As such, the specific types of green walls have only been studied in some of the climate zones. As shown in Fig. 9, studies on direct green façades are only associated with climate zone Cfb and were focused on heating energy demand. They could reduce heating energy demand by 21%–37% in that climate. Furthermore, in the climate zone Csa, indirect green

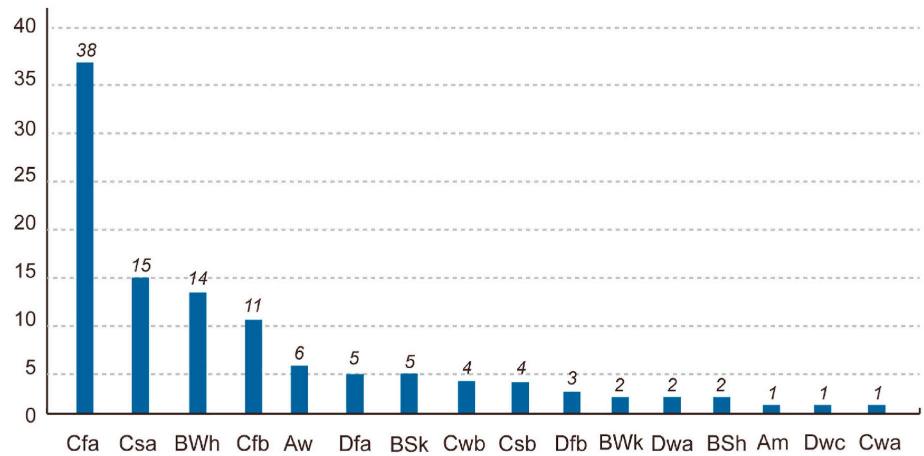

Fig. 7. Distribution of study sites in each climate zone.

Table 2
The description of characteristics of each related climate zone [33].

Code of each climate	Descriptions	Main character
Cfa	Humid subtropical climate	Hot summer
Csa	Hot-summer Mediterranean climate	Hot summer
BWh	Hot deserts climate	Hot throughout the year
Cfb	Temperate oceanic climate	Warm summer
Dfa	Humid continental climate	Hot summer
Aw	Tropical savanna	
Cwb	Subtropical highland climate	Warm summer
Csb	Warm-summer Mediterranean climate	
Bsk	Cold semi-arid climate	Cold throughout the year
Dfb	Warm-summer humid continental climate	Warm summer
BWk	Cold desert climate	Cold throughout the year
Dwa	Monsoon-influenced hot-summer humid continental climate	Hot summer
BSh	Hot semi-arid climate	Hot throughout the year
Am	Tropical monsoon climate	
Dwc	Monsoon-influenced subarctic climate	Cold summer
Cwa	Monsoon-influenced humid subtropical climate	Hot summer

façades and living walls showed similar cooling and heating energy saving potentials. They were associated with over 50% cooling energy demand reduction, and also have the possibility to increase heating energy demand by around 9%. Regarding the literature, in the climate zone Cfa, indirect green façades saved more cooling energy (76%) than living walls (3%). It is necessary to explore the causes behind this significant difference. In addition, in Dfa climate zone where heating energy is required much more than cooling energy [34], living walls reduced more heating energy consumption than that of cooling. Further, in the temperate climate zones of Cfb and Csb, living walls may reduce cooling energy consumption by 26% and 7.3%, respectively.

- The effect of trees, urban forests, green belts and trees, grass and near the river as well as water features on building energy performance

As shown in Fig. 10, the remaining five types are associated with few climate zones. Trees were evaluated across four climate zones, showing relatively insignificant energy savings in the climate zone BWh when compared to Cfa and Csa climate zones. The daily cooling energy savings in the Cfa climate (54%) were 13 times greater than in the BWh climate (3.9%). The causes behind this significant difference are discussed in the discussion. Trees were associated with 2.7% cooling energy reduction in the Cfb climate. In addition, buildings near the green belts may decrease daily cooling energy demand by 2.1% in the climate zone Cwa. Similarly, buildings in close proximity to urban forests and wetlands have the potential to achieve a maximum monthly reduction in cooling energy use of 13.9% and 10.8%, respectively. As for the type of mixture of trees, grass and near the river, it may lead to a decrease in annual cooling energy consumption by 6.7–10.8% in the hot desert climate.

As shown in Fig. 11, it is clear that all the integrated analyses involved green walls or green roofs. However, most analyses did not mention their related specific types. In the integration analysis of green roofs and green walls, most corresponding assessments were in the Cfa climate zone. The integration analysis of extensive green roofs and perimeter flowerpots had similar cooling reduction performance with the combination of semi-intensive green roofs and green walls of around 28%. However, the latter had better heating energy savings than the former. Living walls combined with green roofs also showed 34.6% cooling energy demand reduction in the Bsk climate zone. Furthermore, in Cfb climate zone, extensive green roofs combined with green belts were associated with 42% cooling energy reduction. Green roofs integrated with green walls and trees had a significant impact on reducing cooling energy in climate zones of Cfb (3%–35%) and Dfb (28%–42%). Notably, the combination of trees, green walls, green roofs and grasses may lead to 5% cooling energy decrease in the climate zone Dfa.

Although Figs. 8–11 show the impact of the seven NBS categories evaluated on building cooling and heating energy demand in percentage, they only show the maximum and minimum values. To display the range of distribution for the majority of numerical values, boxplot was used in the study. Notably, the study is restricted to generating boxplots on green roofs and green walls and the climate zones of Cfa and Csa, as there is insufficient data available for other categories and climate zones. The generated boxplots are shown in Fig. 12.

In Fig. 12, the solid line and dashed line in the box of boxplots

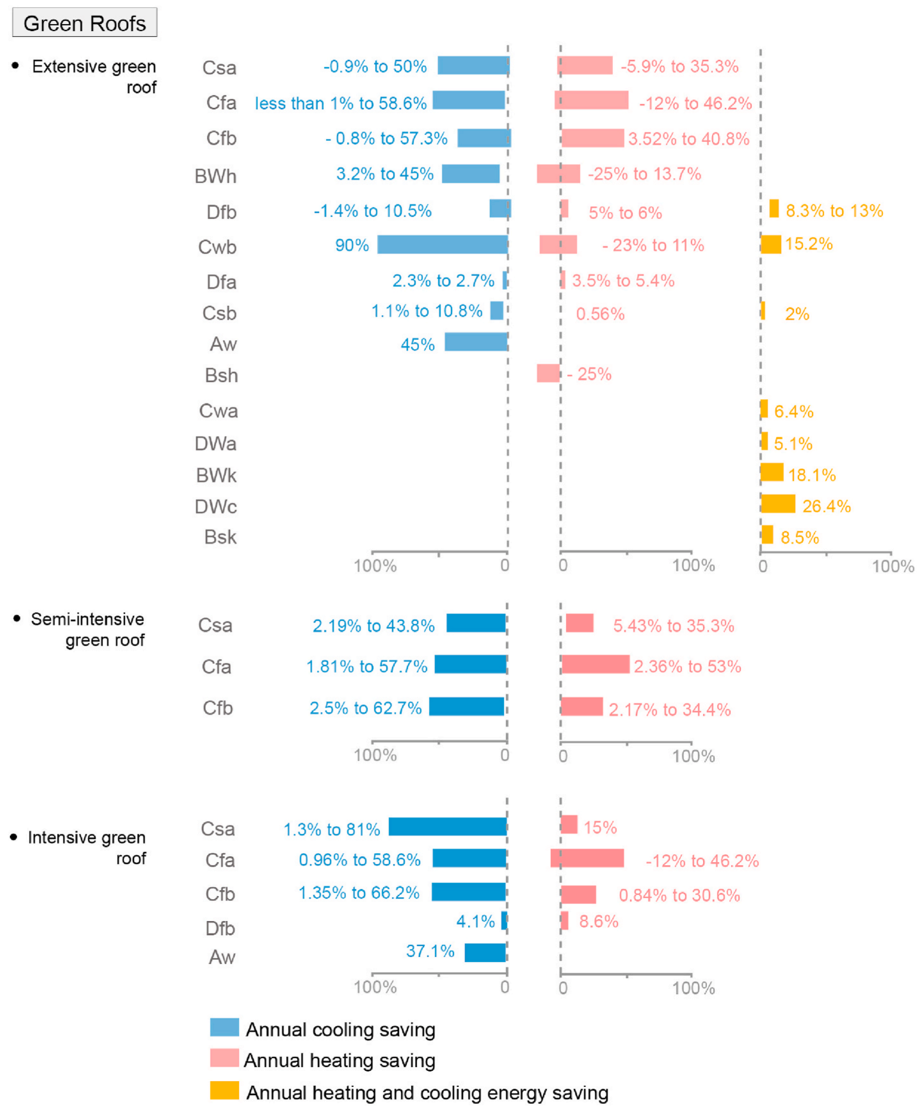

Fig. 8. The effect of green roofs on building energy performance in different climate zones.

indicate the median and mean values, respectively. It is clear that the interquartile range (IQR) of cooling and heating energy reduction of green roofs in the climate zone Cfa is relatively broad compared with other types and climate zones. This indicates a wider spread of data within the middle 50% of the distribution. The values of cooling energy reduction of these data vary between 57.1% and 6.1%; also, the reduced heating energy varies between 36.4% and 2.36%. However, the lower whisker has a value of −12%. This means that green roofs have the possibility of increasing 12% heating energy demand. As for green roofs in climate zone Csa, the data for cooling energy reduction distributed in the middle 50% varies between 43.95% and 4.94%. The corresponding data of heating energy reduction ranges between 28.75% and 5.85%. However, green roofs can increase heating energy demand due to the minus value (−5.9%) of lower whisker. In addition, the data on heating energy reduction above the median is more dispersed. Besides, the green walls in the climate zone Csa show that the data for heating energy reduction distributed in the middle 50% are all below zero, ranging between −5.53% and −8.53%. This reveals a negative impact of green walls on heating energy reduction in the climate zone Csa. In contrast, the cooling energy savings vary from 48.585% to 28.35%. Notably, the ranges of IQR and the mean and median values of reduced cooling energy of green walls are both high than that of green roofs. It could be inferred that green walls have better cooling energy saving performance than green roofs in this climate. Further, study only generated a boxplot for the cooling energy performance of green walls in climate zone Cfa, as only two data associates with heating energy performance. The data for cooling energy reduction distributed in the middle 50% varies between 27.06% and 11.13%; also, the data below the median is more dispersed, and there is one outlier (76%).

5. Discussion

5.1. The current status of the research field

Section 4.1 shows that the current studies in this research field demonstrate a narrow focus. Specifically, more than half of the collected publications were relevant to the studies of assessing green roofs and green walls, especially extensive green roofs. Moreover, most studies also had a significant preference toward to the climates of Cfa, Csa, BWh and Cfb. The former phenomenon could be explained by two reasons. Unlike other NBS types, green roofs and green walls do not occupy additional space in congested urban areas or do not inhibit natural ventilation in certain urban geometries [35]. Moreover, extensive green roofs are lightweight and mainly use sedum (low irrigation requirement)

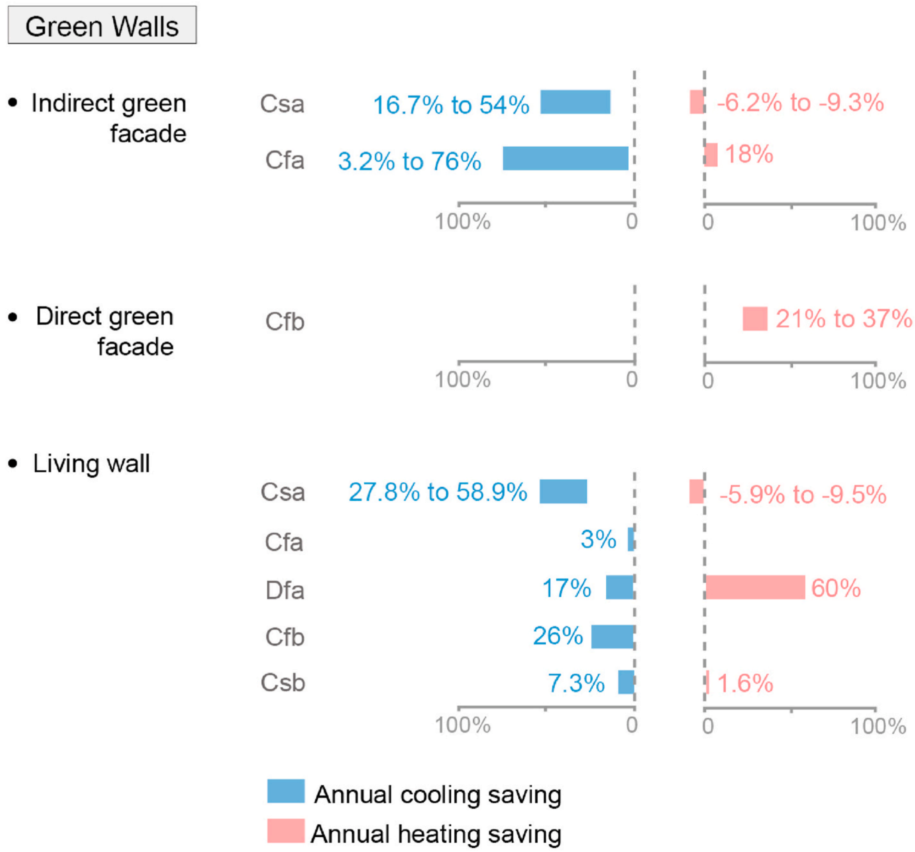

Fig. 9. The effect of green walls on building energy performance in different climate zones.

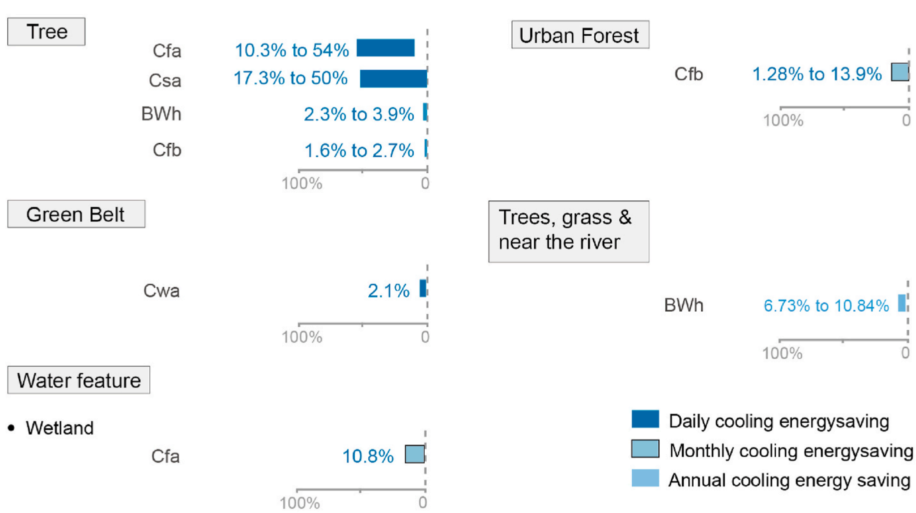

Fig. 10. The effect of trees, urban forests, green belts, and the mixture of trees, grass and near the river as well as water features on building energy performance.

as vegetation layers. This results in low maintenance costs and allows applications on buildings which have weight restrictions [36]. Therefore, they can be widely applied by building renovation projects and new buildings. Furthermore, another cause may be related to current monitoring methods of building energy performance in different types. Although the reduction of building energy use through green elements has been widely valued by scholars, the state of art seems quite incomplete as the evaluation of the performance of different NBS types requires different methods and tools [30,37]. In most studies of the green roofs and green walls, the potential of both types to reduce energy demand is evaluated directly by building energy modeling or by numerical values measured using high-precision equipment. The evaluation process is relatively easy to implement and time saving [37]. However, compared to green roofs and green walls, evaluating the energy performance of large types, such as the permanent blue NBS category or urban forest, requires the implementation of baseline data

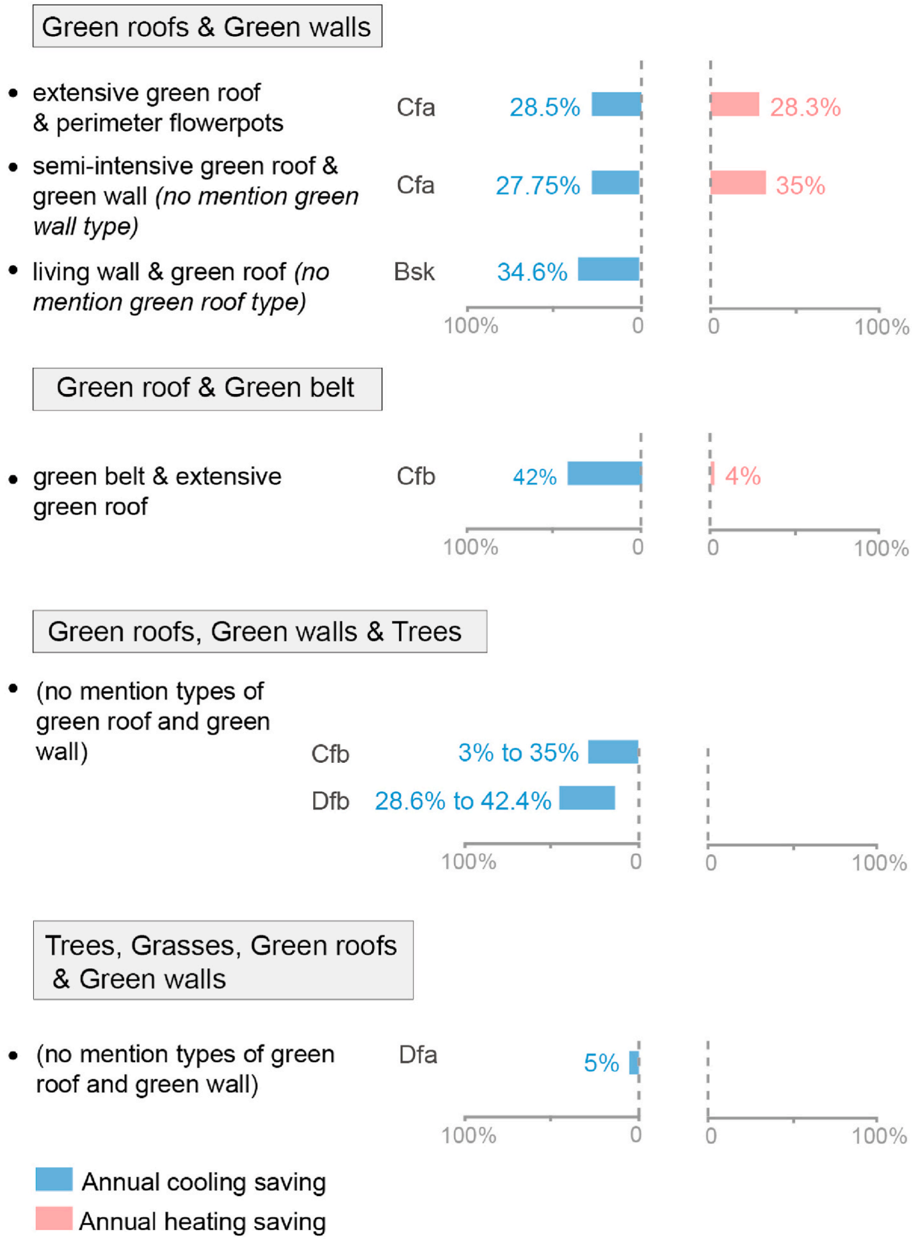

Fig. 11. The effect of different types combination on building energy performance.

collection [37] as the impact of these types on building energy demand is mainly through microclimate regulation. The duration of the monitoring study is therefore very important. In other words, the evaluation process for these types is complex and time-consuming. This may be one of the reasons why scholars prefer to conduct research in easily assessed types.

Further, researchers pay much attention to the climates of Cfa, Csa, BWh and Cfb. This may be related to their climatic characteristics and the inhabiting of large populations. According to Ref. [38], the climates of Cfa, Csa, BWh and Cfb all have the characteristics of hot summers. In addition, these four climate zones correspond to southern China, the western United States, the Mediterranean coast, the Middle East and western Europe, respectively. These areas have relatively developed economies and are inhabited by large populations and have high building density. The superimposed influence of these two factors may cause buildings to occupy a large proportion of the total local energy use. This urges the scholars to looking for alternative solutions to reduce building energy demands in these energy-intense locations. To some extent, this also provides an excellent opportunity for researchers to study the potential of NBS's impact on building energy demand in different climates. Further, among these four climates, the climate Cfa and Csa attracted the largest number of studies. Most of the studies on these two climate zones were published in Italy and China; also, they are the top 2 most productive countries regarding the number of publications. The active performance in this field of these two countries is not only related to the characteristics of the climate itself but also relevant to the huge proportion of building energy demand in society's energy demand. For example, as revealed by the Italy's energy consumption profile in 2018, while household energy demand has been declining since 2010, residential buildings still rank the second highest users among the five sectors, accounting for 29.3% of total final energy consumption [39]. Similarly, in China, building energy use accounts for about 30% of the total social energy demand at present [40]. This proportion is huge as China is the largest energy consumer in the world

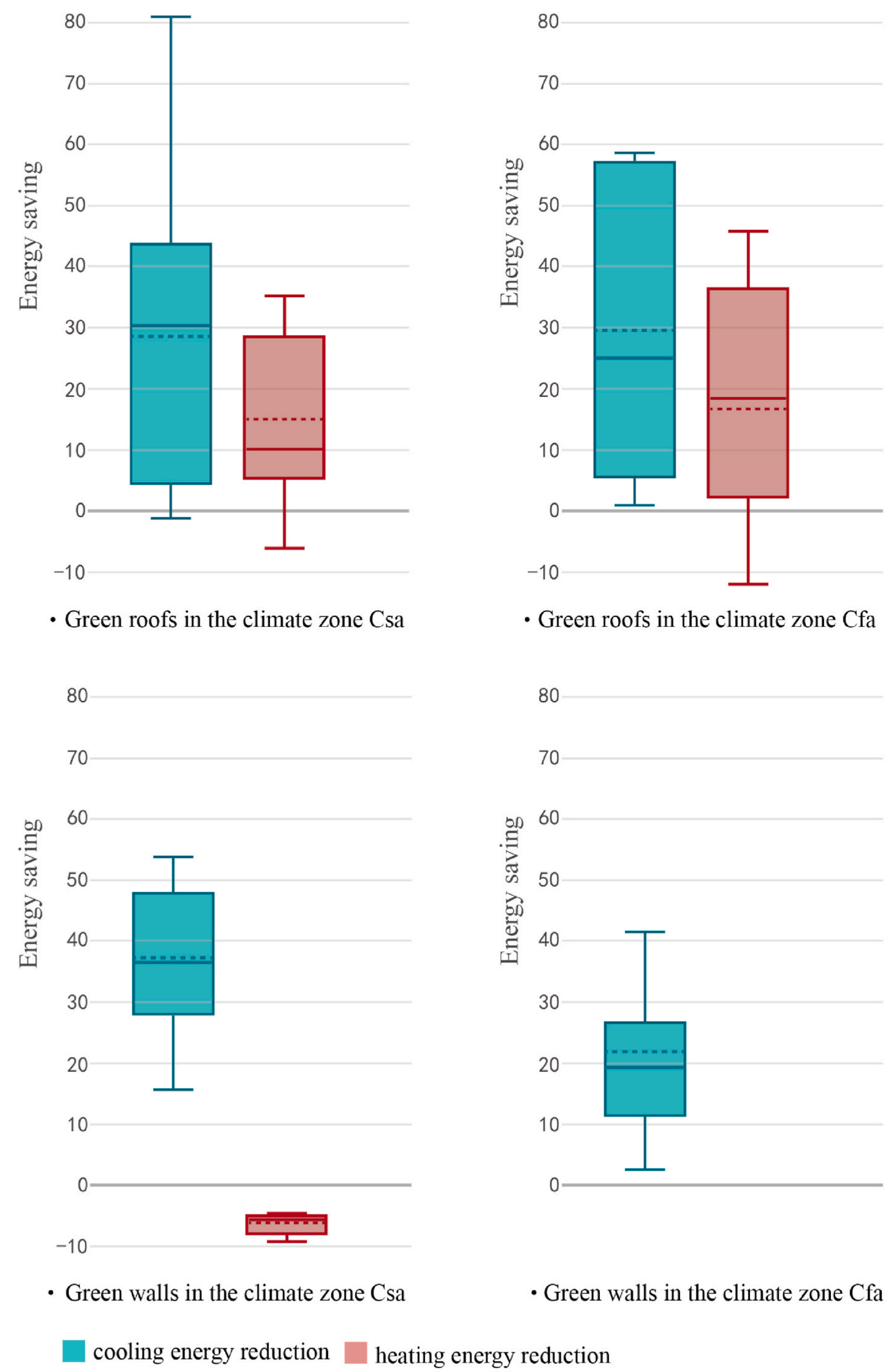

Fig. 12. The boxplots for green roofs and green walls in climate zones of Csa and Cfa.

[41]. Therefore, the urgency of improving the building energy efficiency pushes these two countries to actively encourage the development of this field. For example, the Italian government has involved NBS in the process of improving the energy efficiency of buildings, such as the use of green roofs and walls, through the active implementation of the Energy Performance of Buildings Directive (EPBD) [42,43].

5.2. The impact of different NBS types on building energy performance in different climate zones

As discussed in Section 4.2, nearly all the studies confirmed that green roofs had a positive impact on decreasing building cooling energy demand in almost all climate zones. Only one study pointed out that extensive green roofs have potential to increase cooling energy demand by a small amount in three different European climates (Csa, Cfb and Dfb) if using short sedum as the roof vegetation [44]. Compared with other roof vegetation, the short sedum vegetation used in that study

Factors influence building energy demand		Cooling energy reduction	Heating energy reduction
Green/blue infrastructure factors	Leaf Area Index (LAI)	●	●
	Green roof depth	◒	◒
	Green wall depth	◒	◒
	Leaf Area Density (LAD)	●	◒
	Tree planting pattern	●	○
	Blue infrastrcture types	◒	○
Physical factors	Distance to blue infrastructure or some of the green infrastructure types	●	○
	Size of blue/green infrastructure	●	●
Climate factors	Climate with long hot summer and short mild winter	○	●
	Hot all year around climate	○	●

* Impact level: ● > ◒ > ○

Fig. 13. The factors affect building cooling and heating energy reduction.

represents a sparse plant type with low values of plant height and Leaf Area Index (LAI). It has been already confirmed that LAI is the key parameter affecting the green roof in building energy efficiency when considering the influence of evaporation rate [45,46]. In a similar study on energy consumption in an office building, Ferrante [47] compared six types of plants in the climate zone of Csa, and found that higher LAI could effectively decrease cooling energy consumption. Moreover, the height of plants often acts as additional thermal insulation and mass, which could effectively reduce the heat flux through the roof [48]. Therefore, it is suggested that the type of roof vegetation used should be seriously considered when using green roofs in the temperate climate group with hot characteristics in summer. In addition, although the use of extensive green roofs in five climate zones (Cfa, Csa, Cfb, BWh and Aw) with hot summer characteristics may lead to a significant reduction in cooling energy consumption by up to 58%, this percentage is much lower than in the Cwb climate zone. Study by Ávila-Hernández [46] used simulation approaches and found that extensive green roofs have the potential to reduce cooling energy consumption by up to 90% in one residential building in Tlaxcala (Cwb), Mexico. Compared with the above five climates, the summer temperatures are lower in the Cwb climate. Moreover, the annual average temperature of the simulation site Tlaxcala is around 16.1 °C [46]. In that publication, the authors explored the optimal combination of parameters affecting indoor temperature by constantly adjusting the vegetation parameters for the extensive green roof. Then, these optimal parameters were used for the energy consumption simulations. In other words, that publication described an optimal or ideal state rather than the actual situation; that is, how much cooling energy could be maximally saved with an optimal state of extensive green roof. To some extent, the 90% reduction in cooling energy consumption obtained by that paper lacks broad representation. In simple terms, it does not represent the actual state of the energy performance of the majority of extensive green roofs in the Cwb climate. Therefore, the authors of the current study believe that this high energy saving mut be critically observed and need further investigation.

In addition, study detected that green roofs may lead to an increase in heating energy demand in the climates of Cfa, Csa, Cwb, BWh and BSh; also, green walls have the potential to increase energy demand in the climate of Csa. However, further evaluation is needed to assess the impact of green walls on building energy performance in other climate conditions, as it is only associated with limited data and climate zones. Besides, while studies have found an increase in heating energy demand associated with green roofs in the above 5 climate zones, the statistical analysis using boxplots shows that most studies on green roofs tell a reduction in heating energy needs for buildings in the Cfa and Csa climate zones. To date, the impact of green roofs and green walls on building heating energy demand is still controversial in the above-warm temperature climates. Some unusual findings have been reported in some literature. For example, Coma [49] used experimental approach and observed that indirect green façades and living walls increase heating energy by 9.3% and 9.5% in the climate Csa, respectively. However, Chafer's study [50], which also used experimental methods, found that green façades and living walls respectively reduced heating energy consumption by 2.65% and 2.47%. Similarly, study by Alexandri [51] employed energy modeling tool and found that direct green façades and living walls showed reductions in annual heating energy demand of 1.2% and 4%, respectively. As the above-mentioned studies did not provide key information for simulation or experimentation, the interpretation of these results becomes more challenging. In addition, in the rest of the studies on the types of green roofs and green walls, many studies stress that this phenomenon relates to LAI and the short and mild climatic characteristics of winter [50,52,53]. The general opinion is that despite vegetation losing its leaves (lower LAI) during winter compared to summer, the scattered branches and the remaining leaves can still function as additional insulation layers, preventing most of the heat flow into the interior. As such, compared with the bare wall, green roofs and green walls will increase part of the heating energy need in the winter. Thus, given that green roofs and green walls may increase heating energy demand in temperate and arid climates which are characterized by short mild winters or year around heat, any effort to improve the energy efficiency of buildings should be concentrated in summer, as summer is hot and much longer than winter.

Furthermore, although green walls were not involved in a large number of climate zone studies compared with green roofs, it is shown in the examined climate zone that it performed better in terms of energy efficiency than green roofs, especially in reducing cooling energy demand. To a large extent, this is because the surface area of building walls is larger than that of the rooftop. Furthermore, among the three specific types of green walls, only in the temperate oceanic climate were living walls discussed with regard to the cooling energy saving performance (Cfb). They were associated with 26% reduction in cooling energy use. However, this proportion is much lower than that of extensive (57.3%), semi-intensive (62.7%) and intensive green roofs (66.2%) in this climate. It is necessary to explore the causes. The significant cooling energy reduction of extensive, semi-intensive and intensive green roofs was found in Melbourne by Pianella [54]. The plants used in that study contained multiple types of species. This means that the building roof is well coved by plants. Meanwhile, the vegetation is well irrigated during summer; also, the simulated building had no-insulated layer. In contrast, the study that observed a 26% reduction in cooling energy for green walls showed significant differences in building properties and vegetation maintenance compared to studies on green roofs. Specifically, the simulated building walls had 5 cm insulation layer and the irrigation frequency of vegetation was lower than the green roof analysis of the former [55]. Therefore, the superposition of these two factors may be the reason why the energy saving performance of green walls is lower than that of green roofs in the climate zone Cfb as the irrigation status of vegetation, and insulation layer has been proved by many studies to affect energy saving performance [56–62]. To some extent, this also stressed that optimizing the energy saving performance of buildings through green walls or green roofs requires comprehensively considering the combination of multiple factors.

Additionally, it is worth noting that several current studies on green roofs use a comparative analysis approach on the same rooftop, meaning that one part of roof is transformed to a green roof while another part remains as a traditional roof. Due to the proximity of these two roof types, they may to some extent be influenced by each other [63,64]. Therefore, for this comparative analysis approach, this study suggests that comparing the difference between soil and ground temperature may be a more effective method, as the soil is the heat buffer for green roofs.

As for the remaining five categories, although they have been involved in a small number of studies compared to green roofs and green walls, research in limited climate zones has also shown their positive impact on improving building energy efficiency, especially the energy saving performance of trees in Cfa and Csa climates. Specifically, trees showed a reduction in cooling energy demand by over 50% in both climate zones. This proportion is over 12 times than in the hot, arid desert climate (BWh). The BWh climate has high temperatures throughout the year, whereas the Cfa and Csa are only hot in summer [38]. It is necessary to explore the causes behind this phenomenon. Up to the present time, the relationship between trees and building cooling energy demand has been deeply studied, in which the Leaf Area Density (LAD), the height of tree and the distance to building are considered to be important factors affecting building energy consumption [65–70]. Nevertheless, the studies which mentioned the significant cooling energy reduction of trees in the above Csa and Cfa climate zones benefited not only from the highest value of LAD (dense trees) and the high height of the tree, but also from the unusual arrangement of trees [67,71]. Specifically, the trees were arranged into uniform rows, forming a continuous shading canopy with no space between the canopies. This feature allows the trees to form large shaded areas on the walls. Therefore, this planting pattern combined with the high values used in the LAD and tree height may have allowed significant daily cooling energy savings. To some extent, this revealed that reducing building energy consumption through vegetation is a complex process that requires many considerations, which includes not only the characteristics of vegetation itself but also the planting configuration pattern. Moreover, it also recommended that when planting trees in warm or hot climate zones, the vegetation should be arranged in uniform rows when possible to create a continuous shade on the building surface, thereby, further reducing the cooling energy load, especially in the areas where buildings have low height and have large distances between each other.

In addition, green belts also show good energy saving performance in the subtropical monsoon climate with hot summers (Cwa). Although the daily cooling energy reduction was only found to be 2.1%, the energy savings are significant if this percentage is extended to the entire summer period. Green belts are usually small in size but have flexibility in scale and can be applied to a variety of urban spaces [72]. As such, for the cities with prominent imbalances between people and land, the construction of many small green belts in the dense urban areas could be another option as it is significantly difficult to build new large greenspace in the city centers that have a dense population and urban form.

As for the water feature, wetland performed a significant cooling energy saving performance. This phenomenon also observed in the type of mixture of trees, grass and near the river. Study by Ayad [73] found that water (8.12%) saved significantly more cooling energy than the combinations of trees and grasses (4.78%) in the hot desert climate. Even by increasing the canopy cover ratio, there are still significant differences in energy saving performance between them. To a large extent, this suggests that in the process of achieving a low-carbon city, it is necessary to reasonably plan blue infrastructure and properly design water features in existing urban areas. For example, when implementing tree planting, combining technologies (e.g., sustainable urban drainage system) can be installed to collect the excess water and return it back to the bioswales or ponds at the neighborhood scale. Further, unlike other types (e.g., green roofs, green walls) that can directly produce shading effect on the buildings, the influence of water features on building energy demand is primarily achieved by modifying the microclimate [74]. As such, distance plays a key role in determining the energy saving potential. In simple terms, the closer the distance between building and water feature, the more significant the impact of microclimate on the building. Similarly, distance is also the important factor of urban forests affecting the energy demand of building as it influences the cooling of the outdoor ambient air temperature through transpiration by large areas of plant [75,76]. Nevertheless, the authors of this study suggest that in the early stage of planning building energy efficiency, priority should be given to considering the size or scale of these two types and then determining their distance from the buildings. Because the influence of smaller scale water features or urban forests on the surrounding microclimate is limited compared to larger scales. Being farther away from buildings will further weaken their impact on the adjacent microclimate of the buildings. Therefore, the size of these two types and the distance to the buildings should be seriously considered to maximize their energy saving potential. Moreover, other measures should be taken to further optimize the energy saving potential of urban forests, such as maximizing their transpiration by selecting the appropriate vegetation type and layout to reduce the outdoor ambient temperature.

In terms of the combined analysis of different types, as described earlier, most integration studies involve green roofs and green walls. However, few of them mentioned the specific types of these two categories, making it difficult to discuss them in depth. In the subtropical monsoon climate (Cfa) and temperate oceanic climate (Cfb), the combination of different NBS types all showed a significant and positive performance of cooling energy savings. This is consistent with the results of the single type analysis. Notably, extensive green roofs combined with perimeter flowerpots could significantly reduce heating energy demand in the temperate climate. In contrast, indirect green facades and living walls are likely to increase heating energy consumption in such climates. It might be that the perimeter flowerpots cover the building facade to a lesser extent than that of indirect green facades and living walls, thereby the building walls can receive more solar heat in winter. To some extent, this suggests that in climate zones with short and mild winters, using perimeter flowerpots with green roofs could be another option to avoid increasing heating energy use.

Furthermore, the cooling energy savings of the integration of green roofs, green walls, grasses and trees is not significant in the humid continental climate (Dfa), with only 5%. This climate is cold but has hot summers. Green walls, green roofs and trees can all produce a significant shading effect on the experimental building in the summer. Only one study has involved in this combination analysis, in which the façade and roof material of the simulated building all have high albedo properties [57]. Moreover, this building is well-insulated. Thus, compared with most of the simulated buildings in the collected publications, this experimental building already has a decent building envelope structure in terms of energy saving. Thus, the 5% cooling energy reduction is the comparison between the combination of green wall, green roof, trees, grass and the current cooling materials of simulated building. In other words, if this experimental building does not use high albedo reflective material on the facades and roof, or has no insulation layer, the combination of green walls, green roofs, trees and grass will save more cooling energy consumption. Besides, although no collected publications in this study explored in detail combining green walls and roofs with solar technologies, such as solar photovoltaic (PV) arrays, this combination is being accepted by a growing number of regeneration projects as this combination could bring the benefits of biodiversity and energy generation for building performance. These synergies have the potential to increase the efficiency of PV panels due to the ambient temperature reduction from evapotranspiration. Solar panels are able to protect flora and fauna from direct exposure to radiation and wind, which intensify plant growth and microhabitats. Lastly, photovoltaics is able to increase cost savings from generated energy, which can offset the additional cost of green infrastructure.

To sum up, although the experimental buildings have different characteristics (e.g., with or without insulation, different building materials), the seven NBS types evaluated all have an absolute impact on the saving of building cooling energy. The proportions of cooling savings depend on the NBS types and climate zones; However, the results of reducing heating energy demand are inconsistent. Specifically, green roofs and green walls may increase the heating energy load in the climate zones characterized by short and mild winters or hot year-round temperatures. Notably, the proportion of increased heating energy demand is offset by the saved cooling energy in summer. In this regard, although the energy performance of green walls and green roofs achieve net energy saving over the year, the risk of potentially increased heating energy load in winter still cannot be ignored. As such, it is suggested that when applying green roofs or green walls in these kinds of climates, measures to improve building energy efficiency should be concentrated on solutions for summer months. For the climate zones characterized by hot summers and cold winters, green roofs and green walls can effectively reduce cooling and heating energy demand. As such, it is recommended to widely apply these two NBS types in this kind of climate, which will make contributions to the realization of zero carbon for building sectors.

Based on the above discussion, the main conclusion drawn is that reducing building energy demand through NBS is a complicated process that requires considering various factors, such as the factors of climates (Fig. 13). Importantly, to maximize the energy saving potential of NBS, it is crucial to comprehensively consider the combination of these factors rather than maximizing an individual factor. In other words, exerting the advantages of NBS in reducing building energy demand requires a holistic approach that considers the interactions between different NBS, climatic, and physical components. Moreover, it is important to continue research and development in the NBS to optimize the design and implementation of NBS strategies on building energy reduction.

6. Limitations

There are several limitations in this study. First, although the study employs two literature databases and logically combined search terms, it is impossible to ensure that study collected all the relevant articles. Some papers may employ other search terms, for instance “urban natural elements” rather than “green roofs”, “gardens”, or other specific types. Moreover, the restriction to English articles may also have resulted in a reduced number of data sources, particularly given the rapid growth of research output in China in this research field.

7. Conclusion

As NBS can bring multiple benefits in multiple aspects (e.g., biodiversity, public well-being), they should be considered an important contribution to achieving SDGs. Improving energy efficiency and building sustainable communities and cities are the significant targets of SDGs 7 and 11. Given that direct carbon emissions of buildings still account for a significant proportion of total emissions, and that energy efficiency investment incentives through building materials have weakened, NBS has emerged as an alternative approach for reducing building energy demand. Although this study is framed as a climate specific review, the higher goal is to evaluate the energy saving performance of various NBS types at building scale in different climates, providing evidence for the widespread application of NBS in the city-wide scale.

This review found that there is a positive influence of NBS technologies on building energy reduction. The energy reduction potential of NBS for building cooling varies from 3% to 90%, while the potential reduction in heating energy demand ranges from 0.58% to 60%. The extent of the reduction in both cases is significantly dependent on the NBS type and climate. It should be noted that some NBS types may lead to an increase in heating energy demand by between 5.9% and 25%. In other words, the heating energy performance of green roofs and green walls is controversial; especially in climates characterized by year-round hot temperatures or those with long hot summers and short mild winters. However, the increased heating energy demand in these climates is offset by the savings in cooling energy in summers. Besides, it is crucial to note that although this study quantified the building energy demand for different NBS categories, the proportion of reduced energy was not classified according to different building types and designs (substrate thickness, plant type; etc.). While a direct comparison of previous studies based on these factors would be complex and challenging, further classification of energy saving performance based on these factors is necessary in the future. This will provide guidance for different types of NBS to make appropriate decisions in further reducing energy consumption in buildings.

Besides, this review detected that the studies in this field have feature of a narrow focus. The majority of studies focused only on a few NBS types and climate zones. For example, extensive green roofs were evaluated by 36 studies across 15 climate zones. However, green belt was only examined by one research in one climate. In addition, the six specific categories included in the water features also involve only one study. Moreover, this phenomenon also appears in urban forests and in some combination studies. The significant differences in the quantity of research between different NBS types and climate zones will result in significant differences in the depth and breadth of research among different NBS categories. As such, future research should concentrate on neglected types and climates that have been underrepresented to fully understand the energy-saving potential of different NBS types.

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Declaration of competing interest

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

Data availability

Data will be made available on request.

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Appendix A. The publications in different NBS types associated with the energy consumption related percentage

Extensive green roof				
Reference No.	Climate zone	Annual cooling energy use	Annual heating energy use	Annual cooling and heating energy use
[77]	Cfa	56.1%	22%	
[78]	Cfa	7%–8%		
[67]	Csa	2.92%	5.28%	
[67]	Cfa	2.56%	4.45%	
[67]	Cfb	3.5%	3.5%	
[79]	Csa	50%	31%	
[80]	Bwh	39.7%		
[46]	Bwh	45%	−25%	
[46]	Cwb	90%	−23% to −11%	
[46]	Bsh		−25%	
[46]	Aw	45%		
[81]	Dfa			2.1%
[81]	Dwa			5.1%
[81]	Bwk			18.1%
[81]	Dwc			26.4%
[81]	Cwa			6.4%
[81]	Cwb			15.2%
[81]	Cfa			6.0%
[82]	Csa			55%
[83]	Csa	31.8%–35.2%	1.8%–9.5%	
[84]	Dfb			13%
[85]	Cfa	Less than 1%		
[86]	Cfa	25%	−9.9%	
[87]	Csa	20%	25%	
[88]	Dfa	2.3%–2.7%	3.5%–5.4%	
[144]	Cfa	26.7%		
[143]	Csa			10%
[143]	Cfa			5%
[89]	Bwh	19.4%	−5.6%	
[90]	Csa	17%		3.4%
[91]	Csb	3.2%	0.56%	
[92]	Cfa		2%	
[92]	Csb			2%
[48]	Dfb			8.3%
[48]	Cfb			6.2%
[44]	Csb	1.1%–11%		
[44]	Csa	−0.9% - 11%	5.3%–17.1%	
[44]	Cfb	−0.8% - 10%	5.3%–8.2%	
[44]	Dfb	−1.4% - 10.5%	5–6%	
[93]	Cfa	6.1%	26%	
[94]	Aw	45%		
[95]	Bwh	3.2%		
[96]	Csa	50%	30%	
[97]	Csb	1.2%–6.9%		
[98]	Cfa		5%	
[99]	Csa	16.3%		
[99]	Bwh	23%		
[100]	Cfa	16.7%		
[54]	BSk			8.5%
[101]	Csa	44%	34%	
[102]	Cfa	48.67%		
[103]	Aw	31.7%		
[104]	BWh	7.09%	13.7%	
[105]	Cfa	9.88%		
[106]	Csa	10.8%		
[107]	Cfb	57.3%	40.8%	
[108]	BWh	5%		
Semi- intensive green roof				
[77]	Cfa	13.3%–57.7%	36.4%–53%	
[56]	Csa	2.19%	5.43%	
[56]	Cfa	1.81%	2.36%	
[56]	Cfb	2.5%	2.17%	

(*continued on next page*)

(*continued*)

Reference No.	Climate zone	Annual cooling energy use	Annual heating energy use	Annual cooling and heating energy use
Extensive green roof				
[109]	Csa	28.4%–43.8%	7.1%–35.3%	
[110]	Cfa	10.2%	27.5%	
[107]	Cfb	62.7%	34.4%	
Intensive green roof				
[77]	Cfa	13.3%–58.6%	46.2%–58.9%	
[78]	Cfa	22%–35%		
[56]	Csa	1.33%	8.3%	
[56]	Cfa	0.96%	1.16%	
[56]	Cfb	1.35%	0.84%	
[50]	Cfa	25%	−12%	
[142]	Dfb	4.1%	8.6%	
[111]	Cfa	1.7%–14.3%	5.4%–19%	
[102]	Aw	37.1%		
[110]	Cfa	12.3%	41.6%	
[107]	Cfb	66.2%	30.6%	
[112]	Csa	81%	15%	
Indirect green facade				
[113]	Csa	25%–35%		
[114]	Csa	30%–54%	−5.4%	
[115]	Csa	16.7%–43.4%	−9.3% to −6.2%	
[116]	Csa	33.8%		
[117]	Cfa	76%		
[118]	Cfa	16%		
[119]	Cfa	3.2%–11%		
[120]	Cfa	11.5%		
[121]	Cfa	15%		
[122]	Cfa	25%	18%	
Living wall				
[115]	Csa	27.8%–50.3%	−9.5% to −5.9%	
[123]	Dfa	17%	60%	
[50]	Cfb	26%		
[124]	Cfa	3%		
[116]	Csa	58.9%		
[91]	Csb	7.3%	1.6%	
[125]	Csa	41%		
[126]	Dfa	3%–7%		
Direct green facade				
[127]	Cfb		21%–37%	
Trees (Daily energy use)				
[67]	Cfa	54%		
[128]	Bwh	2.3%–3.9%		
[68]	Cfa	10.3%–15.2%		
[66]	Cfa	10%		
[129]	Csa	17.3%		
[71]	Csa	50%		
[130]	Cfa	50%		
[131]	Cfb	1.6%–2.7%		
[58]	Cfb	1.7%		
[132]	Csa	11%		
Green belt (Daily energy use)				
[72]	Cwa	2.1%		
Urban forest (Monthly energy use)				
[75]	Cfb	1.28%–13.4%		
[76]	Cfb	11.4%–13.9%		
Tree, grass, and the near the river				
[73]	Bwh	6.73%–10.84%		
Wetland (Monthly energy use)				
[133]	Cfa	10.8%		
Green roof and Green walls				
[79]	Cfa	27.5%	35%	
[134]	Cfa	7%–8%		
[135]	Cfa	28.5%	28.3%	
[136]	BWh			3%
[137]	Bsk	34.6%		
Green roof and Green belt				
[138]	Cfa	10%		
[139]	Cfb	42%	4%	
Green roof, Green wall and trees				
[140]	Dfb	28.6%–42.4%		
[141]	Cfb	3%–35%		
Green roof, Green wall, trees and grass				
[57] Zhang	Dfa	5%		

References

[1] Taslim S, Parapari DM, Shafaghat A. Urban design guidelines to mitigate urban heat island effects in hot-dry cities. Tech J 2015;74:119–24.
[2] Du Plessis, Chrisna. Towards a regenerative paradigm for the built environment. Build Res Inf 2012;40. 7–2.
[3] Wendling Laura A, et al. Benchmarking nature-based solution and smart city assessment schemes against the sustainable development goal indicator framework. Front Environ Sci 2018;6:69.
[4] Dasgupta P. The economics of biodiversity: the Dasgupta review. London: HM Treasury; 2021. http://bibliotecadigital.ciren.cl/handle/20.500.13082/32687.
[5] Hole DG, et al. Make nature's role visible to achieve the SDGs. Glob. Sustain. 2021;5:e8.
[6] Chausson A, et al. Mapping the effectiveness of nature-based solutions for climate change adaptation. Global Change Biol 2020;26:6134–55.
[7] United Nations Global Compact. Nature-based solutions to address climate change. https://unglobalcompact.org/take-action/events/climate-action-summit-2019/nature-based-solutions. [Accessed 22 May 2023].
[8] The Global Goals. Affordable and clean energy. https://www.globalgoals.org/goals/7-affordable-and-clean-energy/. [Accessed 22 May 2023].
[9] European Environment Agency. Renewable energy. https://www.eea.europa.eu/en/topics/in-depth/renewable-energy. [Accessed 22 May 2023].
[10] International Energy Agency. Buildings sectorial overview. 2022. https://www.iea.org/reports/buildings. [Accessed 27 November 2022].
[11] Yüksek I, Karadayi TT. Energy-efficient building design in the context of building life cycle. Energy Efficient Buildings; 2017. p. 93–123. https://doi.org/10.5772/66670.
[12] Hemsath TL, Bandhosseini KA. Sensitivity analysis evaluating basic building geometry's effect on energy use. J. Renew Energ 2015;76:526–38.
[13] El-Darwish I, Gomaa M. Retrofitting strategy for building envelopes to achieve energy efficiency. Alex Eng J 2017;56:579–89.
[14] Ismaeel WS. Sustainable site selection using system dynamics; case study LEED-certified project. Architect Eng Des Manag 2022;18:368–86.
[15] Koc CB, Osmond P, Peters A. Evaluating the cooling effects of green infrastructure: a systematic review of methods, indicators and data sources. J. Sol. Energy 2018;166:486–508.
[16] Xianhui F. Study of the environmental effects of urban green space and wind. Chin Landscape Arch 2010;26:82–5.
[17] Ávila-Hernández A, Simá E, Ché-Pan M. Research and development of green roofs and green walls in Mexico: a review. Sci Total Environ 2023;856:158978.
[18] Maier Dorin. Perspective of using green walls to achieve better energy efficiency levels. A bibliometric review of the literature. Energy Build; 2022, 112070.
[19] Mihalakakou Giouli, et al. Green roofs as a nature-based solution for improving urban sustainability: progress and perspectives. J Renew Sustain Energy 2023;180:113306.
[20] Shafique Muhammad, Xue Xiaolong, Luo Xiaowei. An overview of carbon sequestration of green roofs in urban areas. Urban For Urban Green 2020;47:126515.
[21] Song Yan-ling, et al. A review on conventional passive cooling methods applicable to arid and warm climates considering economic cost and efficiency analysis in resource-based cities. Energy Rep 2021;7:2784–820.
[22] Wang Puyi, et al. Vertical greening systems: technological benefits, progresses and prospects. Sustainability 2020;14(20):2997.
[23] Bevilacqua Piero. The effectiveness of green roofs in reducing building energy consumptions across different climates. A summary of literature results. Renew Sustain Energy Rev 2021;151:111523.
[24] Jamei Elmira, et al. Review on the cooling potential of green roofs in different climates. Sci Total Environ 2021;791:148407.
[25] Potschin M, Kretsch C, Haines-Young R, Furman E, Berry P, Baró F. Nature-based solutions". 2015. https://www.researchgate.net/publication/280067191_Nature-Based_Solutions. [Accessed 1 October 2022].
[26] Somarakis G, Stagakis S, Chrysoulakis N, editors. Think nature nature-based solutions handbook; 2019. https://platform.think-nature.eu/system/files/thinknature_handbook_final_print_0.pdf. [Accessed 15 October 2022].
[27] Langergraber G, Castellar JAC, Pucher B, et al. A framework for addressing circularity challenges in cities with nature-based solutions. Water J 2021;13:2355.
[28] World Bank. A catalogue of nature-based solutions for urban resilience. Washington, DC, USA: World Bank; 2021. https://openknowledge.worldbank.org/handle/10986/36507. [Accessed 23 September 2022].
[29] Morello E, Mahmoud I, Colaninno N. Catalogue of Nature-based solutions for urban regeneration. 2019. https://www.labsimurb.polimi.it/nbs-catalogue/#. [Accessed 3 September 2022].
[30] Ascione Fabrizio, et al. Green walls, a critical review: knowledge gaps, design parameters, thermal performances and multi-criteria design approaches. Energies 2020;13:2296.
[31] United Nations. Report of the Conference of the Parties on its twenty-fifth session, Part two: action taken by the Conference of the Parties at its twenty fifth session. 2023. https://unfccc.int/sites/default/files/resource/cp2019_13_a02E.pdf. [Accessed 28 February 2023].
[32] European Council. 5 facts about the EU's goal of climate neutrality. 2023. https://www.consilium.europa.eu/en/5-facts-eu-climate-neutrality/. [Accessed 25 January 2023].
[33] The köppen climate classification. 2022. https://www.mindat.org/climate.php. [Accessed 23 September 2022].
[34] Knight Teri, et al. How effective is 'greening'of urban areas in reducing human exposure to ground-level ozone concentrations, UV exposure and the 'urban heat island effect'? An updated systematic review. Environ. E. 2021;10(1):1–38.
[35] Koch Kyra, et al. Urban heat stress mitigation potential of green walls: a review. Urban For Urban Green 2020;55:126843.
[36] Shafique M, Kim R, Rafiq M. Green roof benefits, opportunities and challenges–A review. Renew Sustain Energy Rev 2018;90:757–73.
[37] Kumar Prashant, et al. An overview of monitoring methods for assessing the performance of nature-based solutions against natural hazards. Earth Sci Rev 2021;217:103603.
[38] Pernigotto G, Gasparella A. Classification of European climates for building energy simulation analyses. In: 5th int. High perform. Build. Conf., purdue, USA; 2018. p. 11.
[39] Italy profile. 2022. https://www.odyssee-mure.eu/publications/efficiency-trends-policies-profiles/italy.html. [Accessed 25 November 2022].
[40] Zhang Y, Kang J, Jin H. A review of green building development in China from the perspective of energy saving. J Energy 2018;11:334.
[41] U.S. Energy Information Administration. China executive summary. 2022. https://www.eia.gov/international/analysis/country/CHN. [Accessed 28 February 2023].
[42] Salvalai Graziano, Gabriele Masera, Maria Sesana Marta. Italian local codes for energy efficiency of buildings: theoretical definition and experimental application to a residential case study. Renewable Sustainable Energy Rev 2015;42:1245–59.
[43] Ministry for Ecological Transition. Strategy for energy retrofitting of national building stock. 2023. https://energy.ec.europa.eu/system/files/2021-12/2020_ltrs_italy_-_en.pdf. [Accessed 12 February 2023].
[44] Ascione F, Bianco N, de'Rossi F, Turni G, Vanoli GP. Green roofs in European climates. Are effective solutions for the energy savings in air-conditioning? Appl Energy 2013;104:845–59.
[45] Zhou LW, Wang Q, Li Y, Liu M, Wang RZ. Green roof simulation with a seasonally variable leaf area index. Energy Build 2018;174:156–67.
[46] Ávila-Hernández A, Simá E, Xamán J, Hernández-Pérez I, Téllez-Velázquez E, Chagolla-Aranda MA. Test box experiment and simulations of a green-roof: thermal and energy performance of a residential building standard for Mexico. Energy Build 2020;209:109709.
[47] Ferrante P, La Gennusa M, Peri G, Rizzo G, Scaccianoce G. Vegetation growth parameters and leaf temperature: experimental results from a six plots green roofs' system. J Energy 2016;115:1723–32.
[48] Mahmoodzadeh M, Mukhopadhyaya P, Valeo C. Effects of extensive green roofs on energy performance of school buildings in four North American climates. Water 2019;12:6.
[49] Coma J, Chàfer M, Pérez G, Cabeza LF. How internal heat loads of buildings affect the effectiveness of vertical greenery systems? An experimental study. Renew Energy 2020;151:919–30.
[50] Chafer M, Perez G, Coma J, Cabeza LF. A comparative life cycle assessment between green walls and green facades in the Mediterranean continental climate. Energy Build 2021;249:111236.
[51] Alexandri E, Jones P. Temperature decreases in an urban canyon due to green walls and green roofs in diverse climates. Build Environ 2008;43:480–93.
[52] Peñalvo-López E, Cárcel-Carrasco J, Alfonso-Solar D, et al. Study of the improvement on energy efficiency for a building in the mediterranean area by the installation of a green roof system. Energies 2020;13:1246.
[53] Djedjig R, Belarbi R, Bozonnet E. Experimental study of green walls impacts on buildings in summer and winter under an oceanic climate. Energy Build 2017;150:403–11.
[54] Seyedabadi Mohammad Reza, Eicker Ursula, Karimi Saghar. Plant selection for green roofs and their impact on carbon sequestration and the building carbon footprint. Environmental Challenges 2021;4:100119.
[55] Perini K, Bazzocchi F, Croci L, Magliocco A, Cattaneo E. The use of vertical greening systems to reduce the energy demand for air conditioning. Field monitoring in Mediterranean climate, Energy and Build 2017;143:35–42.
[56] Koroxenidis E, Theodosiou T. Comparative environmental and economic evaluation of green roofs under Mediterranean climate conditions–Extensive green roofs a potentially preferable solution. J Clean Prod 2021;311:127563.
[57] Zhang A, Bokel R, van den Dobbelsteen A, Sun Y, Huang Q, Zhang Q. An integrated school and schoolyard design method for summer thermal comfort and energy efficiency in Northern China. Build Environ 2017;124:369–87.
[58] Skelhorn CP, Levermore G, Lindley SJ. Impacts on cooling energy consumption due to the UHI and vegetation changes in Manchester, UK. Energy Build 2016;122:150–9.
[59] Malys L, Musy M, Inard C. Direct and indirect impacts of vegetation on building comfort: a comparative study of lawns, green walls and green roofs. Energies 2016;9:32.
[60] Silva CM, Gomes MG, Silva M. Green roofs energy performance in Mediterranean climate. Energy Build 2016;116:318–25.
[61] Gomes M Glória, et al. Impact of vegetation, substrate, and irrigation on the energy performance of green roofs in a Mediterranean climate. Water 2019;10:2016.
[62] Fantozzi F, Bibbiani C, Gargari C, et al. Do green roofs really provide significant energy saving in a Mediterranean climate? Critical evaluation based on different case studies. Front. Archit. Res. 2021;10:447–65.
[63] Irga P, Fleck R, Wooster E, et al. Green roof & solar array–comparative research project final report july 2021. 2021. https://opus.lib.uts.edu.au/bitstream/10453/150142/2/City%20of%20Sydney%20Final%20Report%20EPI%20R3%20201920005.pdf. [Accessed 25 December 2022].

[64] University of technology Sydney. Green roof & solar array – comparative research project final report. July 2021. https://opus.lib.uts.edu.au/bitstream/10453/150142/2/City%20of%20Sydney%20Final%20Report%20EPI%20R3%20201920005.pdf 2021. [Accessed 13 February 2023].
[65] Wang Y, Akbari H. The effects of street tree planting on Urban Heat Island mitigation in Montreal. Sustain Cities Soc 2016;27:122–8.
[66] Rouhollahi M, Whaley D, Byrne J, Boland J. Potential residential tree arrangement to optimise dwelling energy efficiency. Energy Build 2022;261:111962.
[67] Tsoka S, Leduc T, Rodler A. Assessing the effects of urban street trees on building cooling energy needs: the role of foliage density and planting pattern. Sustain Cities Soc 2021;65:102633.
[68] Hsieh CM, Li JJ, Zhang L, Schwegler B. Effects of tree shading and transpiration on building cooling energy use. Energy Build 2018;159:382–97.
[69] Balogun AA, Morakinyo TE, Adegun OB. Effect of tree-shading on energy demand of two similar buildings. Energy Build 2014;81:305–15.
[70] Zhao Q, Sailor DJ, Wentz EA. Impact of tree locations and arrangements on outdoor microclimates and human thermal comfort in an urban residential environment. Urban For Urban Green 2018;32:81–91.
[71] Palme M, La Rosa D, Privitera R, Chiesa G. Evaluating the potential energy savings of an urban Green Infrastructure through environmental simulation. In: Proceedings of building simulation 2019 conference. IBPSA; 2019. https://doi.org/10.26868/25222708.2019. 210698.
[72] Feng W, Ding W, Zhen M, Zou W, Wang H. Cooling effect of urban small green spaces in qujiang campus, xi`an jiaotong university, China. Environ Dev Sustain 2022;24:4278–98.
[73] Ayad A, Fahmy M, Kamel W. Urban green and blue infrastructure simulation in a changing climate from microclimate to energy consumption: a case study in Alexandria, Egypt. In: Proceedings of the 16th IBPSA international conference and exhibition. Rome: Italy; 2019. p. 7–9.
[74] Pisello Anna Laura, et al. The impact of local microclimate boundary conditions on building energy performance. Sustainability 2015;7:9207–30.
[75] Moss JL, Doick KJ, Smith S, Shahrestani M. Influence of evaporative cooling by urban forests on cooling demand in cities. Urban For Urban Green 2019;37:65–73.
[76] Toparlar Y, Blocken B, Maiheu B, van Heijst GJF. Impact of urban microclimate on summertime building cooling demand: a parametric analysis for Antwerp, Belgium. Appl Energy 2018;228:852–72.
[77] Zhang K, Garg A, Mei G, et al. Thermal performance and energy consumption analysis of eight types of extensive green roofs in subtropical monsoon climate. Build Environ 2022;216:108982.
[78] Abuseif M, Dupre K, Michael RN. The effect of green roof configurations including trees in a subtropical climate: a co-simulation parametric study. J Clean Prod 2021;317:128458.
[79] Anwar MW, Ali Z, Javed A, Din EU, Sajid M. Analysis of the effect of passive measures on the energy consumption and zero-energy prospects of residential buildings in Pakistan. In: Building simulation, vol. 14. Tsinghua University Press; 2021. p. 1325–42.
[80] Ragab A, Abdelrady A. Impact of green roofs on energy demand for cooling in Egyptian buildings. Sustainability 2020;12:5729.
[81] Ran J, Yang Z, Feng Y, et al. Energy performance assessment and optimization of extensive green roofs in different climate zones of China. E3S Web Conf 2020;172:16003.
[82] Porcaro M, de Adana MR, Comino F, et al. Long term experimental analysis of thermal performance of extensive green roofs with different substrates in Mediterranean climate. Energy Build 2019;197:18–33.
[83] Cascone S, Catania F, Gagliano A, et al. A comprehensive study on green roof performance for retrofitting existing buildings. Build Environ 2018;136:227–39.
[84] Jahanfar A, Sleep B, Drake J. Energy and carbon-emission analysis of integrated green-roof photovoltaic systems: probabilistic approach. J Infrastruct Syst 2018;24:04017044.
[85] Stamenković MG, Miletić MJ, Kosanović SM, et al. Impact of a building shape factor on space cooling energy performance in the green roof concept implementation. J Therm Sci 2018;22:687–98.
[86] Gao Y, Shi D, Levinson R, et al. Thermal performance and energy savings of white and sedum-tray garden roof: a case study in a Chongqing office building. Energy Build 2017;156:343–59.
[87] Ziogou I, Michopoulos A, Voulgari V, et al. Energy, environmental and economic assessment of electricity savings from the operation of green roofs in urban office buildings of a warm Mediterranean region. J Clean Prod 2017;168:346–56.
[88] Boafo FE, Kim JT, Kim JH. Evaluating the impact of green roof evapotranspiration on annual building energy performance. Int J Green Energy 2017:479–89.
[89] Refahi AH, Talkhabi H. Investigating the effective factors on the reduction of energy consumption in residential buildings with green roofs. Renew Energy 2015;80:595–603.
[90] Ascione F, Bianco N, De Masi RF, et al. Mitigating the cooling need and improvement of indoor conditions in Mediterranean educational buildings, by means of green roofs. Results of a case study. J. Phys. Conf. Ser. 2015;655. https://doi.org/10.1088/1742-6596/655/1/012027. Article 012027.
[91] Feng H, Hewage K. Energy saving performance of green vegetation on LEED certified buildings. Energy Build 2014;75:281–9.
[92] Moody SS, Sailor DJ. Development and application of a building energy performance metric for green roof systems. Energy Build 2013;60:262–9.
[93] Yao L, Chini A, Zeng R. Integrating cost-benefits analysis and life cycle assessment of green roofs: a case study in Florida. Hum Ecol Risk Assess 2020;26:443–58.
[94] Begum MS, Bala SK, Islam AS, Roy D. Environmental and social dynamics of urban rooftop agriculture (URTA) and their impacts on microclimate change. Sustainability 2021;13:9053.
[95] Aboelata A. Assessment of green roof benefits on buildings' energy-saving by cooling outdoor spaces in different urban densities in arid cities. Energy 2021;219:119514.
[96] Evangelisti L, Guattari C, Grazieschi G, et al. On the energy performance of an innovative green roof in the Mediterranean climate. Energies 2020;13:5163.
[97] Zheng Y, Weng Q. Modeling the effect of green roof systems and photovoltaic panels for building energy savings to mitigate climate change. Rem Sens 2020;12:2402.
[98] Gholami M, Barbaresi A, Tassinari P, Bovo M, Torreggiani D. A comparison of energy and thermal performance of rooftop greenhouses and green roofs in mediterranean climate: a hygrothermal assessment in wufi. Energies 2020;13:2030.
[99] Ebadati M, Ehyaei MA. Reduction of energy consumption in residential buildings with green roofs in three different climates of Iran. Adv Build Energy Res 2020;14:66–93.
[100] Zhang Y, Zhang L, Ma L, Meng Q, Ren P. Cooling benefits of an extensive green roof and sensitivity analysis of its parameters in subtropical areas. Energies 2019;12:4278.
[101] Gagliano A, Detommaso M, Nocera F, Patania F, Aneli S. The retrofit of existing buildings through the exploitation of the green roofs–a simulation study. Energy Proc 2014;62:52–61.
[102] Chen CC, Lee SH. Research of Artificial sites green roof for energy-saving efficiency in Taiwan Taichung. Appl Mech Mater 2013:1342–5.
[103] Permpituck S, Namprakai P. The energy consumption performance of roof lawn gardens in Thailand. Renew 2012;40:98–103.
[104] Algarni Salem, Almutairi Khalid, Alqahtani Talal. Investigating the performance of energy management in office buildings by using a suitable green roof design to reduce the building's energy consumption. Sustain Energy Technol Assessments 2022;54:102825.
[105] Lin Yaolin, et al. Design optimization of a passive building with green roof through machine learning and group intelligent algorithm. Buildings 2021;11(5):192.
[106] Battista Gabriele, Emanuele de Lieto Vollaro, Roberto de Lieto Vollaro. How cool pavements and green roof affect building energy performances. Heat Transf 2021;43(3–5):326–36.
[107] Pianella A, et al. Effects of substrate depth and native plants on green roof thermal performance in South-East Australia. In: IOP conference series: earth and environmental science, vol. 588. IOP Publishing; 2020. No. 2.
[108] Yaghoobian Neda, Jelena Srebric. Influence of plant coverage on the total green roof energy balance and building energy consumption. Energy Build 2015;103:1–13.
[109] Bevilacqua P, Bruno R, Arcuri N. Green roofs in a Mediterranean climate: energy performances based on in-situ experimental data. Renew Energy 2020;152:1414–30.
[110] He YF, Peng LH, Yang XS, Feng NY. Annual energy effects and cost-benefit analysis of green roofs in A hot-summer-cold-winter climate. Resour Environ Yangtze Basin 2021;30:2253–63.
[111] Kokogiannakis G, Darkwa J, Yuan K. A combined experimental and simulation method for appraising the energy performance of green roofs in Ningbo's Chinese climate. In: Building simulation. Springer Berlin Heidelberg; 2014. p. 13–20.
[112] Gagliano A, et al. The adoption of green roofs for the retrofitting of existing buildings in the Mediterranean climate. Int J Sustain Build Technol Urban Dev 2016;7(2):116–29.
[113] Bakhshoodeh R, Ocampo C, Oldham C. Exploring the evapotranspirative cooling effect of a green façade. Sustain Cities Soc 2022;81:103822.
[114] Perez G, Coma J, Chafer M, et al. Seasonal influence of leaf area index (LAI) on the energy performance of a green façade. Build Environ 2022;207:108497.
[115] Coma J, Chàfer M, Pérez G, Cabeza LF. How internal heat loads of buildings affect the effectiveness of vertical greenery systems? An experimental study. Renewable. Energy 2020;151:919–30.
[116] Coma J, Perez G, de Gracia A, et al. Vertical greenery systems for energy savings in buildings: a comparative study between green walls and green facades. Build Environ 2017;111:228–37.
[117] Wong I, Baldwin AN. Investigating the potential of applying vertical green walls to high-rise residential buildings for energy-saving in sub-tropical region. Build Environ 2016;97:34–9.
[118] Pan L, Chu LM. Energy saving potential and life cycle environmental impacts of a vertical greenery system in Hong Kong: a case study. Build Environ 2016;96:293–300.
[119] Peng LL, Jiang Z, Yang X, Wang Q, He Y, Chen SS. Energy savings of block-scale facade greening for different urban forms. Appl Energy 2020;279:115844.
[120] Zheng X, Dai T, Tang M. An experimental study of vertical greenery systems for window shading for energy saving in summer. J Clean Prod 2020;259:120708.
[121] Varghese JT, Thomas S, Herbert J. A sustainable green façade retrofit for an iconic built structure: a case study at SAINTGITS. In: ICSBE 2018: proceedings of the 9th international conference on sustainable built environment. Springer Singapore; 2020. p. 419–32.
[122] Tan Hang, et al. Investigation on energy saving potential of a vertical greening system in hot summer and cold winter areas in China. In: Proceedings of the 11th international symposium on heating, ventilation and air conditioning (ISHVAC 2019) volume III: buildings and energy 11. Springer Singapore; 2020.

[123] Poddar S, Park D, Chang S. Energy performance analysis of a dormitory building based on different orientations and seasonal variations of leaf area index. Energy Effic 2017;10:887–903.
[124] Dahanayake KKC, Chow CL. Studying the potential of energy saving through vertical greenery systems: using EnergyPlus simulation program. Energy Build 2017;138:47–59.
[125] Bevacqua M, Grossi G, Fionda MP, Arcuri N. Passive cooling techniques for less energy consumption in buildings a comparative study on green surfaces. In: 2018 IEEE international conference on environment and electrical engineering and 2018 IEEE industrial and commercial power systems Europe (EEEIC/I&CPS Europe). IEEE; 2018. p. 1–6.
[126] Poddar S, Park DY, Chang S. Simulation based analysis on the energy conservation effect of green wall installation for different building types in a campus. Energy Proc 2017;111:226–34.
[127] Cameron RW, Taylor J, Emmett M. A Hedera green façade–energy performance and saving under different maritime-temperate, winter weather conditions. Build Environ 2015;92:111–21.
[128] Aboelata A, Sodoudi S. Evaluating urban vegetation scenarios to mitigate urban heat island and reduce buildings' energy in dense built-up areas in Cairo. Build Environ 2019;166:106407.
[129] Palme M, Privitera R, La Rosa D. The shading effects of Green Infrastructure in private residential areas: building Performance Simulation to support urban planning. Energy Build 2020;229:110531.
[130] Morakinyo TE, Lau KKL, Ren C, Ng E. Performance of Hong Kong's common trees species for outdoor temperature regulation, thermal comfort and energy saving. Build Environ 2018;137:157–70.
[131] Skelhorn CP, Lindley S, Levermore G. Urban greening and the UHI: seasonal trade-offs in heating and cooling energy consumption in Manchester, UK. Urban Clim 2018;23:173–87.
[132] Calcerano F, Martinelli L. Numerical optimisation through dynamic simulation of the position of trees around a stand-alone building to reduce cooling energy consumption. Energy Build 2016;112:234–43.
[133] Shen T, Chow DHC, Darkwa J. Simulating the influence of microclimatic design on mitigating the urban heat island effect in the hangzhou metropolitan area of China. Int. J. Low Carbon Technol. INT J LOW-CARBON TEC 2016;11:130–9.
[134] Hao X, Xing Q, Long P, et al. Influence of vertical greenery systems and green roofs on the indoor operative temperature of air-conditioned rooms. J Build Eng 2020;31:101373.
[135] Li Z, Chow DH, Yao J, Zheng X, Zhao W. The effectiveness of adding horizontal greening and vertical greening to courtyard areas of existing buildings in the hot summer cold winter region of China: a case study for Ningbo. Energy Build 2019;196:227–39.
[136] Andric Ivan, Kamal Athar, Sami G, Al-Ghamdi. Efficiency of green roofs and green walls as climate change mitigation measures in extremely hot and dry climate: case study of Qatar. Energy Rep 2020;6:2476–89.
[137] García M, Vera S, Rouault F. Coupling of two validated heat and mass transfer models for green roofs and living walls with EnergyPlus and evaluation of its impact on the thermal performance of a retail building in a semiarid climate. In: 14th international conference on thermal performance of the exterior envelopes of whole buildings. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE); 2019.
[138] Santamouris M, Haddad S, Saliari M, et al. On the energy impact of urban heat island in Sydney: climate and energy potential of mitigation technologies. Energy Build 2018;166:154–64.
[139] De Munck C, Lemonsu A, Masson V, Le Bras J, Bonhomme M. Evaluating the impacts of greening scenarios on thermal comfort and energy and water consumptions for adapting Paris city to climate change. Urban Clim 2018;23:260–86.
[140] Dardir Mohamed, Berardi Umberto. Development of microclimate modeling for enhancing neighborhood thermal performance through urban greenery cover. Build Environ 2021;252:111428.
[141] Gros A, Bozonnet E, Inard C, Musy M. A new performance indicator to assess building and district cooling strategies. Procedia engin 2016;169:117–24.
[142] Berardi U. The outdoor microclimate benefits and energy saving resulting from green roofs retrofits. Energy Build 2016;121:217–29.
[143] Costanzo V, Evola G, Marletta L. Energy savings in buildings or UHI mitigation? Comparison between green roofs and cool roofs. Energy Build 2016;114:247–55.
[144] Ran J, Tang M. Effect of green roofs combined with ventilation on indoor cooling and energy consumption. Energy Proc 2017;141:260–6.