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Green roofs: A critical review on the role of components, benefits, limitations and trends

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ABSTRACT

Green roofs have been proposed as an efficient and practical tool to combat urbanisation in many countries. This review paper focuses on various benefits associated with green roofs and research efforts made till date to promote green roofs. Through systematic comparison of literature, this review also emphasises knowledge gap that prevail in green roof technology and highlight the need for local research to install green roofs in developing and under-developed countries. Considering that growth substrate, vegetation and drainage layer determine the success of green roof, efforts were made to consolidate desirable characteristics for each of these components and suggests methodology to construct practical green roofs. This critical review also explores limitations associated with green roofs and recommend strategies to overcome. Apart from stand-alone green roofs, there is a huge scope for hybrid green roof systems with other established techniques, which are presented and discussed. Recommendations for future study are also provided.

Contents

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1. Introduction

As a result of rapid economic growth, many countries have been experiencing increased urbanisation. Due to this amplified urban population, tall buildings and other new developments are made at the expense of green areas. This resulted in the shortage of greenery which in turn causes a decrease in canopy interception and transpiration within the urban area leading to an increased temperature and decreased air humidity [1]. These problems can be partially solved by altering buildings' rooftop properties. The introduction of plants and soil to the unutilized rooftop surfaces are often regarded as a valuable strategy to convert buildings more sustainable [2,3]. Green (vegetated, eco or living) roofs are basically roofs planted with vegetation on top of the growth medium (substrate). The concept was designed and developed to promote the growth of various forms of vegetation on the top of buildings and thereby provide aesthetical as well as environmental and economic benefits. Green roofs generally comprise of several components, including vegetation, substrate, filter fabric, drainage material, root barrier and insulation. The role played by each component is well defined in engineered green roof system and type of each green roof component depends on the geographic location [4].

Green roofs are broadly classified into intensive, semi-intensive and extensive green roofs. Intensive green roofs are characterized with thick substrate layer (20–200 cm), wide variety of plants, high maintenance, high capital cost and greater weight. Due to increased soil depth, the plant selection can be more diverse including shrubs and small trees. Therefore, typically require high maintenance in the form of fertilising, weeding and watering. On the other hand, extensive green roofs are characterized with thin substrate layer (less than 15 cm), low capital cost, low weight and minimal maintenance. Owing to the thin substrate layer, extensive roofs can accommodate only limited type of vegetation types including grasses, moss and few succulents. An extensive green roof system is commonly used in situations where no additional structural support is desired. Semi-intensive green roofs accommodate small herbaceous plants, ground covers, grasses and small shrubs due to moderately thick substrate layer. These roofs require frequent maintenance as well as sustain high capital costs. Of the three types, extensive green roofs are most common around the world due to building weight restrictions, costs and maintenance.

Green roofs present numerous economic and social benefits in addition to more obvious environmental advantages such as storm–water management, decreased energy consumption of buildings, improved water and air quality, decreased noise pollution, extended roof life, reduced heat-island effect and increased green space in urban environments [1,5,6]. Many countries and municipalities understood these benefits and started to implement or even mandate green roofs in buildings. Consequently, more and more green roofs are established. Shortly, commercial green roof products started to appear in the market doing brisk business. However, it should be pointed out that the focus of green roof developers has been limited to achieving basic aesthetical benefits of green roofs [1]. Many other benefits of green roofs are just as achievable, but thus far the green roofs generally are not optimised to meet those [7]. This is generally due to lack of research on different aspects of green roofs and premature introduction of products into the market. Thus, there is a great need for green roof research. The objectives of this review are to understand the current scenario in green roof research, provide suggestions to select different green roof components based on requirements and strategies to develop practical green roofs to meet consumer needs. In addition, this review also summarizes the benefits of green roofs as well as recent trends in green roof technology.

2. History of green roofs

Planting vegetation at the building rooftop is an old technique. The most famous ancient green roofs were the Hanging Gardens of Babylon constructed around 500 BC. In more recent times, peoples tend to cover their rooftops with sod for the purpose of insulation from extreme climates. Modern green roofs, therefore, may acquire their concept from ancient technique; however technological advances have made modern green roofs far more efficient, practical and beneficial than their ancient counterparts.

Modern green roofs, in a larger scale being designed, developed and marketed by Germany [2]. Several investigations have been carried out with emphasis on biodiversity, substrate, roof construction and design guidelines [1]. Unfortunately, most of the early studies on green roofs was written in German and also not readily available to rest of the world [8]. However owing to the first initiative by Germany and subsequently by neighbouring European countries, green roofs became popular in other parts of the world. Recently, green-roof coverage in Germany alone increases by approximately 13.5 million m^2 per year [2]; whereby 10% of its buildings utilise green roof technology [9].

Currently, countries like USA, Canada, Australia, Singapore and Japan are making a strong initiative to install green roofs during construction of new buildings, and are retrofitting old ones so green roofs can be added in the near future. As a result of the regulations for new and renovated flat roofs, 15% of flat roofs in Basel (Switzerland) have been greened [10]. In Toronto (Canada), the green roof by-law mandates all newly established development with a floor area of $\geq 2000\ m^2$ to include green roof on 20–60% of the roof area [11]. Similarly, Tokyo (Japan) accelerated the green roofing process by mandating that all new-construction buildings were to have green roofs. Private buildings larger than 1000 m^2 and public buildings larger than 250 m^2 must green 20% of the rooftop or pay an annual penalty of USD 2000 [11]. All new City-owned buildings in Portland are required to be built with a green roof that covers at least 70% of the roof [10]. There were approximately 2 acres (0.81 ha) of green roofs in Portland (USA) in 2005, with about another 2 acres committed to be built. In Hong Kong, governmental best practices for green and innovative buildings encourage construction of green roofs [12].

Green roof research has been performed in several countries. Blank et al. [13] conducted a survey on green roof publications appeared in ISI Web of Science database and identified that USA contributed 34% of total publications in green roofs, whereas EU and Asian counties contributed 33% and 20%, respectively. The authors also indicated that the pace and number of publications in the field of green roof increased significantly compared to early 2000. Earlier research publications mostly focussed on to evaluate/highlight the benefits of green roofs [14,15]. Only recently it was understood that each countries with different climatic conditions and building characteristics has to do local research to identify components for successful establishment of green roofs. Apart from added cost, it is well known that the commercial green roof systems from Western nations or other countries might not be completely adapted to the local context [16]. For instance, the vegetation or substrate successfully performed in the Scandinavian countries may not perform in tropical climates. The same applied to other green roof components as well. These aspects acted as driving force behind the increase in green roof research, with recent studies focussed onto identify new and low-cost or alternative components for practical implementation of green roofs. Graceson et al. [17] examined different types of locally available crushed bricks and composted green waste as green roof substrate. On the other hand, Vijayaraghavan and Raja [18] prepared green roof substrate using locally available perlite, vermiculite, crushed brick, sand and coco-peat to support *Portulaca* *grandiflora*. Razzaghmanesh et al. [19] examined several indigenous Australian ground covers and grass species and identified that *Carpobrotus rossii* tolerated hot and dry conditions of South Australia with 100% survival rate and maximum growth. With this upsurge in research and successful implementation of technology in European countries, green roof research has now gaining momentum in various countries. Therefore, we can certainly hope that furthermore countries adopt green roof in near future.

3. Benefits of green roofs

Incorporating vegetation, growth medium and other landscape components on the rooftop of buildings offer several direct and indirect environmental benefits. These are summarised as below,

3.1. Stormwater attenuation

Green roofs are known to retain rainwater and delay peak flow, thereby reduce the risk of flooding [20,21]. When rain water enter green roof, a portion of water will be absorbed by growing substrate or retained in the pore spaces. It can also be taken up by the vegetation and either stored in plant tissues or transpired back into the atmosphere [22]. The remaining water passes through filter fabric and then enters drainage element. Due to potential to store water between pores (in the case of granules) or compartments (in the case of drainage modules), water will be detained. After complete utilisation of drainage space, the overflow will drain. The retained water inside green roof will evaporate or be used by plants and parts of it will transpire. It is the evaporated and transpired water that explains the runoff retention potential of green roofs. In general, the retention potential of any green roof strongly depends on type and thickness of growth medium, type of drainage element and its storage capacity, type of vegetation and coverage, volume of rain event and time of previous dry period, and slope of green roof. Of the different factors, growth medium plays a significant role in water retention. Considering that most of the components that comprise green roof substrate are light weight volcanic materials, the moisture holding capacity is usually high. Vijayaraghavan and Joshi [7] conducted exhaustive examination of substrate characteristics and identified delay in runoff generation from green roofs was mainly due to high water holding capacity (WHC) of growth medium. During their simulated green roof experiments, Graceson et al. [23] identified that higher WHC resulted in higher runoff retention.

Plants play a significant role in the runoff reduction depending on each plant's capacity for water interception, water retention and transpiration [22,24]. Speak et al. [25] indicated that average runoff retention of 65.7% can be achieved on an intensive green roof (University of Manchester campus), compared to 33.6% on an adjacent paved roof. Nagase and Dunnett [22] screened several vegetation species that are commonly used in extensive green roofs and identified a significant difference in amount of water runoff between plant types. To be precise, grasses were found to be more effective for reducing runoff production, followed by forbs and sedum. The authors also suggested greater runoff control can be achieved through using plant species with taller height, larger diameter, and larger shoot and root biomass. There exists a strong perception that runoff generation is greater from green roofs using minimal-water required succulent species than from other plant species with higher transpiration rates which dry out substrates between rainfall events [26,27]. However, Berghage et al. [28] identified that sedum species can rapidly transpire available water and can contribute up to 40% of a green roof's capacity to retain rainwater depending on the size and timing of rain events. The type of drainage element also enables green roofs to store rainwater. In recent years, plastic drainage modules were used in which water accumulates in small compartments to supply water to plants during dry periods. Vijayaraghavan and Joshi [7] utilised a commercial drainage element and the authors claimed the storage potential of drainage module played a significant role in reduction of runoff volume. Several studies correlated water retention capacity of green roofs with rain fall size, intensity and previous dry periods [1,29]. Villarreal and Bengtsson [30] found that water storage capacity of green roof strongly depends on the intensity of the rain event and slope of green roof. For a rainfall with an intensity of 0.4 mm/min, 62%, 43% and 39% of the total precipitation were retained in the green-roof having slopes of 2°, 8° and 14°, respectively. For rain intensity 0.8 mm/min at slopes of 2°, 8° and 14°, the retentions were 54%, 30%, and 21%, respectively.

3.2. Thermal benefits

Green roofs are attractive option for energy savings in building sector. They reduce building energy demand through improvement of thermal performance of buildings [9,31]. A study in Greece revealed that green roofs reduce the energy utilised for cooling between 2% and 48% depending on the area covered by the green roof, with an indoor temperature reduction up to 4 K [32]. Improvement of thermal performance is basically due to increment of shading, better insulation, and higher thermal mass of the roof system [9]. To be precise, the thermal loads due to the solar radiation and the air temperature are limited due to the presence of vegetation layer. Additionally, the growth medium gives an added insulation to the roof and the water content increases the thermal inertia of the structure. The ability of a green roof to improve thermal performance was also reported by Ekaterini and Dimitris [33]. According to their finding, of the total solar radiation absorbed by the planted roofs, 27% was reflected, 60% was absorbed by the plants and the substrate medium, and 13% was transmitted into substrate medium. Measurements from a green roof experiment installed on a five-storey commercial building in Singapore indicated that a saving of 1–15% in the annual energy consumption, 17–79% in the space cooling load and 17–79% in the peak space load could be obtained [34]. The authors also identified that maximum energy savings depend strongly upon the plant species as well as type and thickness of growth medium. During winter, green roof act as insulators decreasing heat flow; however this benefit is often under debate as some studies claimed green roof as a medium to save energy [35], others identified that green roof has no influence during winter [36] and some viewed it as a cause of more energy consumption [37]. Considering these controversial results, it is suggested to conduct more research on impact of seasonal variations on thermal performance of green roofs.

Green roofs can also be viewed as a practical tool to mitigate urban heat island (UHI) effect i.e. to decrease ambient air temperature in urban areas. Several densely populated and intensely urbanised areas in the world suffer from UHI problems and the worst urban eco-environment [16]. Green roofs are tools that combat UHI and increase the albedo of urban areas [9,38]. Berardi et al. [3] indicated that albedo of green roofs ranges from 0.7 to 0.85, which is much higher than the albedo (0.1–0.2) of bitumen, tar, and gravel roofs. In his review article, Santamouris [39] compared several mitigation technologies to minimise UHI effect and recommended that large-scale application of green roofs could reduce the ambient temperature from 0.3 to 3 °C.

3.3. Water quality enhancement

Green roofs buffer acidic rain [40,41] and theoretically retain pollutants thereby produce good quality stormwater runoff.

However, there exists a difference in opinion among the research studies on runoff quality from green roofs [1,7]. Green roofs can influence stormwater quality in a number of ways. During percolation of rain water through the substrate and the vegetation there is possibility for both cleaning and contamination. Both substrate and vegetation could act as a particle trap for dust and airborne particulates removing them from the rainwater. The substrate medium also performs as an ion exchange filter for nutrients and metals in the rain water. To be precise, if there is a high concentration of an ion in the rain, the green roof components act as sink and thereby lowering the ion concentration in runoff. On the other hand, if the concentration of ions in the rainwater is substantially lower than the concentration in the substrate medium, then some of the ion will be leached from the substrate and the runoff will have a higher concentration of the ion than the incoming rainwater. This is further complicated by plant uptake and fertilisation practices which remove or add nutrients, respectively. The magnitude of contaminants in runoff is also affected by the soil microbes in the substrate, the components of substrate medium, the use of organics in the substrate, and the age of the substrate.

In Toronto, Van Seters et al. [42] examined runoff samples from an extensive green roof for pH, total suspended solids, metals, nutrients, bacteria, and PAH (polycyclic aromatic hydrocarbons). The authors identified that concentrations of most pollutants were lower from the green roof relative to the conventional roof with the exception of Ca, Mg, and total P. Similarly, Rowe [8] reviewed several research articles on green roofs and concluded that green roofs can have a positive effect on water quality. Conversely, some studies pointed out that green roof acted as source for several contaminants. For instance, during a 9-month monitoring period on two green roofs constructed within the Neuse river basin of North Carolina, Moran et al. [43] identified that green roof functions as the best management practice for water retention and peak flow reduction. However, water quality data indicated that higher nutrient concentrations were present in the green roof runoff than those in the rainfall and control roof runoff, respectively. Berndtsson et al. [44] found that while in lower concentrations than normally found in urban runoff, some metals appear in runoff from green roofs in concentrations that would correspond to moderately polluted natural water. On the other hand, Vijayaraghavan et al. [41] conducted a detailed study using pilot-scale green roof assemblies under real rain events and observed that runoff comprise significant quantities of Na, K, Ca, Mg, NO_3 and PO_4 and traces of Fe, Cu and Al. This difference in opinion about runoff quality as reported in different studies is mainly due to large variations in substrate composition, age, construction and maintenance of green roof. Several authors indicated that the quality of runoff in the first year of a newly developed green roof may not be representative of the runoff from a mature and established roof [7,8]. This is because in matured green roof systems, continuous rainfall, plant uptake and other biological activities were expected to flush the pollutants out of the system. Also, it is known that intensive roof pollute runoff significantly higher than extensive green roof due to higher substrate depth. Discharge of nutrients from green roofs can also be directly associated with the usage of fertilizers [45,46], particularly conventional fertilizers cause higher nutrients concentrations in runoff than the controlled release fertilizers [47].

To be specific, important factors influence the quality of runoff from green roof can be summarised as follows,

- Type of growth medium (leaching and sorption characteristics)
- Type of vegetation (Phytoremediation characteristics)
- Size of rainfall
- Local pollution sources
- Type of green roof (intensive or extensive)
- Fertilisation and maintenance practices
- Age of green roof
- Physical and chemical properties of pollutants
- Type of drainage

Of the above factors, substrate and vegetation plays significant role in altering the runoff quality. However, not much effort was taken to study alternative substrate components and vegetation in green roofs. Most of the studies were conducted in already established green roofs or using commercial substrates and established vegetation such as *Sedum* species. Phytoremediation ability was not considered as a critical factor for selection of green roof plants. Similarly, substrate components were not screened based on their sorption capacity or less leaching tendency. Of the few studies, Vijayaraghavan and Raja [18] prepared green roof medium using low-cost materials such as perlite, vermiculite, sand, crushed brick and coco-peat along with seaweed biosorbent as additive. The authors identified that growth medium performed well in retention of heavy metal ions such as Cu, Cr, Cd, Ni, Pb, Zn, Al and Fe from metal-spiked simulated rainfall and thereby produced better quality runoff. Compared to other environmental benefits, enhancement of water quality through green roofs needs extensive research. Precisely, there is lot of scope to screen substrate components with less leaching and high sorption capacity as well as plants with high phytoremediation capacity to obtain high quality runoff from green roofs. This aspect will be covered in detail under Section 4.

3.4. Noise reduction

Considering that green roofs are constructed boundary between the natural exterior and indoor environments, they generally reduce noise pollution in urban spaces arising from road, rail and air traffic [48,49]. Sound can be minimised by a green roof in few ways, viz. providing increased insulation of the roof system and by absorption of sound waves diffracting over roofs [50]. However, research studies on the acoustical benefits of green roofs are rather limited. Connelly and Hodgson [51] performed field experiments on green roofs of varied substrate depths, water content, and plant species; and results indicated that the transmission loss of vegetated roofs was greater than that of non-vegetated reference roofs by up to 10 and 20 dB in the low and mid frequency ranges, respectively. Van Renterghem and Botteldooren [48] studied both extensive and intensive green roofs for their potential over sound propagation. The authors observed good overall efficiency from extensive green roofs (15–20 cm); whereas intensive green roofs (greater than 20 cm) produced no further positive effects. It is also worth noting that the performance of green roofs in sound insulation is more pronounced in low-rise buildings, owing to the fact that growing layer should be exposed to the direct urban sound field to be an effective absorptive surface [8].

3.5. Air pollution

The green roof system is a popular approach that could help to mitigate air pollution in urban environments. Urban air often contains elevated levels of pollutants that are harmful to human health and environment [52]. Among several mitigation technologies, the ability of plants to clean the air is considered practical and environmentally benign technique [8]. In general, plants mitigate air pollution through direct and indirect processes, i.e. directly consume gaseous pollutants through their stomata or indirectly by modifying microclimates [53]. The indirect processes such as reducing indoor temperature which in turn reduce the airconditioning energy usage and subsequent emission of pollutants from power plants along with potential of vegetation to minimise UHI were covered in previous sections. Yang et al. [53] quantified a total of 1675 kg of air pollutants was removed by 19.8 ha of green roofs in one year with O_3 accounting for 52% of the total, NO_2 (27%), PM_{10} (14%), and SO_2 (7%). On the other hand, Johnson and Newton [54] estimated that 2000 m^2 of uncut grass on a green roof can remove up to 4000 kg of particulate matter. Rowe [8] further added that one square metre of green roof could offset the annual particulate matter emissions of one car. It is also worth noting that the potential of green roofs to minimise CO_2 concentration was studied by Li et al. [55]. The authors identified that the performance of green roof was related to the condition of the plants, the position of the green roof and the ambient airflow condition. More precisely, in a sunny day, a green roof may lower the CO_2 concentration in the nearby region as much as 2%. Planting trees in urban areas have been shown to provide better benefits in mitigation of air pollution [56,57]. However, considering the limited available space in urban areas, it is difficult to develop urban forest. Due to above fact, it is a general conclusion that intensive green roofs are more favourable in terms of minimising air pollution than extensive roofs, owing to the possibility of installing small trees and shrubs [2,58].

3.6. Other benefits

Green roofs can also be viewed as a tool to enhance aesthetic appeal of any building. Compared to bland and utterly boring flat roofs, green roofs are more pleasant to experience or view from other buildings. Green roofs also aid to restore biodiversity that have been lost due to urban development. Green roofs offer a safe place for birds, insect and other plants to grow.

Green roofs protect roof membrane from extreme heat, wind and ultra violet radiation.

Due to the presence of vegetation and thick substrate layer, the daily expansion and contraction of the roofing membrane can be avoided. A study in Toronto by Liu and Baskaran [59] evaluated that the membrane temperature on a green roof reached only 25 °C, while that of convention roof increased to 70 °C.

4. Green roof components

In contrast to traditional rooftop gardens, green roofs are structurally engineered and designed to combat urbanisation. Depending on the location and requirements, green roofs generally comprise of several components as listed in Fig. 1. If green roofs are to be considered environmentally benign as well as to meet long-term client expectations, then selection of efficient green roof components are extremely important. Considering that this aspect was not considered in earlier reviews, this review examines the role of each of the green roof component and the factors influence their selection. Of the different types of green roofs, this review devotes special attention to extensive type as it is more commonly used and difficult to construct as well as to maintain.

Fig. 1. Schematics of different green roof components.

4.1. Vegetation

Plants constitute the uppermost layer, which add life to the green roof system. More specifically, success of any green roof depends on how healthy the plants are. Plants improve runoff quality [7], air quality [25,60] and thermal performance [61]. However, it should be pointed out that green roofs are not favourable environment for plant growth [8,62]. Water is always a limiting factor in rooftop environments and its availability fluctuates dramatically between rain events. In addition, building load restrictions limit the depth and weight of substrate. The growth medium also needs to contain only minimal nutrients to avoid weeds and generation of eutrophic runoff. This necessitates usage of nutrient-deficient inorganic recycled materials as main constituents of green roof substrate.

Taking into account the extreme environment on rooftops, the favourable characteristics of vegetation for extensive green roofs are as follows,

- ability to withstand drought conditions
- survive under minimal nutrient conditions
- good ground coverage
- less maintenance
- rapid multiplication
- short and soft roots
- phytoremediation

Even though it is difficult to screen a plant species which possess all favourable characteristics, significant progress has been made towards identification of suitable green roof vegetation. Vegetation comes under succulent types were some of the most intensively examined taxa on green roofs [60,61,63]. Of the different succulent types, *Sedum* species are more popular and reliable for extensive green roofs around the world [64] because of their ability to limit transpiration and store excess water [65] in order to survive drought conditions. Several studies highlighted the potential of *Sedum* species to survive elongated period without water [60]. To highlight few, Durhman et al. [66] indicated that *Sedum* spp. survived and maintained active photosynthetic metabolism even after 4 months without water; whereas Terri et al. [67] highlighted that *S. rubrotinctum* survived two years without water. Succulents can store water in leaves or stems, which enabled them to survive the drought conditions [68]. In addition, some of the species such as *Sedum* also display crassulacean acid metabolism (CAM), which can increase the water-use efficiency of the vegetation by allowing stomatal opening and CO_2 storage during the night, when evaporation rates are lower than during the day [69]. On the other hand, this property of *Sedum* species sometimes considered as disadvantage as they unable to utilise excess water.

Nevertheless, *Sedum* proved successful on shallow extensive green roofs. Getter and Rowe [70] examined several *Sedum* species and identified that a substrate depth of 7 cm was sufficient to achieve greater growth and absolute cover. Good ground coverage is an important criterion for plant selection as growth substrate should not be exposed to direct sunlight and heavy winds. In addition, ground cover plants retard weed growth as well as soil erosion when built on sloped roofs. Short and soft roots of some succulent species are also a vital factor as it prevents the penetration of roots into the roof deck. In such a case, none or less expensive root barrier is sufficient.

Considering that *Sedum* species are non-native to several parts of the world, research should also be focussed on to screen other plant species suitable for green roofs. Blanusa et al. [71] attempted to identify vegetation types which can be alternatively used on green roofs. Among different species examined, *Stachys byzantine* outperformed other species in terms of leaf surface cooling (even in drying substrate, e.g. 5 °C cooler compared with *Sedum*), substrate cooling beneath its canopy (up to 12 °C) and air above the canopy (up to 1 °C, when soil moisture was not limited). Berardi et al. [3] recommended several vegetation alternatives for green roofs and indicated that most of the vegetation types can perform successfully provided proper research has been done in local context. It is always desirable to employ native species for green roofs [72,73]. Native species are already adapted to local weather conditions, known growth pattern in the specific climatic region and resistance to local pests, etc. Vijayaraghavan and Joshi [7] identified local species, *Portulaca grandiflora*, as suitable green roof vegetation for tropical wet and dry climate which possess similar characteristics as that of *Sedum*. Schweitzer and Erell [74] studied four local plant species for use in extensive green roofs under hot dry climates and identified that *Aptenia cordifolia*as as drought-efficient and consume less water. On the other hand, Monterusso et al. [75] after examining the suitability of eighteen native species for potential use on extensive green roofs in Michigan (USA) identified that only four species were able to survive on the non-irrigated extensive green roof.

Several studies have suggested that the use of diverse type of plantations could be helpful for maximising the effectiveness of green roofs [3,72]. In accordance, Cook-Patton and Bauerle [61] pointed out that by limiting the number and type of species in these systems, we may fail to treat green roofs as ecological communities and constrain the short- and long-term functioning of green roofs. Species diversity in green roofs has often been associated with increased aesthetic value [76]. In addition, plant diversity could enhance substrate cooling [77], avoid invasive weeds [78] and conserve water [79]. However, Cook-Patton and Bauerle [61] warned that it is important to strategically select species because increasing diversity for the purpose of variation may not yield positive result. For instance, MacIvor et al. [79] found that adding wetland plants to green roof mixtures tended to decrease performance and recommended that the addition of less appropriate plants diluted the benefits of increasing species diversity.

Phytoremediation ability was never a criterion for selection of green roof plants. In green roofs, vegetation remove dissolved pollutants through phytoextraction and gaseous pollutants through phytovolatilization. The most important green roof species, *Sedum,* was identified as a poor air pollution mitigator [8]; however excelled well in metal hyperaccumulation [80,81]. Even though there were several studies on air and water quality improvement by green roofs, the role of vegetation on pollution control was seldom studied. Of the limited literatures, a study conducted by Yang et al. [53] in Chicago indicated that deciduous trees removed more SO_2, NO_2, PM_{10} and O_3 compared to tall herbaceous plants and short grass. Speak et al. [25] identified that grasses (*Agrostis stolonifera* and *Festuca rubra*) performed effectively in PM_{10} removal than *Plantago lanceolata* and *Sedum album*. To prove phytoextraction ability, Vijayaraghavan et al. [41] conducted experiments on vegetated and un-vegetated green roofs with results indicated that *Sedum*-based green roofs acted as a sink for several metal ions. Few years later, the phytoextraction ability of *Portulaca grandiflora* in green roofs was established by Vijayaraghavan and Joshi [7] with the species portrayed ability to retain Na, K, Ca, Mg, Al, Fe, Cr, Cu, Ni, Zn, Cd and Pb from contaminated rain water. Thus, the author would like to emphasise that the selection of plant type for green roofs should be performed according to the local climatic conditions and nutrient availability as well as the impact of plant on the ecosystems.

4.2. Growth substrate

Growth substrate directly influences the plant growth and performance of green roofs. Therefore, choosing an appropriate substrate is crucial for the success of any green roofs. Several benefits of green roofs are directly associated with the properties of growth substrate, including water quality improvement, peak flow reduction, thermal benefits and sound insulation. Apart from this, harsh conditions prevail in roof top environments demand substrate to have other unique properties. Hence, it is not practical to expect one material to possess all characteristics required to constitute green roof substrate. It is of general practice to mix several components of different characteristics at defined ratios to constitute growth medium. Even though many investigators often used commercial substrates in their studies, there were few authors who suggested alternative low-cost and light-weight materials that could be used in growth substrate [82–84]. It includes pumice [85], zeolite [86], scoria [62,87], vermiculite [7], perlite [82,88], peat [89], crushed brick [90,91] and other low-cost waste materials [58]. More importantly, Ondoño et al. [90] explored nine different crushed bricks and three crushed tiles from different origin for their possibility as green roof substrate. The authors observed that type of amendment of inorganic substrate with 30% of green waste improved physical properties for plant growth and survival, water retention and green roof installation. Vijayaraghavan and Raja [18] conducted a detailed study to prepare a substrate mix using different inorganic and organic constituents. A mix prepared from 30% perlite, 20% vermiculite, 20% crushed brick, 10% sand and 20% coco-peat on volume basis exhibited desirable characteristics of green roof substrate with low bulk density (431 kg/m^3), high water holding capacity (39.4%), air filled porosity (19.5%), and hydraulic conductivity (4570 mm/h) and maximum plant support (380% total biomass increment). In addition to the above scientific findings, there were several substrates developed commercially for green roofs. Nagase and Dunnett [92] used a commercial substrate (Zinco *Sedum* substrate) to study the influence of organic matter for sustainable plant growth in extensive green roofs. Vijayaraghavan et al. [41] utilised commercial DAKU substrate to examine the runoff quality from green roofs. In general, commercial substrates were developed using materials that are locally available and were formulated for the intended plant selection, climatic condition and anticipated level of maintenance. Hence, these types of substrates could not perform well in other geographical areas which are not similar to country of origin. It is also not recommended to import commercial growth mediums as it incurs high cost as well as not permitted in many countries. It is always advisable to design green roof substrate using local waste materials which would make green roofs cheaper to install [92]. In countries where commercial green roof products are not available, consumers often use locally available substrate mediums for green roof establishment and this include garden/potting soil and composts. However, there are obvious disadvantages associated with garden soil in green roofs which are: (1) poor water retention and aeration effect; (2) it is heavy, hence there is a risk that roof may collapse; (3) support weeds; and (4) leach nutrients and easily compact [58]. The usage of 100% composts should also be avoided at roof top as this might cause shrinkage of the vegetation support course, promote growth of unnecessary weeds, increase rooftop load during rain events, and endanger the long term success of the whole roof. Hence, growth medium should be properly engineered to achieve benefits of green roofs and the characteristics desirable for an ideal growth substrate is illustrated in Fig. 2.

It is very important for growth medium to have low dry and wet bulk densities. Of the different components, substrate constitutes major load on the roof structure. Most buildings have load restrictions, especially older buildings whose roofs are not constructed to accommodate green roofs. Hence, it is important to keep the weight of substrate as low as possible. One of main strategy to reduce the weight of growth substrate is to use low density inorganic recycled materials. The bulk density of perlite was reported to be 9.4 times less than that of traditional garden soil [18]. Few research guidelines recommended usage of more than 80% of inorganic constituents in green roof substrate [93,94]; in that way the weight of green roof could be reduced. It should also be noted that lower the density of the substrate, the thicker the substrate layer can be designed and wide variety of vegetation can be planted [58]. Wet bulk density is also an important parameter as during rain events some substrate constituents rapidly become saturated and increase the overall weight. Organic constituent such as coco-peat was reported to enhance 5.2 times their original weight under maximum moisture conditions [18]. Cao et al. [87] reported that bulk density of biochar increased 4.1 times on saturation.

Substrates are expected to have less leaching tendency and high sorption capacity. Several authors reported leaching tendency of green roofs, which influence the quality of runoff as discussed in Section 3.3. Green roof growing media are typically engineered to include micro- and macro-nutrients to promote plant growth. In order to provide these nutrients, it is necessary to incorporate organic constituents to the growth substrate. Some of the common organic constituents used in green roof substrate include peat [7,85], mulch [92], and other composts [92,95]. Nagase and Dunnett [92] even attempted to obtain a relationship between percentage of organic matter in substrate and plant growth in extensive green roofs. The authors identified that increase in organic matter improved plant growth and substrate moisture content. However, the presence of organic constituents in substrate was often identified as a likely source of contaminants in green roof runoff [8,42]. This is mainly due to lack of stability, as organic matter breaks down over time and causes the substrate to shrink. Emilsson and Rolf [96] reported that 3 and 10% peat material used in two different green roof substrates were almost completely decomposed during the first year. Hence, it is recommended to minimise organic matter in green roof substrate. The

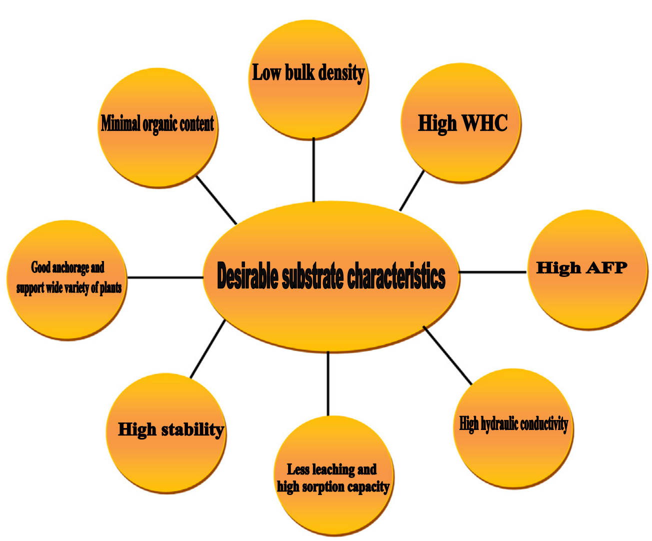

Fig. 2. Desirable substrate characteristics for extensive green roofs.

German guidelines for green roofs, Forschungsgesellschaft Landschaftsentwicklung Landschaftsbau (FLL) recommends only 4–8% and 6–12% organic matter by volume for extensive and intensive green roofs, respectively [94].

Sorption capacity may be a beneficial property for growth medium to improve the quality of runoff. But due to major presence of inorganic constituents, the sorption capacity of green roof substrate is always limited. For instance, expanded perlite, a widely used substrate component, exhibited only 8.6 and 13.4 mg/g sorption capacities over Cu(II) and Pb(II) ions, respectively [97]. Whereas another widely used substrate component, pumice, sorbed only 3.5 and 1.6 mg/g of Cu(II) and Cr(III), respectively [98]. An effective way to increase sorption potential is to increase the organic content of substrate. Through batch sorption studies, Jang et al. [99] determined that mulch sorbed as high as 72.5, 22.8 and 12.2 mg/g of Pb, Cu and Zn. Vijayaraghavan and Joshi [7] highlighted that developed green roof substrate with 20% coco-peat could filter approximately 6000 mm of rainfall without exceeding USEPA freshwater regulations for any of the heavy metals. Some biomaterials commonly referred as biosorbents could also be used as substrate additives. Seaweeds, a well-known sorbent, were shown to remove wide range of pollutants through biosorption process [100,101]. It can also act as fertilizer as it helps to bind soil crumbs together, and it contains all soil nutrients. Hence these biomaterials can constitute organic portion of substrate. However, additional research is required to investigate their mode of application, suitability to different green roof plants and long term impact on soil and water qualities.

Water holding capacity (WHC) of substrate components is crucial for the survival of plants under drought conditions and delay peak flow during storm events. High WHC also enable to use non-succulent species. FLL recommends WHC > 20% for extensive roofs [94]. Increasing substrate volume, depth and organic content increases water holding capacity (WHC); however, alters other substrate properties. In recent years, few research studies suggested usage of additives to enhance WHC of substrate [102,103]. Cao et al. [87] observed that application of biochar as an additive in green roof substrate improved WHC as well as plant available water (PAW). On the other hand, Farrell et al. [103] added silicate granules and hydrogel to improve WHC and PAW of substrate.

Good aeration and flow properties of substrate are not only essential for plant growth, but also the prerequisites to prevent roof leakage and overloaded water. For extensive roofs, FLL suggested AFP (air filled porosity) > 10% and hydraulic conductivity > 3600 mm/h [94]. Large size particles improve AFP and hydraulic conductivity. Vijayaraghavan and Raja [18] reported that the presence of 4–10 mm crushed brick particles with AFP and hydraulic conductivity of 28.3% and 14,200 mm/h, respectively, improved the overall air and flow properties of substrate. Other inorganic materials such as expanded granules, perlite and scoria improve AFP and hydraulic properties of substrate; whereas small sized particles and organic matters decrease air and flow properties.

Growth substrate should also be stable, support wide variety of species and provide good anchorage to plants. Roof top experience severe weather conditions and the substrate should be stable to withstand extremity and at the same time provide support to plants. Considering that light-weight inorganic constituents are preferred in green roof substrate, their stability is of biggest concern. For instance, perlite easily floats in water and big storm event push perlite onto the top surface of substrate. Dried perlite at the top of substrate easily spreads with wind and thereby causing air pollution. Hence, careful approach is needed to select appropriate constituents that offer stability to substrate. Until now, no research effort was made to evaluate the vulnerability of substrate to wind erosion and heavy storm events. Also, the effect of compaction over substrate should be studied as most of light-weight inorganic components are brittle in nature. On a positive note, few studies extensively investigated the ability of various substrates to support wide range of plant species [61]. Rowe et al. [65] identified that substrate prepared basically using heat-expanded slate, sand and peat supported 25 different succulent species. Dunnett et al. [104] utilised commercial ZinCo substrate which supported 12 species including *Sedum* spp., forbs and grasses.

Taking all factors into consideration, it is a difficult task to identify or prepare green roof substrate which possesses all favourable characteristics. Some of the characteristics may be toned down to improve other. Care is however needed that the unique benefits of green roof are preserved. Low bulk density achieved by using light-weight minerals may compromise the stability of substrate and plant anchorage. By decreasing the particle size and improving organic matter content in an effort to increase WHC may affect AFP and hydraulic conductivity. However, optimising these characteristics through continued research is essential for long-term success of green roof.

4.3. Filter layer

The main function of a filter layer is to separate the growth substrate from the drainage layer, and thereby prevent small media particles such as plant debris and soil fines from entering and clogging the drainage layer below. In general practice, geotextiles fabrics are typically used in green roofs [10,84]. These filter fabrics are expected to have high tensile strength in order to withstand the load above; in addition have small pores to allow good water permeability in the normal direction while inhibiting the movement of soil medium particles into the drain layer. The filter fabric also acts as a root-barrier membrane for plants that have soft and short roots. Wong and Jim [105] indicated that nonwoven geotextile filter fabric absorbed approximately 1.5 L of water/m^2. This property also enhances overall water retention capacity of green roofs. Licht and Lundholm [106] identified that nonwoven polymer based fabric effectively managed moisture and separated substrate layers, which helped in the establishment of native herbaceous plants. The authors investigated several native herbaceous species based on thickness of filter fabric and identified that green roofs with thicker fabric retained over 300% more precipitation than did the green roofs with no fabric.

4.4. Drainage layer

Drainage layer is crucial for the success of any green roof. It provides an optimal balance between air and water in the green roof system. Considering that most green roof vegetation requires an aerated and non-water-logged substrate for good growth, drainage layer aids in removal of excess water from substrate to ensure aerobic substrate condition. Drainage layer also protects water proof membrane and improve thermal properties of green roof [10]. In recent times, two major types of drainage layers are used in green roofs:

- Drainage modular panels: It is made of high strength plastic materials (polyethylene or polystyrene) with compartments to store water while allowing the evacuation of excess water.
- Drainage granular materials: These materials have some WHC as well as large pore spaces to store water and examples include light-weight expanded clay aggregates (LECA), expanded shale, crushed brick, coarse gravel and stone chips.

The selection of suitable drainage layer depends strongly on cost, construction requirements, vegetation type and scale of green roof. In general for small-scale establishments like residential buildings, granular materials fulfil the requirements. It can be viewed as the most basic drainage system but in some cases may be just sufficient to lift the substrate layer above the draining water. Vijayaraghavan et al. [41] used 5–15 mm clay pebbles as drainage layer in pilot-scale green roof installations. Pérez et al. [107] even recommended usage of rubber crumbs as an alternative drainage layer. However, an important disadvantage of granular materials is that it can only be applied in flat roofs or slightly angled surfaces ($< 5°$). Also, constraints during installation and workmanship should not be ignored. On the other hand, drainage modules possess ability to store more water in their compartments. Wong and Jim [105] used a proprietary drainage layer (Nophadrain 5+1), which exhibited water storage capacity of 4.3 L/m^2. Vijayaraghavan and Joshi [7] used commercial drainage module (BioRemeGree drain cell), which stored 2 L of water/m^2. Drainage modules are well suited for large-scale installations and can suit flat as well as moderately sloped surfaces. Cost and ultimate disposal are main limitations of drainage modules; however, their easy installation and possibility to open-up in parts during roof repair favour them in modern green roofs.

4.5. Waterproofing layer and Root barrier

Water-proof layer is fundamental for success of any green roof. Even though water-proofing may not be a part of green roof, it is a pre-requisite during any green roof installation to prevent leaks. It is not surprising to assume, from an end-user point-of-view, that a single drop of water leakage in roof often considered as a failure of green roof. Due to wet soil and drainage layer, moisture content of roof is always high. Also, in case of a leak in an operating green roof, all the layers needed to be removed to locate the leak. Hence, application of water-proof layer is always advisable. There are several options available and these include liquid-applied membranes, single-ply sheet membranes, modified-bitumen sheets and thermoplastic membranes [10]. The type of green roof along with cost, availability and life expectancy decides the nature of water-proofing.

Root-barrier is mandatory for intensive green roofs whereas optional for extensive type. The purpose of root-barrier is to protect the structure of roof from roots of plants that could penetrate from green roof's upper layers [108]. Several commercial root-barriers are available in market from hard plastic sheets to metal sheets (usually copper) [10].

5. Short-comings/constraints of green roofs

Green roofs have some constraints, at least according to public or policy-makers' perspective. Even though research reports and environmentalists attempt to highlight positive aspects of greening the rooftop, several factors hinder the growth of green roof. This hindrance is more pronounced in developing countries as policy makers still unable to understand the positive aspects and recommend green roof installation. Without government support or regulations, the justification of green roofs to common public is a tiresome process.

Several factors, as illustrated in Fig. 3, limit the growth of green roof in majority of counties. First and foremost hindrance factor is the cost of green roof. It is often regarded that green roofs are long-term investments with short-term returns [108]. To be precise, installation of green roof requires significant investment and the cost varies with type of green roof, location, labour and equipment. Bianchini and Hewage [108] indicated that costs of standard extensive green roof in British Columbia, Canada varies from \$12/ft^2–\$15/ft^2. On the other hand, costs of extensive green roofs costs \$3–\$5/ft^2 in Chennai, India. In addition to the above, operation, maintenance and ultimate disposal incur additional

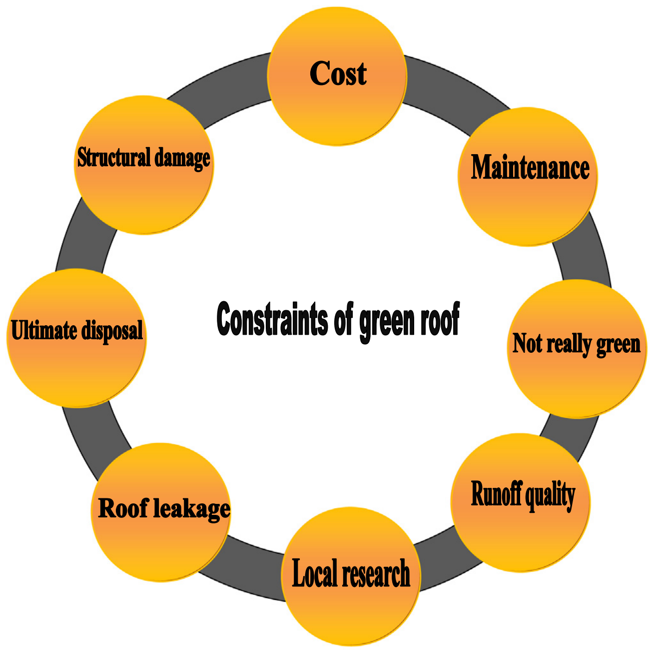

Fig. 3. General constraints of green roof according to public perpective.

cost. Little research has been done to analyse the costs of green roof systems for urban applications. Therefore, return of this investment is either unknown or very complex to comprehend. Clark et al. [109] demonstrated an investment return within 11 years on a single green roof in Michigan when low green roof installation costs and high environmental benefits were considered. Taking a 1795 m^2 roof area in Washington DC, Niu et al. [6] determined that the installation cost of green roofs is 27% higher than that of conventional roofs. However, considering the benefits over the life time (40 years) of the green roof, the net present value (NPV) of the green roof is about 25% lower than that of a conventional roof. In contrast, Lee [110] performed life cycle analysis of a green roof in Oregon by taking into account benefits such as extended roof life, energy savings, and stormwater fee reduction over 60 years and still found that the green roof to be 7% more expensive than the conventional roof over this time. Similarly, Carter and Keeler [111] conducted benefit cost analysis (BCA) for the life cycle of extensive green roof system in an urban watershed and indicated that NPV ranges from 10% to 14% more expensive than traditional roof. This type of contrasting results is expected as study has been conducted in different geographic locations. In addition, majority of studies ignored some aspects in cost-benefit analysis, which biased the final observation. For instance, improvement of air quality and reduction of the UHI effect, are extremely complex issues to quantify. Other benefits of green roofs such as aesthetics, ecological preservation and noise reduction are individual-centric and they do not translate in direct savings for building owners. Hence, it is a formidable task to justify the cost of green roof. However, it is absolutely needed as a part of the decision-making process. From author's perspective, the potential profit of a green roof is much higher than its potential losses.

Maintenance of green roofs is another important barrier that confuses building owners and the research on this aspect is very limited [112]. It is often seen that commercial developers made unrealistic assurances such as green roofs need no irrigation, no fertilisation, and discourage weed growth, etc. To be precise, green roof needs constant watering, at least during drought climates, and occasional fertilisation which in turn promotes weed growth and thus require regular maintenance check. In order to decrease irrigation interval, the plant selection often limited to a few succulent species. Too little choice of plant species make customers uncomfortable and severely affect the aesthetic benefit of green roofs. High fertilised substrate leads to unwanted plant growth; whereas low nutrient substrates affect the growth of vegetation. Hence a proper balance should be determined or controlled release fertilizers can be used [47]. In general, extent and frequency of maintenance depends on the type of green roof. For extensive green roof, relatively simpler tasks such as plant protection, drainage check and weed removal are sufficient. On the other hand, intensive roofs require detailed maintenance operations. Irrespective of the type of green roof, weeding presents serious and time-consuming maintenance operation. Nagase et al. [112] suggested three methods to avoid weeds in green roofs: (1) avoiding light at the substrate surface by using ground-cover or tall plants; (2) using high plant diversity; and (3) removing parent plants before seed which are physiologically capable of germination.

Modern green roof components are generally made of polymer materials, except the growing medium and vegetation. Weight limitations and extreme roof top conditions demanded usage of durable polymeric materials to construct different components of green roofs. The total energy consumed over constructing these components and the resulting pollution raises a big question, how green really are green roofs? Bianchini and Hewage [108] pointed out that, in general, the drainage and filter layers of green roofs are manufactured with 40% recycled polypropylene whereas water retention layer using 100% recycled polymeric fibres. However, the authors quickly pointed out that the pollution released to the air due to the polymer's production process can be balanced by green roofs in long term. It is also recommended to explore materials that can replace the current use of polymers to enhance overall sustainability of green roofs.

Local green roof research is literally non-existent apart from few European, American and Asian countries. Blank et al. [13] conducted a detailed study on green roof research publications and identified that a total of 31 countries participated in green roof publications, of which USA and EU contributed 66% of research. As a result of this limited research in developing/under-developed countries, the respective developers as well as policy makers are unknown of components suitable for their geographical location. Imported green roof components often lead to high installation cost or possible failure due to non-compatibility issues.

Any roof has the potential to leak. However, the idea that green roof installation enhances the chances of leak is technically incorrect. In fact, several authors proved that green roof improves the life of roof by protecting the roof/water-proof membrane from UV, heat and cold waves as well as from mechanical damage [2,113]. Kosareo and Ries [114] highlighted that extensive green roofs improve the life span of the roof system to 25 years, which is approximately double that of a conventional roof. On the other hand, Peri et al. [115] through literature analysis hypothesised a lifetime of 40 years for extensive green roofs. Similarly, properly designed green roof avoids structural risk for buildings. Even though there were few reported building collapses, careful assessment by experts, selection of proper components and examination of their properties prevents structural damage.

Considering the volume of components required to build green roofs, the ultimate disposal of spent green roof generates serious concern regarding the man-power requirement, cost and environmental implications. Even though many studies applied BCA or life cycle cost approach to evaluate cost of green roof, none of these take into consideration the disposal cost of green roofs [115]. In general, disposal stage of green roof includes dissemble of all components and transport them to landfills. Some components such as growth medium can be reused for other applications; whereas vegetation can be used as composts or disposed as biodegradable wastes. However, the presence of plastic materials especially in filter and drainage layer presents few problems; however, they can be incinerated or disposed in land-fills. Peri et al. [115] conducted a case study to evaluate disposal costs of various components commonly used in green roof produced by a green roof supplier based in Italy. It was determined that disposal costs correspond to only 4.6% of the total costs (36.1% initial capital cost and 59.3% maintenance cost).

6. New trends in green roof technology

Recent years witnessed new alternative applications and findings, which boosted the growth and reach of green roofs. Hybrid Photovoltaic (PV)-green roofs is a new trend that provides benefits of green roofs as well as improve PV electrical yield [116]. It is well known that the efficiency of PV modules depends on the temperature of the modules and the surrounding ambient air temperature [117], i.e. cooler the temperature better the PV performance. Compared to gravel or other traditional roofs, the evapotranspirative potential of green roofs cools the surface and ambient air which in turn improve the performance of PV cells. PV panels also counter help green roofs by shading the parts of surface and thereby reduce the sun exposure and high evaporation rates normally experienced on green roofs. In Spain, Chemisana and Lamnatou [118] performed experiments using pilot-scale PV-green roofs and found out an increased efficiency of 1.29% and 3.33% for PV-gazania and PV-sedum green roofs, respectively, compared to PV-gravel roof. Hui and Chan [119] conducted a case study for a PV-green roof installed on an old building in Hong Kong and observed that the integrated approach generates 8.3% more electricity than the stand-alone PV cell. Considering that PV is a mature technology and widely used in several countries, green roofs can act as an important accessory to create more sustainable buildings. Nevertheless, more research is needed especially the effect of different plant species on the performance of PV cell as well as seasonal variations and structural loading.

Green roofs could utilise grey water as an irrigation source [120]. Grey water accounts for 65–90% of the domestic wastewater production, which originates from laundry, bathroom and kitchen activities [121]. Application of grey water also solves water requirement of green roof and also enables to select more vegetation species apart from succulents. Grey water from kitchen applications usually rich in nutrients hence minimise fertilisation requirement of green roof. Unfortunately, very few studies explored this possibility and the results are not encouraging. Ouldboukhitine et al. [122] applied simulated grey water to pilot-scale periwinkle- and ryegrass-green roofs; and the results indicated that grey water irrigation reduced thermal resistance by 30% and produced noticeable physiological harm especially to periwinkle plants. In another study, short term testing of grey water on a green roof [123] has shown that levels of BOD in the grey water were significantly reduced by passing it through a green roof substrate prior to its discharge. So a green roof may serve as a filter for grey water; however the authors expressed uncertainty whether the plants can effectively utilise grey water. Considering that the contents of grey water vary with several unknown factors and activities, it is not easy to generalise the outcome. Other option to reduce the impact of grey water on the plant growth is to collect and treat grey water using sand- or bio-filter before application to green roofs.

Green roofs offer provision to harvest rain water, although the volume will be much reduced and possible presence of some contaminants in the runoff compared to traditional roof. Also, potential of green roof to turn the rain water brownish may also be a concern. For this reason, it is recommended that the collected water could be used for activities outside building such as irrigation of ground plants or treat with sand filter for other non-potable purposes. A typical green home from author's perspective is illustrated in Fig. 4.

In an attempt to simplify the design and practicability, green roof modules are designed and developed. The modules made of high strength polymeric materials comprises of water storage element and space for other components. In most cases, the modules are preinstalled with substrate and vegetation. Thus, it can integrate well with old and new buildings. Also, it offers flexibility to replace part of green roof for roof repair and can be moved to any part of the roof or other buildings. However the cost and eventual disposal of modules should be considered.

7. Recommendations and future directions

Thus through this review, we can understand that green roofs are efficient and practical best management practice (BMP) to combat urbanisation. The benefits of green roof are numerous and some of them are well-researched and established. There are even new findings which allow green roofs to be an integral part of other BMPs and therefore contribute to green environment. Nevertheless, in author's perception, there is significant knowledge gap which prevents green roof to gain more popularity than it is now. One of the main reason is most of the benefits of green roofs are just possible and no research efforts were made to optimise green roofs to achieve them. Green roof components such as growth medium, plants and drainage elements are usually selected based on structural limitation, drought and aesthetical benefits. The influence of these components to achieve other benefits such as improved air/water quality, sound insulation and thermal properties are not well known. Also, research on green roofs is restricted to only few countries in Europe, America and Asia. Hence, the only option for other countries is to import green roof components, which usually results in high cost or ultimate failure due to adaptability issues. Considering that each country has different climatic condition and form of urbanisation, local research is utmost important for success of green roofs. It is important to prepare growth medium using locally available materials and screen native plants for eventual success of green roof. In addition, life-cycle and cost-analysis should be performed

Fig. 4. Schematics of proposed green home.

at each geographic location to enable the end-consumer and policy makers to understand the real scenario. Even with all this, the role of local councils or other levels of government is crucial for the success of green roofs. Policy-makers could step in and support green roofs by giving incentives, clear common doubts and frame regulations.

This review also pointed out that scientific investigation of green roofs is a relatively new and emerging field as evident from the recent publications cited in this article. The research on green roof is expected to grow further as several scientists around the world understood the benefits and implications of green roofs over urbanisation. More research investment and an inter-disciplinary team work are therefore required to examine this technology more comprehensively. In near future, we can expect green roofs in every geographical location around the world.

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