Heliyon 9 (2023) e15917

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Review article

# Green roof and energy – role of climate and design elements in hot and temperate climates

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ARTICLE INFO

*Keywords:*
Green roof
Energy use
Climate condition
Urban overheating
Green roof design elements

ABSTRACT

In the past few decades, the air temperature of built environment and energy demand of buildings has been increased, particularly in summer. As a consequence, the number of heat waves, heat-related mortality and morbidity have increased. The wide application of air conditioning and high level of energy use are inevitable to save people's lives, particularly in hot and temperate climates. Under these circumstances, this study offers a scoping review of the articles published between 2000 and 2020 to evaluate the role of green roofs in building energy use in hot and temperate climates. Given the ongoing trend of urban overheating, the scope of this review is limited to hot–humid, temperate and hot–dry climate zones. This scoping review shows the benefits of green roofs for reducing the demand of building energy in different climate zones and highlights the higher magnitude of energy saving in temperate climates than hot-humid or hot-dry climates provided that the green roofs are well-irrigated and uninsulated. According to the review of the articles published between 2000 and 2020, the reduction in cooling load is maximum (mean 50.2%) in temperate climate zones for well-irrigated green roofs. The effectiveness in saving cooling load reduces in hot–humid and hot-dry climate zones with means of 10% and 14.8% respectively. Green roof's design elements also strongly influence the potential in saving energy, and the effectiveness is heavily influenced by background climatic conditions. The findings of this study assist building designers and communities to better understand the amount of energy savings due to green roofs and present the results in different climates quantitatively.

## 1. Introduction

Based on the forecast of the United Nations, the percentage of the world population living in cities will reach 66% by 2050 [1]. This trend will continue in future, entailing further urbanisation [2], which is the major source of human-induced contributors to climate change [3], global warming and potential growth of the urban heat island (UHI) effect [4].

Since the 1950s and the emergence of energy crisis in megacities, there has been an urgent need to reduce the increased urban air temperatures, and increase green spaces, particularly in city centres. This has been the key drive behind the new wave of approaches

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https://doi.org/10.1016/j.heliyon.2023.e15917
Received 23 November 2022; Received in revised form 18 April 2023; Accepted 26 April 2023
Available online 4 May 2023

**Abbreviations**

| Symbol | Description |
|---|---|
| Am | Tropical monsoon climate |
| Af | Tropical rainforest climate |
| BSk | Cold semi-arid climate |
| BWh | Hot desert climate |
| BWk | Cold desert climate |
| Cfa | Humid subtropical climate |
| Cfb | Temperate oceanic climate |
| Csa | Hot-summer Mediterranean climate |
| Csb | Warm-summer Mediterranean climate |
| Cwa | Monsoon-influenced humid subtropical climate |
| Cwb | Subtropical highland climate |
| Dfa | Hot-summer humid continental climate |
| Dfb | Warm-summer humid continental climate |
| Dwa | Monsoon-influenced hot-summer humid continental climate |
| EGR | Extensive green roof |
| FASST | Fast all-season soil strength |
| GNP | Gross national product |
| HVAC | Heating, ventilation and air conditioning |
| HDPE | High-density polyethylene |
| IES-VE | Integrated Environmental Solutions, Virtual Environment |
| IGR | Intensive green roof |
| KWH/m2 | kilowatt hours per square metre |
| LAI | Leaf area index |
| LCC | Life cycle cost |
| PMV | Predicted mean vote |
| PV | Photovoltaic |
| SIGR | Semi-intensive green roof |
| SLUCM | Single-layer urban canopy model |
| TRNSYS | Transient System Simulation Tool |
| TPO | Polyethylene thermoplastic |
| UAE | United Arab Emirates |
| USA | United States of America |
| UN | United Nations |
| UHI | Urban heat island |

towards building industry and green roof implementation as an ecological concept, and an innovative solution to address the above-mentioned challenges. In fact, the building sector is one of the key contributors to carbon dioxide emission globally (30%) [5]. Although the household energy consumption was reduced by 3.2% from 1990 to 2013 [6], a further improvement in building and infrastructure sectors is essential to lower energy consumption, and mitigate the increased urban air temperature.

In order to address climate change and reduce the energy use in built environment sectors, architects, urban planners and policy makers have to take thoughtful steps in retrofit strategies and update energy rating systems. Among the main mitigation and adaptation strategies to achieve this goal are the provision of green infrastructure and the replacement of impervious surfaces with natural greenery coverage [7–14]. Green infrastructure not only reduces the intensity of UHI and minimises the magnitude of urban overheating, but also contributes to urban wastewater management [15,16] and significant savings in energy use. In consideration of the shortage of areas for converting into green areas in dense urban areas, rooftops offer the greatest solution to increase the green coverage and form a resilient urban climate. Green roofs have been identified beneficial in providing thermal protection to buildings during summer and winter. Green roofs are also considered as a useful strategy to reduce annual building energy consumption and demand. Green roof was first initiated in northern Europe and subsequently, has been implemented in many countries across the world [17].

The technological advancements have promoted the development of extensive green roofs with thin growing medium, low maintenance and cost. This is in contrast to intensive green roofs with deeper substrates and a wider variety of plant types. One of the most recent green roof types are modular eco-roofs that allow greater flexibility in design.

Green roofs are now widely implemented worldwide and various policies have been adopted to foster the green roof application [18–20]. Over the last few decades, there has been an increased interest among the communities toward the application of green roof technology, mainly because of the multi-dimensional benefits (e.g., mitigating UHI [18,21] and reducing building energy consumption [22,23]). The benefits of energy saving by green roofs have raised great attention among researchers to quantify the possible optimisation of green roofs through modification of structural parameters (e.g., thermal insulation [18], growing media [24], irrigation level [25], and plant types [26]). However, the proper choice of each of the above-mentioned parameters heavily depend on background climatic conditions. Therefore, this study aims to review previous findings on the energy saving performance of green roof in relation to their structural parameters with a particular focus on background climatic conditions, specifically the three climatic conditions: hot-dry, hot-humid, and temperate climates. These climatic conditions are selected because they are frequently associated with the high rate of heat-related mortality in urban areas and the impacts on public health are quantifiable.

Our study presents an updated literature review on the green roof effect on energy use published between 2000 and 2020 and highlights the critical role played by the background climatic conditions and the structural design elements of green roofs. The popular Köppen climate classification system is used and target cities are located within the selected climate zones [27]. Moreover, this scoping review aims to compensate for any research gap in previous literature regarding the impact on cooling load by the green roof in three different climates and to ascertain if a relationship exists between climatic background and the energy saving capacity of green roofs.

## 2. Materials and methods

In this study, building energy consumption correlates with the green roof effect on the building energy performance. Green roof installation reduces the heat exchange between outdoor and indoor environments, leading to the consumption reduction of building energy. This study offers a scoping review of published articles that investigated the impact of green roofs on energy use in hot–dry, hot–humid and temperate climatic conditions published between 2000 and 2020 according to the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guideline.

1) This review was conducted using the Web of Science, Scopus, Springer and ScienceDirect databases by utilising the keywords: 'green roof,' 'green roof and energy use,' and 'energy performance of green roofs in different climates.'
2) The review found 83 relevant articles (including original research articles, review papers and scientific reports) and consisted of both measurement and simulation-based studies.
3) We limited the scope of this study to the three climatic conditions: hot-dry, hot-humid and temperate climates and excluded the duplicated papers extracted from different databases. As a result, out of the 83 articles, only 60 were identified as eligible after careful screening and filtering. Therefore, this study gathered and conducted a review of 60 scientific documents published between 2000 and 2020 that studied green roof's energy-saving potential of green roofs.
4) In the second round of filtering, 27 articles were excluded, because they were not within the scope of this review. In fact, we only considered those articles focusing on green roof's impact on energy use, but not their impact on mitigating UHI effect.
5) After the papers were screened and filtered, 33 research articles were chosen and categorised based on the climatic background that they focused on. The literature review process of identification, screening, eligibility and analysis is presented in Fig. 1.

The selected studies examined the three major types of green roofs: intensive, extensive, and semi-intensive green roofs. This review excluded papers that only investigated the impact of green roofs on energy use without quantifying the reduction in energy demand. Some articles reviewed did not provide the percentage/value of cooling load reduction for a particular scenario or case study, but they were included in this study for review. Important structural design parameters of green roofs having considerable effects on their ability to save cooling load (e.g. thermal insulation, growing media, irrigation and plants) were identified. Such an inclusion also assisted in explaining the green roof components, types and heat transfer process models in calculating energy use.

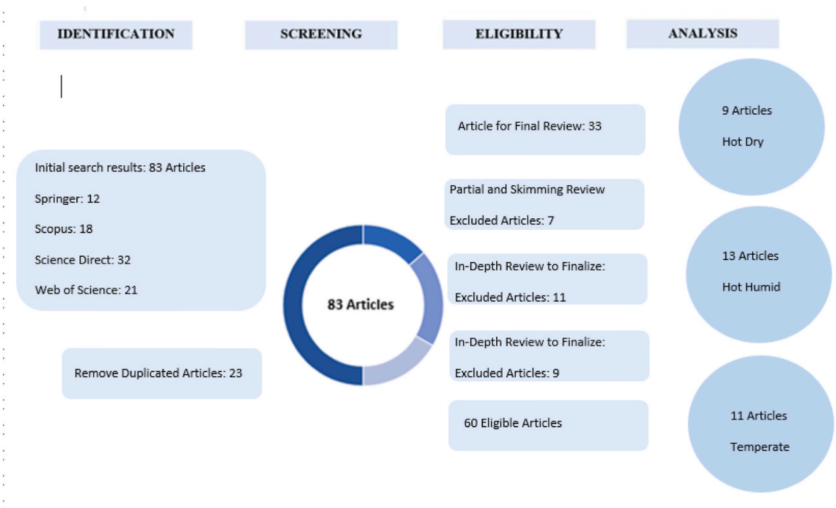



**Fig. 1.** Flow chart of systematic literature review based on the PRISMA guideline (modified from Ref. [28]).

The subsequent sections are to discuss the definition, components and types of green roofs and provide an overview of heat transfer processes that are incorporated into different models to simulate the energy use in buildings. The role of green roof design elements under different background climatic conditions is discussed accordingly to understand how the most efficient green roof can be designed for each climate zone.

## 3. Literature review

### 3.1. Green roofs – definition, components and types

Green roofs comprise of plants, growing media, drainage, waterproofing and insulation layers on the rooftop [29]. The term 'green roof' originates from the German word '*Dachbegrünung*' and is technically called vegetated roof, ecological roof, bio roof and living roof [30]. Germany is renowned for green roof construction because 10% of the rooftops in this country are covered with green roofs. France and Switzerland follow, and Poland is reaching them after the government set new guidelines and packages for green roofs to mitigate the adverse impact of urban development [31].

During the past few decades, green roofs have become popular globally as sustainable design strategies [32]. Green roof studies demonstrate various environmental, social and economic benefits, including better stormwater management, UHI mitigation, improvement of water and air quality, enhancement of the quality of life, reduction of building energy consumption and noise pollution, encouragement of recreational activities, and improvement of biodiversity and aesthetic value in urban environments [33]. Due to the water quality enhancement, green roofs reduce the burden of water treatment facilities [34]. Green roofs have significant impacts on buildings and their surrounding environment, so based on various benefits, more green roofs are established worldwide. Table 1 lists different types of benefits brought by green roofs.

Layers of waterproofing, drainage, thermal insulation, filter, soil and plants are the components of a green roof system. A green roof schematic section with its underlying components, is shown in Fig. 2. Excess water is absorbed from the drainage layer by the moisture mat, and any material damage from the plant roots is prevented by the root barrier. The soil is able to absorb any extra moisture. Some water is retained by the drainage layer and is thus ready for use during dry seasons. Drainage layer features and growing media play critical roles in the evapotranspiration level [38]. The insulation layer between the vegetation and roof slab is considered a protection layer for the root of the plants against the variation in temperature. The coverage areas of the foliage and substrate features are required to be considered to maximise the green roof's thermal behaviour [37].

Green roofs are broadly classified into two main domains: extensive vegetated green roofs (EVGRs) and intensive vegetated green roofs (IVGRs) based on different ranges of weight, substrate thickness, water requirement, plant species, construction cost and maintenance expense [38–40]. Semi-intensive vegetated green roofs (SIVGRs) represent a transition between extensive and intensive green roofs, displaying 25% features of EVGRs [41].

Extensive green roofs come with limited variety of vegetation palettes, thin substrates, minimal weight requirements and relatively low cost [42]. They are popular types of green roofs. Intensive roofs require a higher level of structural support and maintenance and are the most expensive type of roofs. The main merits of using IVGRs are their thicker substrate that allows the selection of a wider variety of vegetation [39]. The thick soil layer serves as thermal mass for increasing the time lag and reducing the thermal transmittance. An intensive green roof has a weight that reaches almost 290–968 kg/m$^2$. Comparatively, an extensive green roof has a lower

**Table 1**
Diverse benefits of green roofs [24].

| Benefits | Variables | Description | Ref |
|---|---|---|---|
| Ecological | Agriculture | 45% of the food was produced in Hong Kong, 1.4% increase in biodiversity and reduced need for irrigation | [32] |
| | Habitat for biodiversity | | |
| | Promoting indigenous plant species | | |
| Surrounding environment | Reduction in air and noise pollution | Decrease from PM10–0.42 to 9.1, SO2-0.1 to 1.01 and No2-0.37 to 3.75 g/m$^2$ | [31] |
| Energy | Carbon sequestration | Energy consumption with a negative effect of −7% to a saving of 70% annually | [35] |
| | Fire resistance | | |
| | Evapotranspiration, thermal insulation and energy conservation | | |
| Water resource | Reduced urban overheating, shading and cooling stormwater management | 0.03 °C–3 °C reduction in temperature | [36] |
| | | 0.3%–63% of the environment uses shading and evapotranspiration methods | |
| | Rainwater harvesting | Irrigation on 20 m$^2$ of urban areas in India would lead to a 20% increase in food on GRs | |
| Psychological Aesthetic Economic | Better quality of life with mental peace | 82.2% of people in cities agree with green roof installations | [37] |
| | Beautify the building | Visual aesthetics and attractiveness | |
| | Reduced cost of life cycle compared with a conventional roof, increased property value with longer roof life | Approximately 40% lower life cycle cost of a green roof than a conventional roof | |

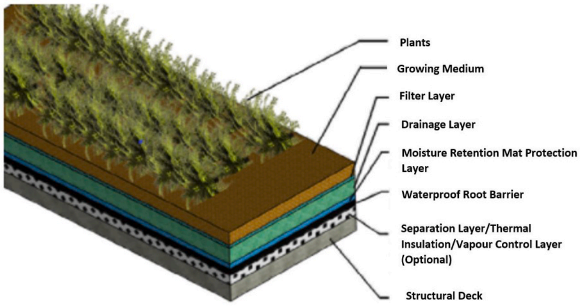



**Fig. 2.** Layers of green roof. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

weight of only 20–169 kg/m$^2$ [43].

The soil thermal performance is affected by three factors: depth, water balance and organic matter of the soil layer [44]. Having 100 mm thick soil is recommended to control heat absorption [45]. A similar study found that by every 100 mm increase in substrate thickness for clay, the roof thermal resistance would increase by 0.4 kW [46]. Soil water content also influences green roof's thermal performance. Higher water content of the soil layer increases its thermal conductivity [47].

Both semi-intensive and intensive roofs share similar features, but semi-intensive roofs involve lower maintenance. Moreover, their substrate layer is thinner than that of intensive green roofs [41]. According to a life cycle assessment study, extensive green roofs involve less construction costs, but offer higher levels of energy savings compared with other green roof types [37].

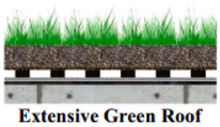
Green roofs require regular maintenance in general, but there is a lack of study on green roof maintenance [48]. For achieving the most favourable benefits from green roofs in hot climate, there is a need for regular fertilisation and watering. Checking on plants, drainage and substrate layers regularly extends the green roof life, but contributes to its maintenance cost.

According to a life cycle assessment of four different green roof types with different assemblies in a study conducted in Czech Republic, hydrophilic mineral wool assembly serves as a partial substitute for plant substrate to address the need to reserve water, thereby improving thermal insulation. In this study, a life cycle study spanning 20 years from a cradle-to-grave perspective was conducted [49], and it was found that the environmental impact is reduced considerably when the hydrophilic mineral wool assembly is used without substitutions. A research conducted in Hong Kong showed a cooler subsoil temperature when comparing green roofs with conventional roofs [30]. The characteristics of different green roof types are summarised in Table 2.

### 3.2. *Comparison of different types of green roof*

Nowadays, academics, engineers and organisations collaborate for carbon emission reduction from different aspects, including the contribution to net-zero energy buildings. Identifying different methods to generate energy for buildings is one approach, whereas decreasing the energy consumption of buildings is another way to achieve this goal [50]. There are numerous scattered data regarding the green roof effect on building energy consumption, which require classifications. For example, the cooling load may be reduced by

**Table 2**
Classification of green roofs in accordance with usage, maintenance and construction requirements [39].

| |  |  |  |
|---|---|---|---|
| Maintenance | Low | Periodically | High |
| Irrigation | No | Periodically | Regularly |
| Plant communities | Moss-Sedum-Herbs and Grasses | Grass-Herbs and Shrubs | Lawn or Perennials, Shrubs and Trees |
| System build-up height | 60–200 mm | 120–250 mm | 150–400 mm on underground garage >1000 mm |
| Weight | 60–150 kg/m$^2$ | 120–200 kg/m$^2$ | 180–500 kg/m$^2$ |
| Costs | Low | Middle | High |
| Use | Ecological protection layer | Designed Green Roof | Park like garden |

green roofs in hot climates on one hand, but the heating loads may be increased in cold climates on the other hand. As such, the fundamental objective of this study is to consolidate relevant information on green roof design elements to compare their impact on building energy consumption with respect to background climatic conditions due to diverse energy performance of green roofs under different climatic conditions.

Green roofs normally have around three additional layers than a conventional roof. Different layers of green roofs serve distinctive roles in the thermal and energy performance of the roofs.

The shading provided by the canopy of vegetation against sunlight in summer for keeping the soil surface temperature lower. The amount of shading is determined by foliage density and plant type. A similar impact can be achieved via shading devices. However, the surrounding temperature will be increased due to the reflected heat from shading devices.

The Energy Plus simulation program has been commonly used to quantify the amount of energy consumption and the energy saving capacity of green roofs. During the validation stage, most studies reported a gap lower than 10% between the measured and simulated energy data and thereby confirmed the accuracy of the simulation. The level of energy saving varied from 2% (in Doha, Qatar) [51] to 62% (Morelos, Mexico) [52]. In a research led by Pianella et al. [53], 50% reduction in energy consumption could be achieved by green roofs. When comparing a green roof with a bare roof, temperature differences of 2.5 °C and 4 °C were observed for 100 mm and 300 thick substrate layers respectively. We identified studies in which the maximum level of energy savings is limited to 9%–10% [54,55].

The relationship between local climatic conditions and green roof energy performance has been widely reported. For instance, in hot and dry climates, green roofs' thermal performance was claimed to improve substantially [56]. However, the study was based on simulation without any field experiment to validate the accuracy of the findings. Besides, studies have indicated that green roofs in high-density cities provide a higher level of cooling compared with those in low-density urban settings [57]. For example, according to a parametric review of green roofs in different urban densities, the energy saving for a subtropical climate can be leveraged if the green roof coverage ratio is 20%–30%. The authors also proposed methods to maximise energy performance via selecting the right plant type for the given hot–humid climate.

As discussed above, green roof design elements and local climate play crucial roles in the energy performance and energy saving capacity of the roofs. Therefore, in subsequent sub-sections, we will offer an overview of the effect of green roof design parameters on energy performance in relation to background climatic conditions. We limit the scope of these sub-sections into four key controllable parameters that affect the green roof energy performance: thermal insulation, growing media, irrigation, and plant types.

#### 3.2.1. Thermal insulation

It is well-established in the literature that the heat gain in the daytime and the heat dissipation through the building in the night-time are reduced due to green roof insulation. However, the reduction amount may vary on the basis of specific weather conditions (especially in hot–humid climates) and specific insulation values of green roofs. Uninsulated green roofs have a different thermal demeanour from that of green roofs that have good insulation. A study of four different climate conditions in North America showed that the green roof thermal insulation significantly affects their heat gain during the day [58].

In hot climates of Phoenix, Chicago, Los Angeles and Shanghai, the variations in insulation enabled green roofs to achieve enhanced summer thermal performance [59,60]. Similarly, insulated green roofs were able to considerably reduce heat gains and enhance building energy performance in Sydney, Madagascar and the tropical savanna climate of Rio de Janeiro [61,62]. The green roof thermal performance in Taipei (tropical) and Chiayi (subtropical) in Taiwan was compared in another study [49]. Green roofs in both climates were found to result in reduced cooling load during the day and play insulating role effects at night [63]. This study also showed that intensive, extensive, and semi-intensive green roofs can lead to heat gain reduction during the hottest period of the day, and the roofs perform as an insulation layer during the coldest time of the day. There was a similar finding obtained in Shanghai, in which an insulated modular green roof resulted in decreased indoor air temperature in the daytime and prevented heat dissipation in the night-time [64].

Our review showed that the use of insulated intensive roofs leads to an improved thermal demeanour in warm–hot climates compared with the use of conventional roofs. Insulated intensive roofs reduce the summer heat gain during the day both in warm and tropical climates [62,64–66]. However, the main concern is the heat sink effect that they may create overnight [63,67,68]. The heat sink effect will in turn reduce the heating demand for uninsulated roofs [69]. Similar results were obtained in the hot–dry climatic condition of the UAE, in which well-insulated green roofs reduced the heat gain through conduction, resulting in decreased cooling load.

Some studies showed different findings in respect of the effectiveness of insulation on the green roof energy performance. According to these findings, a highly insulated extensive green roof did not achieve major impacts on the energy consumption of a five-storey building during summer and winter [70]. For example, a study in Lisbon, Portugal showed that well-insulated roofs did not leverage the evapotranspiration cooling effects [71]. In the Mediterranean climate of Calabria, Italy, a comprehensive evaluation of green roof thermal effect showed that a green roof without an insulation layer would have overall improved energy performance [23]. Similarly, the use of highly insulated extensive green roofs in the hot–dry climatic condition of Saudi Arabia did not provide any cooling benefit compared with the use of bare roofs [72].

#### 3.2.2. Growing media

The material that is used in a container for growing a plant is regarded as 'growing medium.' Growing media are usually formulated using a mixture of different raw materials, so that a proper balance of air and water holding capacity can be achieved for the growth of plants. Similar to insulation parameters, background climatic conditions and thickness of growing media are key governing factors affecting the green roof energy performance. The thermal performance of an intensive green roof in the warm climate of Portugal was modelled; this setting was characterised by dominant cooling energy loads. The study showed that thicker growing media with thicker soil has more capacity in retaining soil water for evapotranspiration, resulting in the overall building energy demand reduction [71]. By contrast, in cold seasons in temperate climates, the increase in the growing media did not work in favour of energy demand. In fact, the thermal insulation of the growing media (provided by soil layer) was found to be critical to reduce the heating load, whereas irrigation and the coverage of the roof were found to have relatively insignificant roles in such climates. In the temperate climate of China, where heating is also the need of buildings, green roofs with 25 mm-thick insulation provide significant savings in the energy use for heating. This finding is in contrast with that for hot climates, where irrigation, green roof coverage and soil features play the key roles in energy savings. Another study in three different climate zones of China found that 0.3 m is the ideal thickness for the growing media to maximise the energy savings in buildings for both summer and winter [73].

The thickness of growing media also affects the soil dampness in all climatic conditions [74]. For example, in arid climates, the substrate dries quickly and prevents the plant's evapotranspiration processes from occurring correctly. In these climates, the use of unirrigated green roofs has insignificant or sometimes adverse impacts on the roof thermal behaviour compared with the use of conventional bare roofs. The main reason for this result is that the plant's evapotranspiration becomes extremely limited under hot and dry conditions [75]. In these climates, the plant canopy prevents the soil from becoming warm during the daytime, and the plant foliage prevents indoor cooling at night. Therefore, there is a need to maximise evapotranspiration for enhancing the green roof capacity for energy saving under arid climate.

The growing media are among the major installation challenges of green roofs. Given that they are often considered engineered substrates, the use of the media is restricted by cost, the environmental footprint of their construction and weight. Several studies have been conducted to overcome these challenges. For example, to reduce the cost and weight of growing media, a soilless medium consisting of fibres has been suggested. This medium also contributes to the cooling load, most notably in humid and subtropical climates [76]. The application of recycled aggregates and landfill materials for growing media reduces the environmental footprints of green roof installation is feasible if these materials can provide suitable growing media for certain plant species. The recycled rubber has higher density and lower porosity compared with those of the commonly used pozzolana, so it can be used as a drainage layer to facilitate energy saving [77]. Hydroponic green roofs demonstrated good thermal performance that they are more energy efficient compared with conventional rooftops in warm temperate and tropical savanna climates [78,79].

### 3.2.3. *Irrigation*

Several studies have identified the effectiveness of green roofs in both rainy and dry climates. The water use of green roofs is influenced by several parameters, including climate conditions (average temperature, relative humidity, annual rainfall and monthly distribution), plant species, green roof type (for example, intensive green roof needs more water than extensive green roof) [80]. Brunetti et al. [81] examined the impact of various daily irrigation scenarios on a non-vegetated green roof in a Mediterranean climate and estimated the irrigation volume of 7 L/day/m$^2$ daily. Schweitzer and Erell [43] assessed that the amount of water for irrigating an extensive green roof in a Mediterranean climate is between 2.6 L/m$^2$ and 9.0 L/m$^2$ daily. Peng and Jim [66] established an automatic sprinkler irrigation system in a humid subtropical climate for an experimental extensive green roof with water supply at 5 L/m$^2$ daily in summertime, achieving the soil moisture content of approximately 0.3 m$^3$ water/m$^3$ soil on average.

Studies in tropical climates highlighted the insignificant role that irrigation plays in the green roof thermal performance for rainy climatic condition. A conventional uninsulated roof retrofitted with a green roof under irrigated and unirrigated scenarios was studied in London. The green roof achieved energy savings of approximately 20% in both scenarios. This result indicated that no additional resources are needed in such fluctuating climates to guarantee a green roof's optimised thermal performance [82,83]. There was a research assessing green roof thermal performance under two irrigation scenarios in Beijing, London, Berlin, Madrid, Cairo, New York City and Mexico City. The finding indicated that lower irrigation levels improved the green roof thermal performance in cities that experience high precipitation, such as London, New York City and Mexico City [84]. The result was the same for Beijing, where precipitation was occurring particularly during summer. However, irrigated green roof shows better performance in cities with scarce rainfall, such as Cairo and Madrid.

Irrigation has a positive role in enhancing green roof energy performance in warm climatic condition according to some studies. Three Italian cities, namely, Catania, Rome, and Milan, each with distinct climates, were the sites for a study regarding the potential energy saving under an irrigated and a non-irrigated green roofs [85]. This study showed the energy savings of green roofs compared with conventional bare roofs regardless of the irrigation scenario. However, irrigation was found to be necessary in warm climates of Rome and Catania to optimise the green roof energy performance. By contrast, a green roof without irrigation in Milan performed better than irrigated green roofs. For green roofs with adequate levels of irrigation in the semi-arid climate, such as Santiago in Chile, their energy performance was enhanced and the energy use for cooling purposes was reduced [86]. In California, the mitigation impact of green roofs on energy demand was assessed to identify the relationship between irrigation and the energy savings of green roofs [87].

If a substrate is well irrigated, then it may be able to improve the cooling load by about 20%–30% in warm climates. Lower values are achieved with light-dry substrates. For example, green roofs with irrigation performed better than unirrigated ones in Singapore's climate [88]. By contrast, a study in Toronto found that irrigation did not affect an extensive modular green roof's energy performance [89]. According to a research conducted in California, radiant cooling could enhance the thermal and energy performance of the green roof in a hot-dry climate when the heat was dissipated from the radiant cooling system through the roof and the green roof was sufficiently irrigated [90].

#### 3.2.4. Plants

Plants are another important structural element that have significant impact on green roof's thermal and energy performance [60, 91]. Plants exhibit different behaviours as the seasons vary, and they also have diverse evapotranspiration rates. During summer, higher transpiration values are often recorded than those during winter. Green roof's energy performance can be maximised if plants are selected with respect to their evapotranspiration rate, background climate and building requirements.

The thermal behaviour of various vegetation species in relation to saving energy was assessed in a Mediterranean climate, and the findings indicated that green roof installation results in heating reduction by 11% and cooling reduction by 19% based on the type of plants [92]. In Hong Kong, the energy-saving potential of two different types of plants in two green roofs (peanut and sedum) was quantified. The green roof with sedum resulted in energy demand reduction, whereas green roof with peanut led to increased summer cooling loads [93]. A similar result was achieved in Toronto, Canada, where a sedum roof resulted in better energy performance compared with a grass roof [89]. The energy and thermal behaviour of extensive green roofs with different plant species in Michigan, USA was evaluated, and the findings indicated that green roofs with sedum plants achieved better performance than green roofs with herbaceous plants. In winter, perennial grass exhibited improved demeanour because it had the lowest thermal loss [94]. In Cuernavaca, Mexico, the plant species with the highest tolerance towards drought (*Aeonium subplanum*) led to improved energy performance for green roofs. However, irrigating these plants would lead to better energy performance [95].

Some studies have proved that the foliage of plants affects their evapotranspiration rate and solar radiation that reaches the soil. These studies also highlighted the significant role of leaf area index (LAI) in reducing energy use in warm climates [86,96]. As indicated by the energy and thermal performance of a fully vegetated green roof in the coastal Mediterranean climatic condition, plants achieved a 60% heat gain reduction, resulting in 9% higher outgoing energy from the roof compared with the incoming energy [97]. In Melbourne, high values of LAI resulted in significant reductions in heat flux and substrate temperature, affecting green roof's energy and thermal performance of green roofs. Zhou et al. [98] evaluated the relationship between LAI and the energy retention capacity of green roofs. He et al. (2017) examined the effect of LAI and the thickness of soil on green roof's thermal performance. Cascone et al. (2019) [99] evaluated the configurations of 30 plant substrate with six different plant species together with five substrates types to identify which one optimised the energy performance of extensive green roofs in Mediterranean climatic condition. The *Salvia* plant was identified to be the best option in summer, whereas *Sedum* and *Sempervivum* showed the best performance for the whole year with respect to the leaf reflectivity, height, LAI, and stomatal resistance.

Studies showed that the impact of plant coverage on the energy performance of green roof is highly affected by local climates and rooftop thermal insulation [100]. The green roof's energy performance with various plant species was evaluated in Palermo, Italy. *Aptenia* and *Mesembryanthenum* on green roofs demonstrated ideal behaviour during summer, whereas those with *Gazania* performed the best during winter [101]. 16 types of green roofs were modelled with varying degrees of plant species and coverage (0%, 50%, 75% and 100%) in different cities in the United States, including Baltimore, Maryland and Phoenix, Arizona, in which higher percentages of LAI led to lower values of cooling energy demand [102]. Likewise, high plant coverage and low stomata resistance for plants resulted in reduced cooling energy demand in Benevento, Italy [103]. Similarly, green roof's thermal and energy behaviour with various LAI values was evaluated and compared in different climates of China. In cold, temperate and hot–humid continental climates of China, higher values of reduced energy demand for cooling and increased energy demand for heating. In warm and temperate climate zones of China, an increase in LAI would result in significant reductions in overall annual energy use, particularly cooling load [73]. In Shanghai, green roofs with the greatest LAI exhibited the best energy performance during summer [104]. In addition to the evapotranspirative roles of plants in saving energy, their reflectance influences green roof's energy behaviour because a high solar reflectance prevents the solar radiation from reaching the soil of green roofs.

## 4. Discussion

Green roofs provide two types of thermal benefits: building energy savings and UHI effect reduction. When outdoor temperatures are higher than indoors, green roofs minimise the energy use of buildings via (1) evapotranspirative cooling, (2) higher albedo than bare roofs, and (3) better insulation due to the growing media. The green roof's impact on UHI is basically the outcome of reduced temperature of roof surface via evapotranspiration and albedo. When the outdoor temperatures are lower than the indoor air temperatures, green roofs can provide energy savings through their substrate insulation. The mechanism of thermal benefits in cold climates has yet to be fully studied.

This review offers an overview of green roof's design parameters that affect their energy and thermal performance with respect to background climatic conditions. Thermal insulation is a design element of green roofs that is found to be important in all climatic types, whereas buildings with better insulation (particularly in a temperate climatic condition) were determined to be beneficial. However, most of related studies were conducted on roofs with much less insulation. Besides, it is common to have a noteable time lag for the heat flux peak in the daytime showing the operation of thermal inertia of roof slabs with good insulation.

The review of articles published between 2000 and 2020 showed that different green roof types have distinct depths of growing media. Intensive green roof systems, for instance, require 254 mm (10.00 in) or more of growing media for the growth of a wide variety of plant species. Comparatively, extensive green roofs have shallower growing media with 76.2–152.4 mm depth (3.00–6.00 in) to support a narrow range of plant species. Having shallow depths of growing media result in decreased water holding capacity and poorer insulation of plant roots from freezing temperatures. Therefore, the depth of the growing media is critical to maintaining both physical and chemical properties to support plant growth for green roofs.

The review also demonstrated that a rooftop environment should be distinguished from traditional plant settings in terms of the selection of growing media for a green roof. Reduced moisture, extreme temperatures and drought, high levels of solar radiation and wind create hostile locations for plants. It is critical for green roof growing media to hold sufficient nutrients and water for plants to survive in different climatic conditions.

Water is a crucial factor affecting green roof's energy performance in summer months. Irrigated green roofs show better environmental benefits in hot season of semi-dry and dry climatic conditions, which can be up to 84% energy saving. Energy saving of irrigated green roofs in tropical and arid climates are 65% and 30% respectively. In sum, green roofs influence thermal efficiency, especially in summer, subject to irrigation and dry periods.

Plant types, coverage and LAI of the vegetation affect green roof's energy retention performance. In Mediterranean climatic condition, the *Salvia* plant was identified to be the best option in summer, whereas *Sedum* and *Sempervivum* showed best performance for the whole year with respect to the leaf reflectivity, height, LAI and stomatal resistance. The recommended plant type for hot–dry and tropical climates was scattered and did not follow a specific plant.

Green roofs (depending on their design elements and background climatic conditions) showed different energy performance behaviour. Fig. 3 shows the range of energy saving in heating (in three climate zones) and cooling in temperate climate as the positive outcome due to the implementation of green roofs in selected climates. Most studies did not indicate all the design elements used in the green roofs and limited the scope to the energy saving capacity of green roofs (Tables 3–5). Therefore, identifying a mathematical correlation between each design element, background climate, and green roof's energy performance was not feasible, but we have captured the findings from the previous studies on green roof's energy saving values in selected climates and plotted them in Fig. 3.

For each data set provided in Fig. 3, the outliers were excluded, and the median variations were quantified and utilised to plot maps that present information on the green roof's energy reduction capacity in different climates.

The box plots in Fig. 3 were extracted from 33 peer-reviewed papers that were critically analysed and categorised into three different classifications. The obtained values are plotted in three box and whisker plots. All three climatic conditions show a common energy demeanour (decrease in overall energy use) but at different extents. According to Fig. 4, the reduction in cooling load is maximum (mean 50.25%) in temperate climate zones for well-irrigated green roof. The effectiveness in saving cooling load reduces in hot–humid and hot-dry climate zones with means of 9.94% and 14.84% respectively.

The maximum saving in cooling load in temperate climate was recorded in Sicily, Italy, with an 80% reduction in energy use. This was followed by Athens, Greece and Catania with 62.5% and 35% reductions in energy use, respectively.

In the hot–dry climate zone, a green roof installed in Saudi Arabia showed the best performance by reducing the cooling load by 29.5%. This was followed by Cairo and UAE, showing 23% and 18% savings in energy use. Hot–dry climates take the second position, with vegetation coverage and irrigation listed as the key design factors that affect the energy performance of green roofs. In such climates, the use of dense foliage plants with low absorption level results in lower roof surface temperature and thereby saves higher energy level.

Our review also showed that in hot–dry climates, unirrigated roofs present lower moisture content than bare roofs, and water availability plays a critical role in maintaining their function for reducing the energy. The reason for this finding is that irrigation affects the evapotranspiration rates in plants, and this rate grows quickly when green roofs are irrigated in hot–dry climates. Evapotranspiration rate is influenced by both plant types and substrate conditions. Plants with high LAI values should be preferred in all three climatic types to maximise the plant transpiration rate.

The urban structure and building design also play crucial roles in green roof's performance in energy efficiency. In temperate climates, minimally insulated green roofs lead to further reductions in energy use compared with well-insulated roofs. Some studies highlighted the influencing factor of urban form for improving green roof's energy performance. The height, orientation and arrangement of urban blocks cause different energy performance for green roofs as they trap portion of incoming solar radiation through shading from the surrounding buildings and green infrastructure.

Based on Fig. 3, from the studied articles, green roofs have common energy behaviour in all selected climatic conditions. By

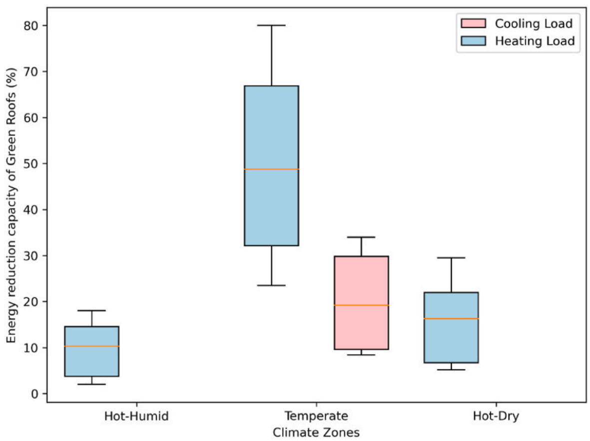



**Fig. 3.** Comparison of green roof's energy saving capacity in the reduction of cooling and heating loads (%) in different climates based on 33 reviewed articles. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

**Table 3**
Green roof's energy saving capacity in hot–dry climates.

| Ref | Location | Climate | Type | Methodology | Findings |
|---|---|---|---|---|---|
| [105] | Dhahran (Saudi Arabia) | Bwh | Extensive | DesignBuilder, field measurements | The energy saving between 24% and 35%. |
| [106] | Bandar Abbas, Tehran, Tabriz (Iran) | BWh, Csa, BSk | N/A | Weather research (WRFv3.8.1) with a single-layer urban canopy model (SLUCM) | Reduction of the annual electricity consumption up to 16.3%, 12.5% and 23% in Tehran, Tabriz and Bandar Abbas, respectively. |
| [107] | Dhahran, Riyadh (Saudi Arabia) | BWh | Extensive | Ecotect | Reduction of the energy consumption by 6.7% and 6.8% in Dhahran and Riyadh, respectively. |
| [108] | Cairo (Egypt) | BWh | Extensive | DesignBuilder | Reduction of the annual electricity consumption by 17%–25%. |
| [109] | Cairo (Egypt) | BWh | Extensive | DesignBuilder | Energy savings varied from 15% to 32% compared with traditional and un-isolated roofs. |
| [110] | Sharjah (UAE) | BWh | Extensive | | Reduction of the cooling load by 6% and 12% in winter and summer respectively. |
| [55] | Bandar Abbas, Tehran, Tabriz (Iran) | BWh, Csa, BSk | Extensive | DesignBuilder | Reductions of 6.19%, 2.07% and 9.45% in energy use were realised for Tehran, Tabriz and Bandar Abbas, respectively. |
| [111] | Cairo | BWh | Intensive, semi-intensive, extensive | ENVI-met and EnergyPlus | Reduction of the energy consumption of 5.2% with fully intensive green roofs in a hot–dry climate, whilst the least saving of 0.1% with semi-extensive green roofs in a temperate climate. |
| | Hong Kong | Cwa | | | |
| | Tokyo | Cfa | | | |
| | Paris | Cfb | | | |

**Table 4**
Green roof's energy-saving capacity in hot–humid climates.

| Ref | Location | Climate | Type | Methodology | Findings |
|---|---|---|---|---|---|
| [96] | Incheon, (South Korea) | Dwa | Extensive | EnergyPlus | Reduction of overall annual building energy consumption by 3.7% |
| [112] | Portland, Chicago, Atlanta, Houston (US) | Csb | N/A | EnergyPlus | Reduction in heating by 2% |
| | | Dfa | | | |
| | | Cfa | | | |
| | | Cfa | | | |
| [95] | Yucatán (Mexico) | Cwb | Extensive | | Reduction in electricity consumption by 10.3% |
| [58] | Toronto, Vancouver, Las Vegas Miami | Dfa, Am, Cfb, BWk | Extensive | EnergyPlus | Reduction in cooling by 29% in Miami; reduction in cooling by 54% in Vancouver; reduction in cooling by 45% in Toronto; and reduction in cooling by 41% in Las Vegas |
| [113] | Toronto (Canada) | Dfa | Extensive | EnergyPlus | Reduction of energy demand by 3% |
| [114] | Chicago, Houston (US) | Dfa | Extensive | EnergyPlus | Energy savings of 2% for both cities. |
| | | Cfa | | | |
| [115] | Athens (Greece) | Cfa | N/A | Numerical simulation model | Energy consumption savings by 9%. |
| [116] | Florida (US) | Cfa | Extensive | Experimental approach | Energy consumption savings by 18%. |
| [46] | Singapore | Af | Extensive & Intensive | DOE-2 energy simulation | Saving of annual energy consumption by 0.6%–14.5% |
| [117] | Toronto (Canada) | Dfa | N/A | Modified version of an environmental system performance programme simulator | Energy savings of 73%, 29% and 18% for one-, two- and three- storey design, respectively |

contrast, green roofs in hot–humid climates have dissimilar effects, as indicated by the conflicting results obtained by some studies, particularly during rainy seasons. Our review also indicated that there were only limited studies on green roof's impact on cooling energy load. Tables 3–5 present the key results of the studies on green roof's impact on energy use based on their background conditions: hot–humid, hot-dry and temperate climates.

Our review further showed that green roof components (insulation, substrate, irrigation and plant choice) have critical impacts on their thermal and energy performance. However, creating correlation between each design element, climatic conditions and energy performance was not achievable because of insufficient information provided by authors regarding green roof's design elements in their studies. From the reviewed articles, we concluded that thicker growing media and substrate reduces heat gain, especially in warm climate zones [125]. In temperate and hot–dry zones, the main governing factor in reducing energy is the growing media that influence

**Table 5**
Green roof's energy-saving capacity in temperate Mediterranean climates.

| Ref | Location | Climate | Type | Methodology | Findings |
|---|---|---|---|---|---|
| [118] | La Rochelle (France) | Cfb | Extensive | A green roof thermal model with a building model | Reduction of the annual energy demand by 6%. |
| [119] | Catania (Italy) | Csa | Extensive | | Reduction of the energy consumption for cooling by 31%–35% and reduction of the energy consumption for heating by 2%–10% in winter |
| [120] | Athens (Greece) | Csa | Extensive | In-situ measurements EnergyPlus | Overall savings of 15.1% for a whole year |
| [121] | Athens (Greece) | Csa | Semi-intensive | TRNSYS | Energy savings for heating from 21.1% to 28.4% and cooling from 60.5% to 62.5% |
| [112] | Portland, Chicago, Atlanta, Houston (US) | Csb Dfa Cfa Cfa | N/A | EnergyPlus | 2% reduction in heating |
| [71] | Lisbon [Portugal] | Csa | Extensive, Semi-intensive Intensive | EnergyPlus | 20% saving in energy use |
| [122] | Calabria [Italy] | Csa | Extensive | TRNSYS | Annual savings of 34.9% |
| [87] | Los Angeles [US] | Csa | Extensive | EnergyPlus | Savings by 20%. |
| [99] | Catania [Italy] | Csa | Extensive | EnergyPlus | 8.41% energy savings in winter 23.53% energy savings in summer |
| [123] | Vittoria [Italy] | Csa | Extensive | Transient simulation programme | Reduction of the cooling and heating loads by 80% and 34%, respectively |
| [124] | Amman [Jordan] | Csa | N/A | Ecotect | Total energy savings up to 17% |

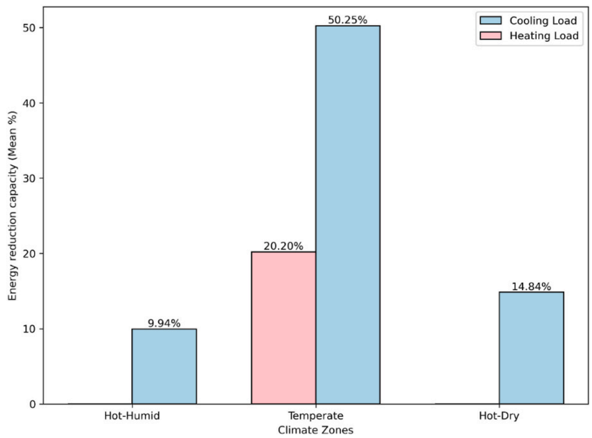



**Fig. 4.** Comparison of the mean reduction in energy consumption across different climatic zones.

heat capacity, thermal conductivity, and albedo [126]. Plant type is another critical factor that affects green roof's energy performance, especially in hot–dry and hot-humid zones, because maximising the transpiration from plant canopy, shade and increased roof albedo can improve the performance; all these factors can be directly influenced by vegetation types [127]. An increased building surface albedo has a greater effect on the net global cooling than transpirative or evaporative cooling [128]. Therefore, different cooling mechanisms may vary in terms of their overall environmental benefits.

In all climate zones, plant choice seems to affect the surface temperature of substrates and, as a result, reduce building energy performance and mitigate UHI mitigation. The reduction of leaf surface temperatures, together with transpiration rates and albedo, play a role in decreasing heat transfer to buildings and lowering air temperatures [129,130]. Studies have shown that the selection of best- and worst-performing plants would make a 9.7% difference in growing medium surface temperature [131]. These studies also indicated that a wider range of plant species results in differences of 14%–24% in growing medium surface temperature, and this value increases due to increased vegetation coverage over time. A similar study found that green roofs' performance is improved once the low-performing plants are replaced with high-performing plants [132].

By contrast, in cold climates, the insulation from the growing media is the main factor in maximising green roof's energy performance. Our literature review examining the cooling loads of buildings showed that similar to hot climates, LAI of the plants can also affect green roof's energy performance in winter. Contrary to warm seasons, higher LAI values in cold seasons decrease the direct solar heat gain and lead to a lower level of energy savings.

Snow coverage is also affected by plants and contributes to lower levels of variations in temperature in cold seasons in temperate climates [133]. Lundholm studied the thermal performance of different plant species on winter energy saving, which indicated a substantial difference between the minimum and maximum growing media temperatures, resulting in overall savings in energy use. In addition, plants with higher biomass levels during winter capture more snow, thus contributing to moderate temperatures [127].

The winter performance of green roofs has been under debate because some scholars claimed that they save energy, whereas others claimed that they consume energy. Regardless of the conclusion, green roof's performance in winter is influenced by four factors, which must be considered when selecting green roofs that will be used in cold or temperate climates. These variables are: (1) the volumetric moisture content of soil, (2) solar radiation, (3) ambient outdoor temperature, and (4) snow.

It was concluded that there is a lack in comparative research on heat flux and other energy performance indicators of green roofs with different plant types (with respect to the climatic background). Furthermore, given the simplifications made by the majority of numerical simulations on key plant parameters (e.g. LAI or stomata resistance), future research should aim to fill this gap by conducting empirical characterisation of these parameters in different plant species in diverse climates.

Each climatic type examined in this study showed distinctive responses with respect to the cooling energy demand for HVAC systems and green roof's impacts on reducing energy demand. Nevertheless, there were some similarities on the energy reduction of some of the parameters studied in this review. All selected climate zones benefited from green roof implementation. Cities situated in temperate climates have high reduction in energy use due to the implementation of different green roof settings. Therefore, policy makers and governments are strongly recommended to implement mandatory policies and incentive schemes to encourage building owners and developers to provide green roofs for reducing energy consumption towards sustainability development goals.

The impact of thermal insulation on reducing energy consumption fluctuated for green roof implementation, presenting various level of effect based on the background climate and green roof settings. In temperate climates, insulation positively affects green roof's energy reduction, whereas the impact of insulation on green roof's energy performance is slightly lower in hot-humid climatic condition. Comparatively, the irrigation level and plant type were identified as key elements in hot-dry climates that governments and policy makers should invest on.

## 5. Conclusion

This study provided a literature review on green roof's impact on building energy use in different climates: hot–humid, hot-dry, and temperate and hot–dry that were published between 2000 and 2020. The main findings with respect to green roof's energy saving performance in different climates and relevant references available in literature are summarised in Tables 3–5. Future research should include further climate zones and geographical areas that have not been included in this review article. This is quite critical to expanding the literature on green roof's energy saving capacity, particularly when they are deployed widely.

Our review revealed that although structural parameters (e.g. insulation, substrate, irrigation, and vegetation) may affect green roof's thermal and energy performance, which heavily depends on background climatic conditions. Moreover, green roofs consistently provide positive impact on reducing the demand of building energy. However, the energy saving amount of cooling load in temperate climates (well-irrigated and uninsulated) is significantly higher than the other two climate types. Plants, particularly their LAI, are crucial in maximising the green roof's energy performance in all climates.

This study concluded that in cold seasons in temperate climates, the soil layer thermal insulation can be traded off by plant shading and evapotranspiration. For instance, a soil layer with 40 mm thickness can provide an ideal thermal insulation in hot–humid climates. No additional benefits are derived as the soil layer becomes thicker. Irrigation is essential in reducing the energy use in hot–dry climates. However, green roofs that are not irrigated in dry climates will have a negligible effect on building energy demand. Likewise, irrigation has a negligible effect on green roofs in rainy climates. Moreover, the review demonstrated the importance of LAI in reducing building energy demand in all selected climates. However, it has a lower effect on cloudy days.

This review is fairly extensive, yet it can still be expanded further in future to include more studies on areas that have been investigated and to include additional climatic conditions that were not included in this review. Nevertheless, the findings in this review can provide assistance and support for architects, policymakers, urban planners and city councils, such that they can design efficient by-laws and regulations to mitigate UHI and minimise building energy demand by considering background climatic conditions.

Given that green roof's energy-saving potential and their economic and environmental benefits differ from one climate to another, future research should focus on the development of a comprehensive plant database (with optimal LAI level and foliage density) by examining the requirements of various plant species based on background climatic conditions. For example, research on green roof's thermal performance in cold climates is limited but crucial to improving our understanding of their potential to contribute to improved energy efficiency and enhanced thermal performance for buildings in winter.

Green roof research has been challenging and offers a lot of opportunities for further research. Despite of significant benefits, there are other factors including high construction costs and maintenance issues, which are required to be taken into account for future applications globally. This study highlights how green roof can help saving energy in hot and temperate climates and highlight the areas of collaboration required among cities for resource management and urban planning to reduce energy consumption across three climate zones. Future research should focus on detailed parametric research of diverse spatial configurations of green roofs for both newly constructed and retrofitted buildings in various climate zones. Future research direction should also take building use, urban morphology, roof insulation, plant types and substrate thickness into consideration.

## Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

## Funding statement

Dr. Elmira Jamei was supported byCity of Melbourne (COM) and the DDepartment of Environment, Land, Water and Planning (DELWP) [GOR0052019].

## Data availability statement

Data included in article/supp. material/referenced in article.

## Declaration of interest's statement

The authors declare no competing interests.

## Acknowledgment

We would like to thank City of Melbourne and Department of Environment, Land, Water and Planning (DELWP) to fund our project related to Green Our Rooftop Grant application, which assisted us in conducting a systematic review on the existing literature and provided the required background for our research-project titled Quantifying and optimising the impact of green roof coverage on UHI, energy consumption and outdoor thermal comfort (GOR0052019).

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