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Green roof substrates—A literature review

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Green roofs are becoming increasingly popular in urban construction due to their wide array of benefits for creating a sustainable ecosystem. Many stakeholders invest in green roofs in the 21st century to enhance the environmental quality and mitigate urban ecological pollution. The substrate layer is the most important and critical component of green roof systems. The objective of the review study is to present the important information regarding the required elements that need to be considered for substrate selection of green roofs by critically reviewing the scientifically published articles. Research findings from past studies relevant to green roofs, vegetation and selective substrate parameters were extensively discussed under different topics related to water retention, drought resistance and related physico-chemical parameters. The generalities in past research articles were presented and special focus was provided on specific research articles those presented novelty regarding green roof substrates. Furthermore, the hotspots in all the considered research articles were commentatively identified and the appropriate solutions were evaluated. The critical review of published research articles indicates that most of the research on green roof substrates was conducted in either controlled laboratories or greenhouses and did not provide much importance to actual field tests. Therefore, these research findings are not sufficient to obtain the realistic field outcomes of the research. Future studies on green roof substrates should need to incorporate field experiments along with classical controlled tests by adhering to standard guidelines for assimilating climatic influences in substrates. Few studies have focused on dry climates, and further research needs to be conducted on dry climates due to their high susceptibility to drought and evapotranspiration. This manuscript would be the first review article that mainly focuses on substrates for green roofs, which is a novel aspect.

KEYWORDS

green roof, substrates, physico-chemical properties, sustainable ecosystem, critical review, research gaps

1 Introduction

There are a substantial number of articles available regarding green roofs and their benefits to ecosystems (Oberndorfer et al., 2007; Rowe, 2011; Vijayaraghavan, 2016; Francis and Jensen, 2017), its hydrological attributes (Stovin, 2010; Kim et al., 2021) and on its contribution to mitigate UHI (Dunnett, 2011; Kolokotsa et al., 2013; Yang et al., 2018). The green roof is the ideal solution to the urban heat island (UHI) effect and urban ecosystem scarcity (Parizotto and Lamberts, 2011; Blank et al., 2013; Vijayaraghavan, 2016; Pianella et al., 2017; Barriuso and Urbano, 2021; Park et al., 2022; Wang X et al., 2022). UHI is a common problem in various intensely populated cities in the world. Hence, it harms the urban ecosystem and human health (Santamouris, 2020). According to a research study on green roof benefits from an environmental perspective, successful implementation of green roofs would effectively mitigate the UHI effect, enrich the biodiversity of urban ecosystems, purify the air from pollutants, and reduce the runoff quantity (Li and Yeung, 2014; Raimondi and Becciu, 2021; Liu et al., 2022) to promote urban sustainability.

Substrate (growing medium) is the most important component of the green roof system. It ensures the stability and longevity of sustainable cultivation (Ampim et al., 2010). Commercial substrates are common in industrial applications. Non-commercial substrates are customizable with preferred ingredients (Ampim et al., 2010). Appropriate substrate selection is essential for the sustainable survival of vegetation. If the substrate is light-weighted and consists of low organic matter, then it will require additional water and supplements to enhance plant growth (Getter and Rowe, 2006). Stakeholders in the construction industry are more concerned with the economic benefits of increasing user accommodations, with little regard for building sustainability.

Most of the tests in either laboratory or greenhouse environments are conducted according to either American Society for Testing Materials (ASTM) or German Landscape Research, Development and Construction Society (FLL) guidelines. The most popular one in Europe and the UK is the FLL guidelines. These guidelines have specific limits for each specified physico-chemical property to enhance the optimal output from green roof substrates. However, since these FLL guideline recommended values are reaped from various research experiments conducted in various regions within Germany (FLL, 2008), not all the FLL guideline recommendations are applicable to entire areas of the world since their climatic conditions are different from Germany (Kazemi and Mohorko, 2017). It has created a need for more sophisticated guidelines for selecting appropriate green roof substrates.

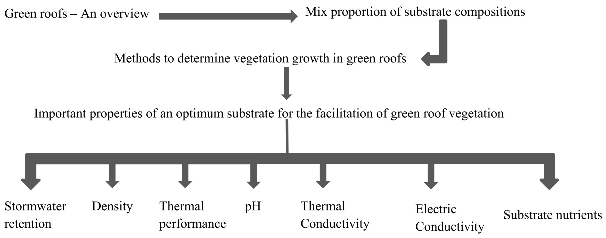
The 2014 ASTM International guidelines differ significantly from the FLL guidelines. This guide provides more preference than FLL guidelines for climatic comparisons (Kazemi and Mohorko, 2017). However, the complex test procedures of the ASTM international guidelines for substrate characterisation have made it rarely used in industry. AS 4419-2003 is the sole standard followed in Australia (Standard, A., 2003). It has some specific sets of criteria to evaluate the performance of soils, organic and inorganic matters. However, it is highly recommended to use both AS 4419-2003 and AS 3734-2003 together (Haege and Leake, 2014) for a comprehensive selection of green roof substrates.

The necessity to find all the necessary information regarding the growing medium is high due to the increasing demand for green roofs in urban cities. If all the required details regarding the substrates were available in a scientific article, this would serve as a resource pool for agricultural researchers, soil scientists, and environmental scientists.

There was a successful experimental study conducted in Poland by using the selected set of appropriate physical and chemical properties to check the viability of waste silica as a growing medium for green roofs (Krawczyk et al., 2017). Innovative methods were also designed to test the viability of using recycled aggregates as substrates by analysing the selected set of parameters essential for plant growth (Mickovski et al., 2013; Molineux et al., 2015). However, a rationalised review article is essential in current environmental circumstances to provide entire information based on proper substrate selection for green roofs. Because correct substrate selection is the most important metric in the successful implementation of green roof technology in skyscrapers due to the high probability of experiencing intense evaporation due to the acute sunlight (Yeang and Richards, 2007; Sheweka and Magdy, 2011; Rich, 2021). This review paper extensively discusses the required physical and chemical characteristics of a growing medium to implement it as a substrate on green roofs. The objective of the study is to provide vital information about the aspects that must be addressed for substrate selection of green roofs by critically examining scientifically published literature. Previous research findings pertaining to green roofs, vegetation, and selected substrate factors were widely reviewed under several subjects pertaining to water retention, drought resistance, and associated physico-chemical parameters. In this regard, this review article appears to be novel since there were no contrary reviews found in past studies related to the green roof substrates.

2 Green roof substrates

The review study was made into the following framework to facilitate the understanding of the content in previously published research articles, their significances, key outputs, peripheral findings, major hotspots and interactive discussion in a concise way:



2.1 Green roofs—An overview

Green roof technology dates back to 500 BC with the reference to Babylonian hanging gardens (Li and Yeung, 2014). Green roofs are specifically enfolded with growing medium, waterproofing membrane, and vegetation either partially or completely. In other words, it is the installation of vegetation on a rooftop (Getter and Rowe, 2006). The number of high-rise buildings is increasing at an astronomical rate in the current scenario due to the demand for a metropolitan lifestyle and urbanization. This change in the trend of construction has resulted in a drastic loss of forest coverage, water resources, flora and fauna. As a result of the existing environmental, economic, and social concerns, urban construction mechanisms have been forced to introduce new technologies for the mitigation of harmful environmental consequences (Rowe et al., 2012; Pianella et al., 2017). The green roof concept was revitalised with highly endorsed research projects in developed countries like Germany (Thuring and Dunnett, 2014) and United States (Bousselot et al., 2020) during the last four decades to utilise it as a tool to mitigate urban environmental pollution.

Intensive green roofs and extensive green roofs are the two major types currently practised in the construction industry. Intensive green roofs can support large trees and shrubs, and they require a high-depth substrate layer of more than 15 cm (Cascone, 2019; Pandey et al., 2021) and these types of green roofs need frequent maintenance (Molineux et al., 2009; Jaffal et al., 2012). However, extensive green roofs are designed to equip with ecological function rather than an anaesthetic (Ampim et al., 2010). The plants laid on extensive green roofs are soft-stemmed species like herbs, grasses and mosses are used (Getter and Rowe, 2006). Due to that, the substrate depth used is less than 15 cm, requiring lower maintenance than the intensive green roofs (Jaffal et al., 2012). Therefore, extensive green roofs are cheaper than intensive ones, and they require less maintenance. These inherent benefits of extensive green roofs have made them the most significant green roof type in use in the world compared to intensive green roofs.

The conventional roofs allow rainwater to rapidly run-off from their surfaces, which would aggravate flooding, escalate erosion and affect the combined sewer overflows that could possibly discharge untreated or partially treated sewage straight into waterways. In solving this matter, green roofs are considered to be of greater importance as they absorb rainwater by delaying its run-off and promoting evapotranspiration (VanWoert et al., 2005; Blank et al., 2013; Stovin et al., 2013) and enhance the efficacy of storm water management (Stovin et al., 2013).

Green roofs have a significant contribution to the reduction of carbon footprint as they reduce the emission of greenhouse gases, which leads to an atmosphere with mitigating air pollution and also with reduced noise pollution (Jaffal et al., 2012). The green roof also provides long-term benefits, such as helping to reduce the UHI effect (Dunnett, 2011; Kolokotsa et al., 2013; Yang et al., 2018) through facilitating indoor thermal comfort where the requirement for a cooling system has also become lessened, offering energy benefits as well (Dareeju et al., 2010; Pianella et al., 2017). Furthermore, the incidence of high-intensity solar radiation is controlled with a strong roofing membrane (Parizotto and Lamberts, 2011). The sophisticated amount of green roof vegetation in cities has increased floral availability and established animal diversity (Jaffal et al., 2012), thus demonstrating the importance of green roofs over conventional roofs.

The green roof is made up of several layers, including a waterproofing layer, insulation, drainage layer, geotextile or filter layer, growing medium, and vegetation (Cascone, 2019). Several research studies have used various prototypes. In a research study to distinguish between the variation of temperature and moisture content over extensive green roofs (Baryła et al., 2019), the green models were designed using a wooden base, protective membrane, root-resistant hydro isolation, filtration layer, 15 cm thick layer of mineral substrate, drainage mat, and a 2.5 cm thick prefabricated vegetation mat. This prototype was successfully executed with sedum plant vegetation.

Another study used a pressure-treated wood platform, insulation, waterproofing, media, drainage layer, and vegetation carrier, as well as a retention fabric layer with a thickness of 0.75 cm and the ability to hold up to 5.69 kg/m^2 of water (Rowe et al., 2012). In this study, the models of green roofs consisted of only a wooden base, waterproofing membrane, drainage layer, geotextile, growing medium, and the vegetation layer because of their being the vital layers to a green roof. A unique field study was conducted using gravel and pebble drainage layers instead of the classical plastic drainage layer (Parizotto and Lamberts, 2011) to determine the albedo and emissivity magnitudes to analyse the thermal benefits and energy efficiency of green roof buildings.

2.2 Mix proportion of substrate compositions

The main objective of this subtopic is to study regarding the growing mediums utilised in previous research studies and to know their corresponding mix proportions. Because the best fitting ration would not only enrich the vegetation with nutrients and water seepage (Young, 2014), but also prevent the substrate system from becoming a heavyweight component which is an essential requirement for the longevity of medium rise and high rise buildings (Ahmed and Alibaba, 2016; Khan and Asif, 2017; Mahmoodzadeh et al., 2019; Kader et al., 2021). Table 1 illustrates the details regarding the mix proportions and compositions used for substrate preparations in the past studies.

The regional context is important because there would be maximum benefits under various substrate proportions based on the climate of the considered region and the selected type of vegetation (Ampim et al., 2010) along with other green roof requirements such as type and weight. It is recommended to conduct a preliminary study using prototypes to determine the best fitting mix proportions prior to the initiation of a green roof installation.

The overall durability of green roofs is hugely influenced by the substrate thickness. The following study results in Table 2 were adapted based on water retention capacities in the past.

The comparison of results obtained from the above studies has shown that a greater quantity of water is retained with a 4 cm depth of growing medium (Rowe et al., 2012) albeit it did not focus on thermal performances in 4 cm thickness. The ultimate requirement is to select a lightweight substrate with optimum plant-growing conditions.

2.3 Selection of vegetation

The decisive parameters in the selection of vegetation are the climate of a particular region and the availability of plant resources. There were previous studies where vegetation was selected based on the corresponding regional climates. An experimental research study based on plant performances concludes that, plants like *Lomandra longifolia, Stypandra glauca,* and *Dianella admixta* were considered for green roof studies to withstand thermal radiation in the buildings (Pianella et al., 2017). Furthermore, there are also some studies in which seeds were used instead of plant species (Nagase and Dunnett, 2010) and seed mixture with plant remains (Lundholm et al., 2010). It was evident that there were no restrictions on selecting the vegetation since it is based on the climate and the desire.

Buffalo grass (*Bouteloua dactyloids*) is a type of tropical turf grass which copes with the Sri Lankan climatic zones. It is widely available in countries like Sri Lanka. The majority of Sri Lankan green roofs are planted with buffalo grass because it requires less maintenance, less water, and is less prone to disease (Dareeju et al., 2010). Due to these user-friendly attributes, germinated buffalo grass can be recommended in preliminary studies to identify the proper substrate mix proportions.

In order to calculate the growth rate, several past studies were analysed. In a particular study, the parameters such as vegetation growth, survival rate, and the abscission of leaves were empirically identified using overhead photos of plant specimens (Butler and Orians, 2011). There has been a successful study completed on plant growth by considering the diameter of the plant stem, blossomed flowers, total flower ratio per plant, and the plant height (Nagase and Dunnett, 2012). Since the first two parameters are unavailable with buffalo grass, it is best advised to consider the plant height as the metric during preliminary studies where buffalo grass is used. Plant height is measured from soil level to the peak apex of each substrate specimen during preliminary studies.

Drought resistance of selected vegetation types has been measured in past studies using various modes. Binary rating (MacIvor et al., 2011) is one such method where "0" was given if the plant was dead and "1" was given if the plant was alive, after a prolonged period using visual inspection. The experiment was concluded after the determination of the survival percentage of selected plants. This method is non-compatible with short-term drought resistance experiments and the mode of analysis is highly prone to errors, which requires accuracy in observations.

There were some visual methods applied in some studies with detailed methodologies using planting dishes. One such study has been conducted on 31 species and installed on the rooftop for 3 months under progressive observation of the growth under controlled conditions, such as the only mode of water supply was through the researchers. After the dedicated three-month duration, plants were allowed to grow under only natural circumstances, and the observations were obtained through photographs on a regular basis (Liu et al., 2012). This method is not very effective since it lacks mathematical justification and relies more on visual instincts.

One of the similar aspects in the previously mentioned studies was that the plant specimens used in all of those studies were "separable." Since buffalo grass would be used in this study, none of those methods is effective in this research. In order to compensate for this drawback, some practically feasible alternatives were devised. For these types of compacted grasses, finding the survival vegetation by considering the vegetation coverage area would be the most appropriate method of analysis rather than counting the number of plants.

2.4 Methods to determine vegetation growth in green roofs

Various techniques were used in previous studies for the measurement of the growth of the vegetation. In one experimental study, vegetation growth was measured seven times over a two-year period, and the total coverage of plots, the seeded species, the succulents Sedum acre and Sedum album, and the bryophyte layer were estimated by visual inspection (Van Mechelen et al., 2015). In another study, photos of each sample were taken weekly during the growing season (Butler and Orians, 2011) and these images were used to calculate parameters such as vegetation survival, growth during wet periods, and leaf losses caused by water shortage.

The above method can be applied when there is a horizontal expansion of vegetation rather than vertical growth. In the preliminary study of this research, stems of buffalo grass were used, so there was vertical growth rather than horizontal expansion. Therefore, the overhead photos could not be used as a method to measure the growth rate of the sample vegetation used in this study.

One researcher used a different method to measure the growth rate of his vegetation (MacIvor et al., 2011). A three-dimensional pin frame was used to assess the vegetation cover. The rate of growth was determined by calculating the difference between the number of times that a plant hit one pin of the frame at its peak (or final) measurement and the total hits recorded at the initial measurement (MacIvor et al., 2011). The technique used in this research had a different setup than the one adopted in the current research, whereby this method was precluded.

In another research (Braatz et al., 2021), the number of flowers per plant, the number of blossomed flowers, plant height, and the diameter of the plant had been used to determine the growth of the vegetation, whilst another study had measured the plant height from the bottom to the highest leaf apex (Nagase and Dunnett, 2010). The comprehensive approach is that, whereas vegetation growth was measured in the current study by taking the plant height from the bottom to the apex of the leaf at the highest elevation.

2.5 Important properties of an optimum substrate for the facilitation of green roof vegetation

2.5.1 Storm water retention

The models used in the studies to determine the storm water retention properties of the growing medium were approximately equal, but the dimensions were different. Platforms with 0.67 m × 2.44 m dimensions were used for a study to analyse the effects of substrate surface, slope and layer thickness on storm water retention (VanWoert et al., 2005), while 1 m × 2 m platforms were used in both of the studies designed to observe the effect of vegetation cover on runoff reduction (Soulis et al., 2016) and to determine the influence of temperature and moisture content on storm water retention (Baryła et al., 2019). All three research projects used a platform slope of 2%, thus showing that it would be the ambient inclination of the substrate layer in green roofs.

Different techniques were used to collect run-off and precipitation data in the previous studies. A study was conducted to illustrate storm water reduction and the Combined Sewer Overflow (CSO) scenarios (Bliss et al., 2009) demonstrated by a unique prototype. The experimental setup included a "Hydrologic Services RG703 8-inch tipping bucket rain gauge" to collect precipitation data. Two "Campbell Scientific SM616 Soil Water Content Sensors" were placed on the contrapositions of the green roof to measure the soil volumetric water content at 5 min intervals. In order to collect run-off data separately, the roof drain was also separated from the remainder and a "Tracom 60-degree extra-large trapezoidal flume" was used. Moreover, a "Greyline LIT25 ultrasonic sensor" has been adopted to measure the depth of water. However, this technique is not adaptable to mediocre budget research projects due to the high cost and fewer facilities.

On the other hand, a field study to collect run-off data was facilitated in a greenhouse by introducing a temperature gradient between the interior and exterior environment (Nagase and Dunnett, 2012). There were no special requirements to measure the rainfall separately because the amount of water falling on the vegetation surface was determined using a simulator in this research experiment. The only disadvantage of this study (Nagase and Dunnett, 2012) is that it the experiment was performed using natural rain, so a separate precipitation measuring process was required. The interior environment of the greenhouse was heated above 20°C and the outside environment was below 20°C. Another study used metal troughs made of aluminium sheets on the platforms' low end to direct storm water run-off (VanWoert et al., 2005) through the measuring devices. In this case, the trough had been divided into separate sections corresponding to the nature of the experiment, and tipping bucket rain gauges were used as run-off measuring devices.

In some other studies, precipitation data had been collected from a nearby weather station, which was 10 km away from the study site (Van Mechelen et al., 2015). In this case, the accuracy of the data is doubtful. Hence, the accuracy of precipitation data was of paramount importance for this current research; the stated method was not adopted in most of the industrial applications.

2.5.2 Density of green roof substrates

Methods of measuring bulk density can be divided into two main categories: The first category is the direct method, which consists of three subcategories named core method, cold method, and excavation method. The second category is the indirect method, which consists of two subcategories named the radiation method and the regression method (Al-Shammary et al., 2018). According to a study on different soil types for crop production (Soane and Van Ouwerkerk, 2013), all the direct methods are suitable for undisturbed soil. Hence, indirect methods are quite advanced and expensive. Since the growing mediums are generally disturbed soils, direct methods were not entertained.

The most recommended sampling method was "Frame sampling," implemented to find bulk density and soil compaction relations (Campbell, 1994). The steel frame of 0.5 m^2 was hammered through the required layers, and the elevation of the soil surface was measured using the upper edge of the frame as a reference plane. A layer of soil of an appropriate thickness was removed using hand tools and weighed. Then the elevation of the new soil surface was measured. The volume of removed soil was calculated using those readings. With knowing weight and volume, density was determined (Soane and Van Ouwerkerk, 2013). Any method can be used to find the density as per convenience and the scope of the experiment. The optimum lightweight substrate in terms of density would consist of the lowest unit weight and high moisture content (Harmayani, 2012; Johansson et al., 2012), and the substrate selection experiments should focus on these requirements due to their rational outcomes.

2.5.3 Thermal performance

Many studies have been conducted to demonstrate the thermal performance of the green roof. A certain study has been performed using a building with a green roof and an adjacent building without a green roof as samples (Niachou et al., 2001). In that research, the exterior and interior surface temperatures were measured with the use of an infrared thermometer, while a thermometer-psychrometer was utilised to measure the air temperatures. Measurements were obtained on a specific day at the end of June at noon. According to the findings of this study, the spaces beneath green roofs can be cooled by reducing thermal fluctuation at the green roof's exterior while increasing the thermal capacity of the green roof substrate. Such implementation would prevent thermal losses and passively contribute to the energy consumption reduction of green roofs.

In another study (Dareeju et al., 2010), Each consisted of a 125 mm thick concrete slab and two 125 mm thick cement block walls on either side. Hence, the dimensions of the walls were 1.25 m in length and 0.5 m in height. On a typical sunny day, the soffit temperature of the slab, the slab top temperature, and the indoor temperature were acquired. These results were obtained for scenarios with a grass cover and without a grass cover. The findings illustrate that the grass cover enhances thermal performance significantly.

In terms of temperature measurements, the temperature variation between the top and bottom of the substrate layer was measured using different techniques. Thermistors were placed in different locations across the green roof (four, five, and six locations for the 100, 150, and 200 mm green roofs, respectively) to measure the temperature gradient (Pianella et al., 2017) across substrate layer. In a study performed on Reunion Island, type-T thermocouples were used to measure the superficial temperature and the temperature under the green roof (Morau et al., 2012). DS18B20 temperature sensors were used in this study by locating the sensors in two places on each platform. The surface temperature and bottom temperature of the substrate were continuously measured and recorded by the sensors.

2.5.4 Thermal conductivity

Thermal property is a fundamental parameter for analytical inspection in many fields like engineering, materials science, and agriculture. Recent studies have shown that there is an increasing trend of research activities to find the thermal conductivity of compounds made of soil aggregates. Findings of a past study (Vaneková et al., 2020; Liu et al., 2021) Soil thermal properties influence microclimatic features, most particularly the stand establishment, germination of crops, and the emergence. Thermal conductivity of soil substrates depends on factors that can be divided into two groups, namely soil-inherent and factors that could be externally manageable.

Soil texture and mineral content can be categorised into soil—inherent properties (Wierenga et al., 1969; Haddix et al., 2020) while soil management and moisture content can be included in the externally manageable factors, where moisture content is the most difficult parameter to manage (Yadav and Saxena, 1973; Shiozawa and Campbell, 1990; He et al., 2021). Therefore, the early studies (Parikh et al., 1979; Riha et al., 1980) provided special attention to study the effect of moisture on the thermal conductivity of soil aggregates, and it has been found that the maximum state of soil conductivity is observed during the moist state of soil since the flow of mineral ions facilitates more thermal conduction compared to the dry state of soil. Furthermore, saturated sedimentary deposits like loess have a significant increase in thermal conductivity at the "liquid bridges" formed between particles (Yan et al., 2021). These results were obtained after the Transient Plane Heat Source (TPS) method test on soil samples from Shaanxi, China.

With the advance of time, scientific studies (Noborio and Mcinnes, 1993; Abu-Hamdeh and Reeder, 2000; Li et al., 2019; Yan et al., 2021) have observed a decrease in thermal conductivity along with the increased concentration of mineral salts such as $CaCl_2$, $MgCl_2$, NaCl, and Na_2SO_4 in 0.1 mol/kg of heterogeneous soil solution. The thermal conductivity of quartz sand with water moisture was comparatively higher than the thermal conductivity of the same weight of quartz sand with moisture of 0.25 mol/kg KOH (Globus and Rozenshtok, 1989). Therefore, this review study found that the moistening species of substrates have a substantial impact on the thermal conductivity of substrates.

The trial approach to measuring the thermal conductivity of soil by using temperature rise or fall was first developed in the studies based on soil analysis (Black, 1965) and the method was further sophisticated with volumetric heat capacity of soil from volumetric proportions in accordance to shape of the soil aggregates (De Vries and Peck, 1958) and by the incorporation with dual probe methods (Nusier and Abu-Hamdeh, 2003). In dual probe technique (Bristow et al., 1993; Kluitenberg et al., 1993), two needle probes in parallel are placed. One contains a heater and the other consists of a temperature sensor. Dual probe technique studies were conducted under ASTM D5334 guidelines to measure the thermal conductivity of eco roof soils (Sailor et al., 2008) for dry samples and wet samples. The experimental outcomes stated that, wet samples possess higher thermal conductivity than dry samples. Hence, dry samples have a higher albedo than wet samples, although their thermal emissivity magnitudes are relatively the same. Nevertheless, the needle probe method is an effective and relatively expensive way, and it requires certain expertise in using microcontrollers and sensors.

Lee's disc method is effectively used to find the thermal conductivity of uniform specimens that are bad conductors (Sombatsompop and Wood, 1997; Philip and Fagbenle, 2014; Kharshiduzzaman et al., 2019). Since it is impossible to mould the organic substrate specimens like wood bark and bio char into uniform disc shapes (Philip and Fagbenle, 2014), it is not advisable to incorporate Lee's disc method to find the thermal conductivity of growing mediums. Even if the soil substrates are possible to get moulded into disc shapes, the non-uniform aggregate distribution of soil substrates will result in significant deviations in thermal conductivity if Lee's disc method is used further for such substrates (Philip and Fagbenle, 2014). Therefore, it is more rational to identify the thermal conductivity results in experimental conditions based on proper specimen preparation and relevant theoretical calculations.

2.5.5 pH of substrates

Determination of substrate pH is essential to save vegetation from leaf spotting, bronzing and mineral deficiency (Cu, Zn, Fe, B, and Mn) (Bailey et al., 2000; Neina, 2019). pH experiments generally conducted soil mixtures like substrate using ASTME70 guidelines (Industrial, A. C. E.-O. and Chemicals, S., 2015). The mean pH values that would be obtained in a pH test for substrates should be compared along with the ambient pH values for vegetation types found from previous research. This comparative study facilitates the analysis of the viability of using a growing medium on a green roof. A past study on the influence of pH on essential soil nutrients (Bailey et al., 2000; Gentili et al., 2018) have provided the allowable substrate pH ranges for greenhouse crops as in Table 3. If a new growing medium needs to be tested for pH to determine its feasibility to become a green roof substrate, then a comparative study needs to be conducted with other substrates (Woś et al., 2021) that exhibit similar properties. For example, if there are no previous studies available regarding the pH of coir substrates and there are plenty of results were determined in past for substrates made of Sawdust, then the pH results those would be obtained for Coir substrate need to be compared with already available sawdust results from previous research findings. Since both substrates are organic plant wastes, they exhibit almost similar properties.

TABLE 1 Substrate proportions with respective compositions considered in past studies.

Study	Constituent of substrate	Mix proportion (%)
Ampim et al. (2010)	Peat (Michigan)	10
	USGA sand	40
	Compost yard wastages	3.33
	Dolomite	5
	Turkey litter (Composted)	1.67
	Heat expanded slate	40
Soulis et al. (2016)	Grape marc compost	15
	Pumice	65
	Zeolite	5
	Attapulgite clay	15%

TABLE 2 Preceded studies on substrate depths.

Study	Dedicated depths (cm)
Soulis et al. (2016)	8, 10, 14, 15, 16, and 20 cm
Rowe et al. (2012)	Less than 15 cm
Dareeju et al. (2010)	2.5, 5, and 7.5 cm
VanWoert et al. (2005)	2.5, 4, and 6 cm

The interaction of raw substrates like minerals and organic matter material with soil aggregates forms least-electronegative carbonyl, nitrile, and phosphoryl groups. Due to the fall in electronegativity, low concentrated electrons form. It increases the amount of free hydrogen in associated water molecules trapped in substrate voids due to the dormancy of reactive hydrogen. The presence of free hydrogens causes the pH to rise (McCollom et al., 2020). Optimum pH range based on FLL guidelines is 6.0–8.5 (Eksi and Rowe, 2019) for horticultural plant growth. These ranges of values were verified as correct in this research study by relating the substrate types and their depths to the performance of extensive green roofs. However, 7.0 pH is the most appropriate magnitude for substrates in terms of plant growth support. Therefore, substrates with a pH value closer to 7.0 are highly preferred for use in green roofs since such growing media exhibit neither acidic nor alkaline properties. It facilitates the stakeholders to reduce additional costs needed to improve the soil health. Accordingly, the growing medium with the least deviation from 7.0 is considered the most suitable substrate in terms of pH.

2.5.6 Electric conductivity of substrate

EC is a measure of salinity of aqueous solutions (Gougoulias et al., 2013). Salinity of growing mediums is a basic requirement

TABLE 3 Allowable pH ranges for significant greenhouse crops.

Greenhouse crops	Minimum pH	Maximum pH	Significance of ambient pH range
Azalea	4.5	5.8	Fe defeciency mitigation
Blue Hydrangea	5.2	5.6	Fe defeciency mitigation and contribution for blue coloration
Celosia	6	6.8	Fe and Mn toxicity mitigation
Dianthus	6	6.8	Fe and Mn toxicity mitigation
Easter lily	6.5	6.8	F toxicity and Ca defeciency mitigation
Geranium	6	6.8	Fe and Mn toxicity mitigation
Marigold	6	6.8	Fe and Mn toxicity mitigation
Pansy	5.4	5.8	Avoid defeciency of B and Fe defeciency and avoid Thielaviopsis
Petunia	5.4	5.8	B and Fe defeciency mitigation
Pink Hydrangen	5.8	5.8	Fe defeciency mitigation and assist blue coloration
Salvia	5.4	5.8	B and Fe defeciency mitigation
Snapdragon	5.4	5.8	B and Fe defeciency mitigation
Vinca	5.4	5.8	Avoid defeciency of B and Fe defeciency and avoid Thielaviopsis

in many fields like environmental engineering, materials science, and agriculture. Excessive salinity in soil mixtures could develop cytotoxicity due to the high content of Na^+ and Cl-ions, which accelerate water stress and cause nutritional imbalance (Isayenkov and Maathuis, 2019). This phenomenon could diminish plant growth, soil health, and undermine the viability of soil to be used in a productive manner. Therefore, it is essential to check whether the salinity level of the soil is below the maximum threshold. The biochemical processes such as seed germination and vegetative growth have been diminished in recent times due to salinity changes in the soil (Hu and Schmidhalter, 2004; Akbarimoghaddam et al., 2011; Safdar et al., 2019) those brought on by the complex interplay of industrial chemicals, polluted water, plastic waste, and soil erosion (Reynolds, 2001). Salinity changes would have a significant impact on nutrient deficiency (N, P, K, Ca, Fe, and Zn), osmotic stresses, and ionic toxicity (Shrivastava and Kumar, 2015). Therefore, it becomes a paramount requirement to devise the most comprehensive and readily available method to find the electric conductivity to forecast the salinity of a growing medium.

Recent studies have shown that there is an increasing trend of research activities using salinity properties. Significant contributions are made by the raw substrate source and the soil composition of substrate solution (Brovelli and Cassiani, 2011) at EC of a substrate. Increased concentration of mineral salts such as $CaCl_2$, $MgCl_2$, NaCl, $NaHCO_3$, and Na_2SO_4 results substantial increment in EC (Noborio and Mcinnes, 1993) due to abundant existence of cations. The runoff water from substrate mediums has high salinity, especially in dry climate (Gougoulias et al., 2013). Because, the EC boosts due to the existence of residual salts after the evaporation of water. However, due to the lack of research studies on EC of growing mediums, it is difficult to arrive for a conclusion solely based on past studies and it induces the requirement of a comprehensive research work in this regard to get rational outcomes.

An EC meter quantifies the electric charge accumulated by ions in a solution. The EC of soil is the summation of total salinity in water and the dissolved minerals. The common method to find EC is 1:2 dilution (Herrero et al., 2015; Analysis, A. I. C. D. O. I, 2016). 1-part of growing media is diluted with 2-parts of distilled water. Tap water is not categorised as distilled water due to its consistence of mineral ions. EC readings were obtained using an EC meter/multimeter in the obtained solutions. However, this method fails to account for the reading discrepancies due to temperature variation. Another method has been developed for measuring EC called the "Pour-Through technique" (Fisher et al., 2014; Palimąka et al., 2016; Altland, 2021; Bañón et al., 2021). It consists of two steps: first, the medium in the container is irrigated upon saturation and then left for 2 h. Then 100 ml of leachate is produced by pouring distilled water into the media. The volume of water depends on the type of growing media and the container volume (Landis and Dumroese, 2006; Harris et al., 2020). The overall idea of the Pour-Through technique is to have the exerted water force out of the solution surrounding the roots. Since prills are not squeezed or damaged in this technique, it is ideal for outdoor growing media. However, the procedure needs much time, and the external factors such as temperature and pressure cannot be distinguished by elaborative EC readings using this method since the readings are empirical.

The latest technique for finding EC is using Direct Sensors (Skierucha et al., 2004; Rossel and Bouma, 2016; Bañón et al., 2021) and different algorithms were incorporated into developing a signal analysis for finding EC (Dos Santos Sousa et al., 2021) during ambient contact between soil and electrode, Sensor technology is a modern, time-conserving, and effective method when it comes to laboratory solutions in small containers. If the battery gets drained, then the accuracy gets slowed. The recommendation in such a scenario is to monitor for about 1 h after the irrigation and to get mean values (Visconti and de Paz, 2016) which will avoid the major deviations, although still, these modified EC values will not get much closer to the absolute values. Tests based on several trials using Direct Sensors have shown that this method is highly effective against small containers and on miniplugs (Visconti and de Paz, 2016). However, if the plug of the sensor is inserted into a medium that contains Controlled Release Fertilizers (CRF) and the tip of the probe is very close to a prill, then EC values are increased. It requires the second insertion into a different area of the medium.

Most soil and water testing laboratories used Saturated Media Extract (SME) to calculate the absolute EC of growing media, where saturation is used as the standard soil water content (Huang et al., 2006). This method consists of sample collection and the addition of an ample distilled water amount. The resulting solution was glistened and sucked by a vacuum pump for measurements. In practical applications, on an existing media sample in a living environment, it was implemented by collecting the raw sample, bringing it to saturated moisture content, and then squeezing it after covering it with cheesecloth to extract the solution (Huang et al., 2006). Although this SME method uses a fixed amount of water for tests and does not count the effect of moisture content on EC, the main drawback is the excessive time consumption of test procedures. Furthermore, this technique is not suitable for growing media containing bare root soils.

2.5.7 Nutrient content of substrates

Total Dissolved Solids (i.e., TDS) is a metric that represents the total mineral content of a substrate solution. If the substrate were optimum in pH and excessive in TDS, roots would utilise the soil nutrients without hindrances (Gorenflo et al., 2007). High TDS and pH disturb the nutrient absorbing rate of plant root systems (Weber-Scannell and Duffy, 2007). Therefore, the selection of green roof substrate should not solely focus on its consistence of high TDS. A multimeter is used for the measurement of TDS (Phan et al., 2021) in the aqueous solution of soil substrates.

Different methods are adapted such as spectroscopy (Krawczyk et al., 2017; Singh et al., 2019), voltammetry (Massah and Vakilian, 2019) and chemical sensors (Mahmud et al., 2020) to find the nitrate and phosphate abundancy. Nitrates stimulate the production of chlorophyll in leaves and help with better energy production in plants *via* photosynthesis (Sen et al., 2016; Gondek et al., 2020). Because the presence of nitrates in the substrate medium is essential for nitrogen fixation. Plants ingest nitrate (NO_3^-) and ammonium (NH_4^+) ions for amino acid production, which is required for protein synthesis. The analytical outcomes state that compost is one of the best sources for nitrates (Gondek et al., 2020) and it is certain that compost substrates would greatly facilitate the rate of photosynthesis in vegetation.

Phosphorous in a growing medium facilitates the formation of better plant structures such as root systems, flowers, and fruits. Orthophosphates are the major source of phosphorus for soil mixtures (Turner et al., 2003). Orthophosphates formed by the reaction between the added fertilisers and the organic minerals embedded in the growing medium. The plant's intake of phosphorous from the substrate is highly influenced by the substrate pH. If the pH is high, then it substantially disrupts the plant roots' phosphorus absorption. Substrates with low pH facilitate the reaction of phosphorous with iron (Fe) and aluminium (Al) to form compounds of ferric phosphate (FePO4) and aluminium phosphate (AlPO4). Phosphorus is richly abundant in soil substrates with 6.5–7.0 pH magnitudes (Da Silva Cerozi and Fitzsimmons, 2016). Rationally, if the substrate pH is between 6.9 and 7.1 (i.e., closer to 7.0) and if it consists of high nitrogen and phosphate levels, this growing medium would provide its overlaying vegetation with a platform for a high rate of energy production while appropriate light is available to enhance photosynthesis.

3 Discussion

This study illustrates the strategic considerations that need to be incorporated for the effective selection of sustainable growing media for green roofs to comply with the structural stability of buildings and with climatic concerns. According to the research paper, the mix proportions of substrate composition, thickness of the substrate layer, type of green roof vegetation, drought resistance, substrate growth contribution, storm water retention, substrate density, thermal performance, thermal conductivity, pH, salinity, and substrate nutrient content all have a significant impact on the selection of appropriate substrate species. However, there are no details available on which parameter among those twelve is the most important and needs to be considered with utmost inspection.

Because sandy soils are more prone to frequent evapotranspiration, soil substrate with good drought resistance and high water retention is essential in green roofs of Saudi Arabian buildings (Kazemi and Mohorko, 2017). However, this type of enriched water-retention substrate is not essential on green roofs in Iceland or in Scandinavian countries. The substrates in these nations should be equipped with high nutrient content and less salinity since the soils in Iceland and Scandinavia are less fertile (Mankasingh and Gísladóttir, 2019; Schjoerring et al., 2019) and more chemically contaminated (Lam, 2018; Rudnicka-Kępa and Zaborska, 2021). A future study focusing on such an aspect is essential to select green roof substrates for accommodating the climate of the corresponding environments.

Most of the articles are mainly focused on finding the viability of using various substrates in terms of substrate depth (Dunnett et al., 2008b; Schneider et al., 2014; Ondoño et al., 2016; Thomaidi et al., 2022), storm water retention (Bliss et al., 2009; Baryła et al., 2019; Wang J. et al., 2022; Yan et al., 2022) using alternative substrate materials (Razzaghmanesh et al., 2014), climatic conditions (Williams et al., 2010; Rayner et al., 2016; Koroxenidis and Theodosiou, 2021; Liberalesso et al., 2021; Varela et al., 2021) and amendments with substrates like organic matter (Emilsson, 2008; Thuring et al., 2010; Kanechi et al., 2014), pertlite (Ntoulas et al., 2013) and hydrogels (Savi et al., 2014). This review provides significant outputs related to substrate performance on vegetation by focusing on microclimatic features such as drought resistance and thermal conductivity. The information provided in this article on those two aspects is not available in any of the similar kinds of review articles published before.

Organic wastes like biochar exhibit high pathogenic resistance (Bonanomi et al., 2015; Jacoby et al., 2017). Laying immune substrates like biochar would guarantee the longevity of vegetation. Furthermore, biochar with a large pore volume and a medium pore diameter has a high water retention capacity (Zhang et al., 2016; Haider et al., 2020). This leads to reducing additional water supply costs for green roofs in urban skyscrapers (Afrin, 2009; Rich, 2021). The porosity of biochar is measured by considering the skeletal density and the envelope density of biochar (Brewer et al., 2014) as per Eq. 1.

$$\text{Porosity} = 1 - \frac{\rho e}{\rho s};\ \rho_s - \text{Skeletal density},\ \rho_e - \text{Envelope density} \tag{1}$$

Similar studies need to be initiated for any substrate to determine their viability to withstand drought as a substrate layer. This approach would help with comprehensive selection of green roof substrate to enhance the longevity of plant survival against drought and to improve the indoor thermal comfort of skyscrapers with minimal heat absorbance from solar radiation (Tsang and Jim, 2011; Jim, 2014). Because vegetation is the most viable solution to mitigate the drastically higher global warming potential and the carbon impact in skyscrapers, which is an alarming environmental concern in 21st century (Raimondi and Becciu, 2021).

The growth rate needs to be measured to identify the substrate that accelerates the vegetation growth to its maximum level within a short period. Therefore, spiderwort species of Trandescantia fluminensis can be recommended for use in growth test experiments on a laboratory scale using tray tests since the growing ability is high for Tradescantia fluminensis (Standish et al., 2001). However in industrial scale experiments, Pasture plots with known dimensions can be used to study the drought resistance. In this phase, the initial area of vegetation needs to be calculated and the area of dead vegetation needs to be calculated per week. This process needs to be executed from 0 to 6 weeks continuously and the survival area versus time curve needs to be projected to find the most applicable substrate in terms of growth contribution and drought resistance when an array of substrates needs to be tested for viability.

An experimental study was implemented successfully to find the vegetation cover in grasslands using Unmanned Aerial Vehicles (UAV) imagery with vegetation overlays to determine the growth rate and drought resistance (Théau et al., 2021). For statistical analysis, two approaches were made; a regression model for biomass prediction using the Green Normalised Difference Vegetation Index (GNDVI) and a qualitative classification of vegetation cover using the clustered GNDVI values. The main advantages of this research were that the outputs were generalizable and the methodologies were simple to construct.

Significant research studies were considered in this review such as (Dunnett et al., 2008a; Dunnett et al., 2008b; Stovin et al., 2013; Molineux et al., 2015; Van Mechelen et al., 2015; Wang J. et al., 2022) have necessitated the requirement for long-term inspection studies. Most of the research studies were conducted for a short term due to technological and budget constraints, and they failed to elaborate on the dynamic changes in green roof substrates over the growing time of vegetation to a rational conclusion. Long-term studies would effectively forecast the success rates of several further required research aspects, such as the use of alternative substrate materials, the effectiveness of the proposed substrate mix proportions, the relationship between the stability of vegetation and water retention capacity of substrates, and the adaptability of green roof vegetation species for hot and dry climates.

4 Conclusion

This review study manifested the important details regarding green roofs and growing media to facilitate the optimistic selection of substrates for green roof technology. From the findings in this research study, even though it is evident that the mix proportions of substrate compositions, thickness of substrate layer, type of green roof vegetation, drought resistance, growth contribution of substrate, storm water retention, substrate density, thermal performance, thermal conductivity, pH, salinity, and substrate nutrient content have significant impact on the substrate selection, it is still unknown to which extent each of them affects the lifecycle of the substrate layer for sustainable vegetation in green roofs. This knowledge is a fundamental requirement for selecting green roof substrates in accordance with different climatic regions. Because a sustainable substrate should be selected for green roofs as light-weighted as possible, it should also consist of great water retention, thermal performance, drought resistance, salinity, and other related peripheral attributes while sustaining the climatic conditions of the particular region. Therefore, future studies need to be climatically-specified and should adhere to widely accepted standards and guidelines. It is also prescribed to designate endemic guidelines for dry climatic zones since they are highly affected by evapotranspiration due to high temperature fluctuations.

This review study's critical approach demonstrates that the majority of studies on green roof substrates are conducted in greenhouses, field prototypes, and controlled laboratory environments. Although these proctored experiments are necessary for gaining a thorough understanding of the impact of each discrete factor on substrate selection, they are insufficient for determining realistic field outcomes. Therefore, after executing their controlled laboratory experiments and greenhouse tests as preliminary studies, it is highly recommended for the researchers to undertake a mandatory field-research study to facilitate a sophisticated research outcome on substrates regarding their practical applications in social and industrial contexts.

There are some research gaps observed in the considered research studies on green roofs as mentioned in this review article in relation to climatic factors, thermal performance, and the lack of field research studies and long-term observations. Further studies are required to find the effects of particle size distribution in the substrate, its water retention, its thermal conductivity and the light weight of the substrates to mitigate structural stability concerns of building slabs overlaid with green roofs. These research gaps need to be filled to select sustainable and climate-adaptive growing mediums for green roofs with lightweight substrates to integrate with architecture to create a sustainable solution for future urban construction. The viability of these kinds of substrate candidates should be tested based on "long-term experiments" that incorporate not only the greenhouse and laboratory conditions, but also the actual field conditions of the particular environment. These types of experimental preferences would provide a comprehensive and rational experimental outcome with precise results regarding the viability of a candidate to be used as a green roof substrate. These research aspects would be the main future scopes of construction projects studied in this decade since the investment of stakeholders is gradually increasing to create sustainable building structures in the urban ecosystem.

Author contributions

Conceptualization, SK; methodology, SK, SC, and LJ; validation, SC, VS, and BD; formal analysis, SK, SC, and LJ; investigation, SK, SC, LJ, and BD; resources, SK, LJ, VS, and BD; data curation, SK, LJ, VS, and BD; writing—original draft preparation, SK, LJ, VS, and BD; writing, review and editing of final draft, SK, SC, LJ, VS, and BD; visualization, SK, VS, and BD; supervision, VS and BD; project administration, SC, VS, and BD. All authors have contributed to the article and approved the submitted version.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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