Brudermann & Sangkakool (2016) 587 words

In recent decades and years, improved recognition of the benefits of green infrastructure has led to an increasing number of cities adopting policies in support of green roofs. German cities started to support green roofs as early as the 1970s (Berardi et al., 2014). For example, in Munich, all suitable flat roofs with a surface area of over 100 m2 have to be ‘greened’; the city of Esslingen subsidizes 50% of the costs for green roofs, and in Darmstadt, building owners receive up to D 5000 if they install a green roof (Getter and Rowe, 2006). In the city of Copenhagen, Denmark, green roofs are required for all newly constructed roofs with a pitch of less than 30◦ (Berardi et al., 2014). In the Austrian capital Vienna, financial support of D 8 – D 25 is granted per square meter of green roof, with an upper limit of D 2200 per project. During seven years of its existence (2003–2010), this policy has resulted in an additional 16,000 m2 of green roofing (at a cost of D 150,000 of public funding1). Chen (2013) reviewed city policies in several Asian and American cities, and found policies and by-laws favoring green roofing in Singapore, Japan, Hong Kong, USA and Canada. Despite these developments, green roofs remain a niche technology and are, with a few exceptions, not yet widely dispersed in urban European areas.

Green roofs are in general classified into two major categories; intensive green roofs and extensive green roofs (Czemiel Berndtsson, 2010). Intensive green roofs are characterized by a rather high thickness of growing media; soil layers usually are thicker than 200 mm, with soil weights exceeding 300 kg/m2 (Berardi et al., 2014). Such deep soil allows for the growing of relatively large plants, and thus provides greater planting flexibility. Roof top gardens and roof gardens require intensive green roofing (Bianchini and Hewage, 2012b; Kosareo and Ries, 2007). Basic maintenance of such roofs includes weeding, fertilizing, and watering of the plants (Czemiel Berndtsson, 2010). Extensive green roofs, on the other hand, are limited to smaller plants such as sedums, small grasses, herbs, flowers and herbaceous plants (Berardi et al., 2014). The thickness of the growing medium is usually below 150 mm (Hakimdavar et al., 2014), with soil weights between 60 and 150 kg/m2 (Berardi et al., 2014). The construction of extensive green roofs is relatively simple; less effort is required in irrigation and maintenance (or may not be necessary at all). Due to their light weight and low level of maintenance, extensive green roofs are popular solutions in cities and are particularly appropriate for large scale rooftops (Hakimdavar et al., 2014; Jungels et al., 2013).

Green roofs are generally known to be an environmentally friendly product and an elementary component of sustainable construction (Bianchini and Hewage, 2012b). It has been shown that green roofs have a positive environmental performance in the long-term (Bianchini and Hewage, 2012a) as emissions generated during component manufacturing are offset 13–32 years after installation. There is still some criticism, however, concerning the nature of the materials used. Despite this, green roofs still promise to be a suitable technology in the domain of climate change adaptation and mitigation. Green roofs can also be financially attractive. In particular, extensive green roofs are considered to be a low risk investment since they can entail payback periods below 10 years (Bianchini and Hewage, 2012b).

Lee & Jim (2018) 601 words

Compact cities are susceptible to the double impacts of global climate change and urban heat island effect. Anthropogenic heat can degrade urban liveability in thermal terms. Growing urban expansion, densification and associated natural-to-urban land conversion have continued to intensify the thermal stress to affect the comfort and health of urban dwellers. Different measures have been adopted to bring relief. Vegetation and natural areas in cities can ameliorate the thermal load of cities. However, compact cities often lack ground-level space for green spaces. Green roofs provide a feasible alternative nature-based solution to mitigate the thermal plight and bring an array of associated benefits.

Green roof denotes building-integrated vegetation planted deliberately on the roof of a built structure (Grant, 2006). It is sometimes called roof garden and living roof in the literature. Green roofs can be classified according to key vegetative and substrate features (Grant, 2006; Dunnett and Kingsbury, 2008; Roehr and Fassman-Beck, 2015). Intensive green roof (IGR) has at least 0.15 m-deep substrate to support complex vegetation including herbs, shrubs and sometimes trees. In comparison, extensive green roof (EGR) has substrate shallower than 0.15 m to accommodate mainly herbaceous vegetation, incurring lower establishment cost and maintenance requirements. To reduce the gross load of IGR on building structure, light-weight materials such as pumice, zeolite and perlite have been used as substrate (Kotsiris et al., 2013). Existing research conducted in compact cities mostly focus on EGR (e.g. Jim, 2015a,b). With increasing installation of IGR, empirical research is needed to ascertain their design, management and benefits.

Green roofs bring multiple thermal benefits. Shading by vegetation canopy shields green roof soil surface from incoming solar radiation. Jim and Tsang (2011a) observed woodland vegetation on a Hong Kong green roof filtering 80% of solar irradiance. Reduced solar irradiance can bring surface cooling vis-a-vis conventional bare roof. Cooling performance depended on vegetation characteristics. The respective maximum ground surface cooling for green roof with turf, shrubs and trees reached approximately 18 °C, 26.5 °C and 23.5 °C (Wong et al., 2003a). The insulation effect of the landscape materials could dampen the temperature oscillation experienced by roof materials and lengthen their service life (Wong et al., 2003c; Teemusk and Mander, 2009). Besides the surface, green roof also cools the air above the ground surface. For instance, Speak et al. (2013) observed a nighttime median air cooling of 1.06 °C at 0.3 m height above the short vegetation canopy on a British IGR. For woodland IGR, the beneath-canopy air would affect the heat transfer into the building, which could mitigate the impact of urban heat island effect on indoor building users (Lee et al., 2014). More elaborate measurements of subcanopy air and surface cooling of IGR could improve understanding of relevant thermal functions. Both outdoor and indoor thermal comfort could be enhanced by green roof. On a Singaporean shrub green roof, decrease in globe temperature and mean radiant temperature were respectively 4.05 °C and 4.5 °C against bare roof (Wong et al., 2003b). Green roof serves as additional insulation layer to reduce indoor-outdoor heat exchange. Below a Greek EGR in summer, the indoor air temperature was maintained below 30 °C most of the time versus exceeding 30 °C most of the time in the outdoor air (Niachou et al., 2001). A controlled experiment in India found an average indoor air cooling of 5.1°C (Kumar and Kaushik, 2005). However, thermal comfort is influenced by local climate. The subtropical region lacks studies on the thermal behavior of IGR. Data harvested from field monitoring would be essential for a deeper understanding of the IGR-induced impact on thermal comfort.

Grunwald, Heusinger & Weber (2017) 553 words

Given the ongoing trend of global urbanization and the impacts of climate change on cities, there is an increased awareness and perception of different positive effects of urban vegetation, e.g. as a local climate adaptation measure (Seto et al., 2011; Rosenzweig et al., 2011; Larsen, 2015). A way to assess positive aspects of urban vegetation is the framework of urban ecosystem services (UESS), i.e. the benefits the urban population receives from ecosystems. This concept is increasingly applied in scientific studies (e.g. Gómez-Baggethun et al., 2013; Luederitz et al., 2015). UESS define provisioning (e.g. food), regulating (climate), supporting (habitat) and cultural (recreation) services of ecosystems or of specific components of ecosystems, i.e. trees, parks or street greenery (Luederitz et al., 2015).

Green roofs are one specific type of vegetated urban ecosystems (Berardi et al., 2014; Sutton, 2015). The construction of green roofs concerning number and surface area of green roofs has been globally increasing during recent years (e.g. Charpentier, 2015). As an example for Germany, a leader in green roof construction, it is assumed that about 8 million m2 of green roof area are installed annually (FBB, 2015). Green roofs are composed as either extensive or intensive roof vegetation systems (cf. Oberndorfer et al., 2007 for a detailed review). While the former have shallow substrate depths (2–20 cm) and primarily are composed of drought-tolerant sedum vegetation and mosses which require little maintenance, the latter have deeper substrates (>20 cm), are more diverse, not limited to specific plant types, and require regular maintenance and irrigation (Oberndorfer et al., 2007; Pfoser et al., 2014). The implementation of a green roof depends on statical characteristics and on roof slope. Generally, green roofs can be installed at slopes between 0 and 30◦ (FLL, 2008; cf. Section 2.2).

Green roof ecosystems are characterised to provide a range of UESS, e.g. microclimate regulation, air quality improvement, stormwater retention, habitat for flora and fauna, and aesthetic values (Oberndorfer et al., 2007). The benefits of green roof ecosystems have been intensively reviewed in scientific literature (e.g. Oberndorfer et al., 2007; Rowe, 2011; Sutton, 2015) and will only be briefly summarised at this point. One of the most recognised environmental benefits of green roofs is the capacity for (local) thermal regulation. A couple of studies report a significant decrease of surface and air temperature above green roofs in comparison to conventional roofs (Gaffin et al., 2009; Teemusk and Mander, 2010; Jim and Peng, 2012; Heusinger and Weber, 2015). Additionally, green roofs were studied for their potential to mitigate air pollution (Getter et al., 2009; Rowe, 2011; Speak et al., 2012), and to reduce rainwater runoff (DeNardo et al., 2005; VanWoert et al., 2005; Mentens et al., 2006; Yang et al., 2015). Furthermore, the positive impact for urban biodiversity, e.g. as additional habitat for different animal species, was studied by a couple of researchers (Francis and Lorimer, 2011; Cook-Patton and Bauerle, 2012). These benefits, most of which are also related to other types of urban green infrastructure such as parks, forests or community gardens (Coutts and Hahn, 2015), are of specific importance especially in dense built inner city areas where the implementation of additional green is limited due to space constraints, space competition and regulative aspects. Green roofs, however, can be implemented on roof area already in existence.

Karachaliou, Santamouris, Helli Pangalou (2015) 455 / 561 words

Urban warming is a major threat to urban populations. Increase of the ambient temperature in cities is due to the combined effect of the heat island phenomenon and the global climate change. Urban heat island is the more documented phenomenon of climate change and deals with the increase of the urban temperature compared to the temperature of the surrounding rural areas. Urban warming has a very important impact on the quality of life of urban dwellers. It increases considerably the energy consumption spent for cooling purposes [1], it rises the peak electricity demand [2], while it deteriorates the environmental quality, and causes discomfort and increased health problems in cities [3].

To counterbalance the serious impact of urban warming, important mitigation strategies have been proposed, developed and implemented in real scale projects [4]. Urban mitigation technologies aim to decrease the strength of heat sources and enhance the potential of heat sinks in the cities. Among the more efficient of the mitigation technologies are: (a) those aiming to expand the green spaces in cities through the use of green roofs or additional park and green areas [5], (b) technologies increasing the albedo of the cities through the use of cool materials presenting a high reflectivity in the solar spectrum together with a high emissivity factor [6,7], (c) strategies to decrease the anthropogenic heat released in cities and (d) technologies employing the use of low temperature sinks to dissipate the excess urban heat [8].

Urban green involving parks, green roofs, trees in the streets and open spaces contribute extensively to mitigate urban warming as it provides solar protection and cooling of the ambient air through evapotranspiration processes. Vegetative roofs are partially or completely covered by plants over an engineered planting substrate on specialized build up of polymer materials. They are differentiated by the type of plants they may support. Extensive type green roofs are covered by low vegetation while intensive green roofs may support growing of shrubs and small trees. Important benefits are associated with the use of green roofs. Because of the solar and heat protection they provide, contribute to lower the energy consumption of buildings, while through latent heat processes, decreases the surface temperature of the roofs and reduce the release of sensible heat to the atmosphere. In parallel, green roofs help with the storm water runoff management, provide better air quality, reduce noise, prevent erosion and increase the durability of the roof materials [9]. Disadvantages associated with planted roofs are the additional load that the building has to support actually mitigated with the installation of lightweight specialized build up systems and the relatively high investment cost.

The energy and mitigation performance of the vegetative roofs is governed by several climatic, optical, thermal and structural parameters. In particular, air temperature, solar radiation, ambient humidity, precipitation and wind speed are the main climatic parameters influencing the performance of green roofs. In parallel, thermal, optical and hydrological parameters like the thermal capacitance and U value of the roof, the absorptivity of the green roof as a system, and the frequency of watering of plants determine the efficiency of the green roofs. Finally, the total one sided area of photosynthetic tissue per unit of ground surface area, LAI (Leaf Area Index), is a crucial parameter defining the latent heat losses of the roof [10].

Rasul & Arutla (2020) 402 / 505 words

Industrialisation, increase in luxury of the people and deforestation has been causing a lot of damage to our natural environment, and human and animal life over time. Implementation of green infrastructure (GI) initiatives have been emerging as thriving measures in bringing back the urban living spaces in many developed and developing countries across the world [1]. There are several types of GI in practice. The Green Roof, otherwise called a living roof, is one of the GI practices, which have many advantages besides a few disadvantages. This has been in practice for centuries; however, it has received more attention in recent years, particularly in Australia, due to its environmental, energy and economic benefits. It reduces air conditioning energy consumption in both winter and summer by keeping a building hot during winter and by acting as a barrier for the heat of the sun during summer [2]. It reduces: (a) life cycle expenses of the roof as green roofs are approximately 3 times more durable than conventional roofs, (b) construction wastes leading to the reduction in construction costs, and (c) sound propagation by acting as insulation medium due to making the roof thicker. Due to better amenity, buildings with green roofs would attract higher rent and higher occupant retention. Environmental benefits include: (a) by acting as a medium which can hold the moisture and water content, it reduces the passage of storm water, consequently reducing erosion, (b) it improves the air quality, and (c) it diminishes the urban heat island effect because, during the summer season, urban areas are hotter than the rural areas. Social benefits include that it increases the educational opportunities, employment opportunities, provides space for food production and provides green space for recreational use. The green roofs protect and extend the roof life against the high temperature and fluctuations, act as insulation to sound. They also allow the improvement in the air quality by capturing carbon dioxide. In general, there are two-types of green roofs. These are intensive (Fig. 1) and extensive (Fig. 2) green roofs. The growing medium is thicker for intensive (more than 300 mm) than for extensive (less than 300 mm) green roofs. Intensive green roofs need a deep soil layer and skilled labour, and higher maintenance than extensive green roofs. The different layers of the green roof are a vegetation layer, substrate layer, water retention layer, filter layer, drainage layer, root barrier layer and protection layer.

There are lots of buildings which are old and low rise that do not have green roofs. Green roofs on low-rise buildings give more benefits than on the tall buildings, hence a low-rise building was selected for this study. In this study, environmental impacts of both types of green roofs are compared with the non-green roof system. The life cycle of the green roofs was set to 25 years. The major objectives were to evaluate and quantify the environmental impacts of green roofs and to develop a simple model and the database for an LCA of green roof systems using SimaPro simulation software.

Mahdiyar, Tabatabaee, Nobahar Sadeghifam, Reza Mohandes, Abdullah, Moharrami Meynagh (2016) 655 words

Sustainable approaches in construction industry are known to make a significant contribution to the purpose of reusing and recycling materials, energy saving, and reducing emissions in order to alleviate the resultant adverse impacts on the environment created by the construction industry (Akadiri et al., 2013; Alyami et al., 2013; Lundholm and Peck, 2008). Green roofs have been introduced as the environmentally friendly approach to inspire sustainable construction (Bianchini and Hewage, 2012a), and carry a large number of environmental benefits (Berardi et al., 2014; Ondono et al., 2016; Simmons et al., 2008). However, there are still some barriers in many countries like Australia, Hong Kong, and Malaysia in installing green roofs (Rahman et al., 2013; Williams et al., 2010; Zhang et al., 2012). Additional initial costs and the maintenance-related costs are stated as the major barriers for green roof installation (Wong, Tay et al., 2003).

There are two different classifications for green roofs: a) intensive and extensive green roof, and b) built-in-place versus modular (Morgan et al., 2013). Intensive green roofs show remarkable similarities to roof gardens; they need adequate and reasonable depth of soil and also require a constant maintenance during their entire lifespans. However, extensive green roofs consist of a relatively thin layer of soil in comparison to the other types (Czemiel Berndtsson, 2010). Furthermore, they are designed in such a way to be virtually self-sustaining for which high maintenance is not required (Dvorak, 2009). Private benefits and costs for the installation of green roofs vary along with the types; however, all these types provide positive environmental benefits (Mahdiyar et al., 2015). Storm water retention (Dunnett et al., 2008), mitigation of urban heat island (Susca et al., 2011), increasing the property value (Jim and Peng, 2012), and providing recreational spaces (Ascione et al., 2013) are some of the benefits of green roof installation.

Green roofs have been implemented in many countries with different economic and climatic circumstances (La Roche and Berardi, 2014), and a number of studies have been investigated into economic impacts of installing green roofs. Clark et al. (2008) demonstrated that Net Present Value (NPV) for a conventional roof is between 20% and 25% more than the extensive green roof during its lifespan (over 40 years). Carter and Keeler (2008) collected data during an experimental study for green roof in order to conduct a cost-benefit analysis. The NPV of extensive green roofs in their study indicates that this type of green roof is more expensive than the conventional one ranging from 10% to 14%. Consequently, they concluded that a 20% reduction in initial cost is necessary to consider this type of green roof as an economic-feasible construction practice. Bianchini and Hewage (2012b) assessed the costs and benefits involved in personal and social sectors in installing green roofs. The results from their study indicate that by installing any type of green roof, both private and social sectors are at a lower-risk investment, and green roofs are a personal investment. They also found that the social benefits of green roofs play an important role in obtaining the results. Indeed, considering social costs and benefits directly affects the decision making related to this investment. Niu et al. (2010) aimed investigating into the scale of environmental benefits of green roof installation, from the range of private buildings to the city scale using the financial NPV model. Sproul et al. (2014) conducted an economic comparison between white roof and green roofs, and they found that white roofs provide more net savings for the owner; however, green roof might be preferable due to its environmental benefits. Blackhurst et al. (2010) focused on the beneficial aspects of green roofs such as reduction in building cooling load, storm water runoff, carbon dioxide, air pollutants and mitigation of UHI. They found that green roofs are not cost-effective in private sectors; nevertheless, adding the social sector makes it more cost-efficient.

Vijayaraghavan (2016) 611 words

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.

Shafique, Kim & Rafiq (2018)

Climate change and urbanization are the topics of current interest. In the developed countries, urbanization forecasted to attain approximately 83% in 2030 [1]. Due to the rapid economic growth, urbanization is increasing in many countries which degrade the natural landscape as well as the nearby environment [2,3]. These problems can be solved by applying the green stormwater infrastructure strategies. The introduction of new urban development strategies such as rain gardens, green roofs, green walls and bioretention systems can mitigate the adverse effects of urbanization and improve the environment of an area [4,5]. Green roofs also referred as vegetated roofs [5], cool roofs [6], eco roofs (due to ecological benefits), roof garden or living roofs [7–12]. Green roofs are the basically roofs planted with different kind of vegetation/plants on the top of growth medium (substrate). This concept was designed to encourage the vegetations on the top of building to get multiple social, economical and environmental benefits. A green roof typically consists of several components, including vegetation, substrate, filter layer, drainage material, insulation, root barrier and water proofing membranes [13]. The optimal selection of each component of the green roof is very important to get the best outcomes from the green roofs. Each component is equally important and plays very important role for the better performance of green roof in an area [14]. Due to multiple benefits, green roofs are being implemented in many countries. More research is going on the implementation and performance of green roofs in different regions around the world. Fig. 1 shows the 2016 green roof for excellence awards in buildings.

In recent decades, green roofs proved as the sustainable practices and have gained much popularity around the globe [16]. Research on the green roofs shows numerous social, environmental and economical benefits. Significant evidence shows that green roofs can give multiple benefits, such as stormwater management, reduced urban heat island, increased urban plant, wildlife habitat and roof life, enhance the air and water quality and quality of life, decreased the energy consumptions costs of the building, decreased the noise pollution, procreates the recreational activities and increased the green areas and aesthetic value in urban environments [16–20]. As the result of water quality enhancement, green roofs decrease the burden of the water treatment facilities in an area [10,21–25]. Due to the above benefits many countries started to implement the green roofs in buildings. As the result of this more and more green roofs are established day by day around the globe.

Green roofs commonly classified into four categories. These are intensive, semi-intensive, single-course extensive and multi-course extensive [26]. Intensive green roofs are categorized on the basis of substrate thickness (> 12 in.), a wide variety of plants/vegetations similar ground-level landscapes, high water holding capacity, high capital and maintenance costs and larger weight. Due to the large soil depth, it has more water holding capacity and the plant selection can be more diverse as small trees and shrubs. This also requires more consideration about the building structure capability to bear large weight. Therefore, this type of roofs requires high maintenance in the form of irrigating, weeding and fertile. Green roofs with 6–12in. substrate thickness, referred as semi-intensive green roofs. Semi-intensive green roofs contain the moderately substrate thickness and usually contain small plants, small shrubs and grass. These roofs require regular maintenance and high capital costs for the better performance. On the other hand, Single-course extensive roofs are the roofs with substrate thickness 3–4 in. In Single-course extensive roofs, mostly sedum uses as the vegetation layer and typically not required irrigation. It required little capital and maintenance costs as compared to all other roofs. These roofs usually very light weight and very useful where the building weight restrictions. While multi-course extensive roofs consist of 4–6 in. substrate thickness. This roof type is usually light weight and mostly use in the USA. Of the four types, single and multi-course extensive roofs are most common around the world due to less weight, not require irrigation and less capital and maintenance costs.

Razzaghmanesh, Beecham, Salemi (2016) 653 words

Urbanisation growth, climate change and water scarcity are current environmental challenges in many cities around the world and it is estimated that more than half of the human population currently lives in cities (United Nations, 2004; Hopkins and Goodwin, 2011). The urban heat island (UHI) effect is one of the main consequences of a changing climate in the cities. The heat island effect is attributed to higher urban temperatures in city districts compared to the surrounding suburban or rural areas. This phenomenon is mainly associated with a high density of buildings and urban structures with low albedo coefficients resulting in the buildings absorbing more solar radiation (Giuseppe and D’Orazio, 2015). Albedo is the ratio of reflected radiation to incident radiation from at a surface. The use of heat absorbing materials, the reduction in vegetated or green spaces, the characteristics of urban canyons and the production of anthropogenic heat have caused the UHI potential to markedly increase in metropolitan areas (Santamouris et al., 2011, 2014; Sun and Augenbroe, 2014). One of the possible solutions to tackle the consequences of urbanisation growth is to introduce green infrastructure to a city’s urban environments. The implementation of green infrastructure is of considerable interest because it is a most effective climate change adaptation tool (Carter, 2011; Berardi et al., 2014; Li et al., 2014). Several methods have been proposed in the literature for combatting the Urban Heat Island (UHI) effect. The addition of green roofs and replacing conventional roof with cool roofs are among the proposed mitigation strategies that aim to reduce UHI. The sensible heat available for transmission to the air or to building envelopes is decreased by both strategies. However, the mechanisms for green roofs and cool roofs to reduce UHI are quite different. Generally, a green roof increases the evapotranspiration rate in urban areas through the addition of soil and plants onto rooftops and redirecting available energy to latent heat. In contrast, a cool roof increases the reflection of incoming solar radiation in urban areas by increasing the albedo of roof surfaces (Li et al., 2014).

A green roof is an engineering multi-layered structure with the outer layer consisting of vegetation. Green roofs are normally categorised into two types, namely extensive (depth < 150 mm) and intensive (depth ≥ 150 mm) roofs (Berndtsson, 2010; Fassman and Simcock, 2012; Roehr and Fassman-Beck, 2015). Green roofs can bring amenity and enhanced aesthetic value (Getter and Rowe, 2006; Razzaghmanesh et al., 2012; Jungels et al., 2013), increased building value (Nagase and Dunnett, 2010), stormwater runoff mitigation (Mentens et al., 2006; Durhman et al., 2007; Voyde et al., 2010), potential for storm water quality improvement (Berndtsson et al., 2006, 2009, 2010; Razzaghmanesh et al., 2014a), noise reduction (Dunnett and Kingsbury, 2004), the ability to mitigate UHI effects (Wong et al., 2003; Castleton et al., 2010; Chang et al., 2011) and other benefits for urban environments. An investigation of the effects of adding green roofs and green walls to the urban environment of 9 cities around the world with different ranges of climate was undertaken by Alexandri and Jones (2008) who showed that they have a significant effect in reducing urban temperatures. Susca et al. (2011) evaluated the positive effects of vegetation at both the regional and building scales. They monitored the urban heat island in four areas of New York City, and found an average of 2 ◦ C difference in temperatures between the most and the least vegetated areas. Temperature decreases due to vegetation are primarily affected by the vegetation itself (amount and geometry), more than the canyon orientation in hot periods. If applied to the whole city scale, green roofs could mitigate increased urban temperatures, and, especially for hot climates, bring temperatures down to more acceptable levels. They could at the same time lower the energy costs associated with cooling buildings by 32 to 100% (Susca et al., 2011).

Mahdiyar, Tabatabaee, Abdullah, Marto (2018) 696 words

Green roof, as a sustainable alternative of the conventional roof, is defined as the use of vegetation covering the roof of a building (Refahi & Talkhabi, 2015). Installing green roof among private and public sectors is increasing due to the fact of having multiple benefits (Claus & Rousseau, 2012; Pianella, Clarke, Williams, Chen, & Aye, 2016). Green roofs are one of the solutions to increase green area (Susca, Gaffin, & Dell’osso, 2011), especially in central business districts. The technique of green roof installation on flat roofs was described in 1867 (Jim, 2017), while from that time, different types of green roof construction details have been installed throughout the world (Kosareo & Ries, 2007). Generally, green roofs are categorized into two major types, extensive green roof and intensive green roof (Peng & Jim, 2015; Williams, Rayner, & Raynor, 2010). However, several researchers stated that there is a third type of green roofs as a simple-intensive green roof which name is semi-intensive green roof (Berardi, GhaffarianHoseini, & GhaffarianHoseini, 2014; Bianchini & Hewage, 2012a; Luo, Huang, Liu, & Zhang, 2011; Mahdiyar, Abdullah, Tabatabaee, Mahdiyar, & Mohandes, 2015). It is notable that, there are significant differences in benefits, costs, maintenance periods and the plant types that can be planted in each type of green roofs (Peri, Traverso, Finkbeiner, & Rizzo, 2012). However, all types of green roofs are considered sustainable and environmentally-friendly (Gargari, Bibbiani, Fantozzi, & Campiotti, 2016).

Intensive green roof has a thick layer of growing medium, wherein a variety of plants can be grown, especially where irrigation is available (Kosareo & Ries, 2007; Peng & Jim, 2015). It is worth mentioning that, additional structural support is needed due to the heavy weight of substrate; thus, this type of green roof is applied to the buildings considering additional structural support (Mahdiyar et al., 2016). On the other hand, extensive green roof has a thinner layer of substrate, which is a relatively lightweight and thus in some cases little or even no additional structural support is needed. It makes this type of roofs applicable to a larger range of buildings (Nardini, Andri, & Crasso, 2011). This advantage, together with minor need for irrigation and maintenance, has led to a larger application of extensive green roofs (Berardi, 2016). Moreover, extensive green roof provides a harsh environment for plant growth with wide temperature fluctuations, limited water availability, and high exposure to solar radiation and wind, which causes a highly stressed environment for growing plants (Nagase & Dunnett, 2010). Furthermore, according to Allnut et al. (2014), semi-intensive green roof is a simple intensive green roof which needs lower additional structural support and maintenance in comparison with intensive green roof. Additionally, different types of plants can be used in semi-intensive green roof, while the thickness of soil is lower than intensive green roof. However, Yang, Yu, and Gong (2008) demonstrated that semi-intensive green roof is a green roof combination of both extensive and intensive green roof with at least 25% of extensive green roof.

In terms of building retrofitting, it has been proved that there are significant benefits resulting from green roof retrofits (Berardi, 2016; Castleton, Stovin, Beck, & Davison, 2010; Williams et al., 2010). As reported by Castleton et al. (2010), all types of green roofs are technically feasible for retrofitting; however, not all types are economically feasible. Moreover, Gargari et al. (2016) stated that the most important barrier of green roof installation for the owners is their opinion regarding the maintenance costs of green roofs. Intensive and semi-intensive green roofs need a large amount of costs for maintenance; however, it is not true regarding the extensive green roof. According to Jim and Tsang (2011), extensive green roof is the suitable type of green roof for retrofitting due to its light weight and low required maintenance. It is noteworthy that the requirements for additional structural support for building retrofitting with any type of green roofs depend on the building’s roof structure (Berardi et al., 2014). As a result, initial costs, maintenance costs, structural capability, and the projects’ requirements should be considered during decision making (DM) on green roof type selection for retrofitting.

Tam, Wang, Le (2016) 872 words

In Hong Kong, high pollution and lack of greenery have become serious problems to our built environment and communities [1e5]. Majority of buildings are high-rises and their roof areas are typically very limited. As built environments are commonly very densely concentrated, putting greenery on some intermediate roofs and man-made structures such as podia, sky gardens and covered walkways could significantly enhance the surrounding built environment [6e13].

Although green-roof research is comparatively new, its publication rate has dramatically increased in the last 20 years [14]. Green roofs suffer from water stress during long dry periods. Periodically, irrigation is usually required to maintain the health of green roofs [15]. Net shortwave radiation of the canopy is also one of the key parts for green-roof energy balance [16]. Hydroponic green roofs can also reduce rooftop's temperatures and heat amplitude in subtropical climates such as Taiwan [17]. The implementation of green roofs may also relieve heat-island effect problems [12,13]. However, its economy and environmental protection have not been clearly identified [18e26]. Thirty-three green roofs in southern Ontario were surveyed and samples of planting media were recovered for hydrological analyses [27]. Different vegetation types and covers were also studied and found to be important for roof cooling [28]. Green roofs' temperatures have initially been found to be close to the air temperature and green roofs may also provide thermal insulation, runoff reduction, and carbon uptake, but might require irrigation during dry periods [29]. Despite their rising popularity, studies on green roofs thermal insulation performance are however limited. A study in a Central New York climate found that a green roof dampens the extreme responses often observed on urban roofs. Vegetation and substrate layers may be used as insulation, but they are not recommended in lieu of insulation [30]. Energy balance analysis indicates that evapotranspiration and long-wave radiation dissipate most of heat gain for green roofs, and soil water content has a significant impact on energy balance [31]. It is difficult to find out the intangible benefits, i.e. visual aesthetic improvement, health and therapeutic value and ecological value [32e35].

According to the direction announced by the Hong Kong Special Administration Region in 2000 to green-up Hong Kong by planning more planting in the urban areas, the Steering Committee on Green established in December 2002 formulated related strategies and supervised the implementation of major programmes. However, no short-term measures or long-term programmes have been set up because of different opinions from bureaux and departments, lack of public consulted opinion and professional knowledge. This paper thus investigates the effectiveness of green-roof applications in Hong Kong. Thermal insulation, capital and maintenance cost, and tangible and intangible benefits are also examined to provide short-term and long-term recommendations for green-roof applications in Hong Kong.

A green roof is a conventional roof that is covered with a layer of vegetation [36]. Green roofs serve several purposes for a building, such as absorbing rainwater, providing insulation, creating a habitat for wildlife, lowering urban air temperatures and combating heat-island effects [36]. A green-roof system should include a waterproofing layer, a root barrier, a moisture mat, a drainage grill, a filter layer, vegetation soil and vegetation. The purpose of the root barrier is to prevent plant roots damaging waterproofing materials. The moisture mat is to absorb surplus water overflow from the drainage grill. Excessive moisture will be absorbed by vegetation soil during a dry period through evaporation processes. The drainage grill is used to keep a certain amount of water so that the vegetation soil can remain moist during dry period.

Green-roof can be classified as extensive and intensive systems. An extensive green roof is characterised by thin soil, limited or no irrigation requirement, low water retention and poor nutrient conditions can be classified as either extensive or intensive green roofs. An extensive green roof is characterised by thin soil, limited or no irrigation requirement, low water retention and poor nutrient conditions for plants [37]. An intensive green roof is characterised with deep soil, irrigation requirements, high water retention and fertile conditions for plants [37]. A summary of the characteristics of extensive and intensive green roofs is shown in Table 1.

The top three critical barriers encountered in implementing green roofs were highlighted as ‘Lack of promotion from the government and social communities among the public and private sectors’, “lack of incentive from the government towards the owners of the existing buildings” and “increase in maintenance cost” [38]. Barriers exist in the whole building life cycle process, including plan and design, construction and operation and management stages. It was also argued that the current gap in the lifecycle analyses on green roofs is due to weak focusing on the substrate [39]. These major problems are practically because of fertilizer usage during a disposal phase. Various types of green roofs, components of a green roof, economic revenues and technical attributes have been reviewed [40]. The use of indigenous vegetations for reducing water consumption and increasing energy efficiency for different geographical regions was recommended as possible solutions. Optimal green-roof areas being kept within the cost of a conventional home over a specific life time, such as 50 years have also been discussed [5].

Catalano, Marceno, Armando Laudicina, Guarino (2016) 595 words

Urban sustainability is one of the urgent challenges of the 21st century (Wu, 2014), since more than 50% of the world’s population live in urban areas, and this figure is estimated to reach 66% by 2050 (UNDESA, 2014). Continuously spreading cities and the growth of intensive agriculture are the major causes of habitat loss and fragmentation worldwide (Grimm et al., 2008). However urban green spaces can play a key role in biodiversity conservation (Goddard, Dougill, & Benton, 2010) and enhance urban ecosystem resilience (Colding, 2007). In particular, green roofs can partially compensate for the loss of green areas by replacing impervious surfaces, contributing to an increase in urban biodiversity (Brenneisen, 2003, 2006). In fact, by replicating specific habitat features and conditions, these artificial biotopes can host native flora and fauna in relatively undisturbed stands where plants, insects and birds can become established (Köhler, 2006; Kadas, 2006; Baumann, 2006).

The first known study on the biotic colonisation of green roofs dates back to 1940, when Kreh (1945) listed the plant species colonising some tar-paper-gravel roofs in Stuttgart, Germany. This roofing technique was developed at the beginning of 19th century in Silesia and consisted of a combination of tar and four layers of paper covered by a mixture of gravel and sand (Köhler and Poll, 2010). In Kreh’s study (1945), species were categorised according to the following functional group: bryophytes, CAM (Crassulacean Acid Metabolism) species and therophytes, substrate depth preferences (5–20 cm), pollination and dispersal strategies.

Modern green roofs can be classified as intensive, extensive and simple-intensive (German guidelines; FLL, 2008). Extensive green roofs consist of a shallow substrate ranging from 6 to 15 cm, planted or sown with drought tolerant plant species, and require low maintenance; intensive green roofs consist of a >20 cm thick substrate (normally top-soil), planted with woody and/or herbaceous species, and generally require irrigation and high maintenance; and simple-intensive green roofs can be seen as an intermediate roof type, consisting of 15–20 cm thick substrate (including top-soil), hosting perennial grasses and tall herbaceous species, and requiring medium maintenance.

Several studies of spontaneously colonised tar-paper-gravel, simple-intensive as well as extensive green roofs in central Europe, have described the recurrent plant communities thriving on different depths and kinds of substrate (Darius and Drepper, 1984; Thommen, 1986; Borchardt, 1994). These studies found that on 5–8 cm gravel roofs, stress tolerant species (Sedo-Scleranthetea) are enhanced while greater depths favoured ruderal species (Artemisietea vulgaris and/or Stellarietea mediae) and competitive species (Molinio-Arrhenatheretea and Festuco Brometea) (Bornkamm, 1961; Bossler & Suszka, 1988). Moreover, humus accumulation, nutrient supply and water holding capacity were identified as the main environmental drivers for plant establishment and community dynamics over time. Recently, plant functional traits including Grime’s CSR strategies (Grime, 1974, 2001) and life forms, have been used to predict green roof ecosystem services and identify suitable plant species (Nagase and Dunnett, 2010; Lundholm, MacIvor, MacDougall, & Ranalli, 2010; Van Mechelen, Dutoit, Kattge, & Hermy, 2014).

Despite the importance of long-term data in providing adequate planning recommendations (Rowe, Getter, & Durhman, 2012), only few studies have examined green roof dynamics for more than a decade (Krüger, 1999; Köhler, 2006; Köhler and Poll, 2010). Köhler & Poll (2010) assessed the effects of growing media on the vegetation quality and species richness of roofs in Berlin over a time span ranging from 13 to 48 years. Krüger (1999, 2001) instead focused on the changes in species composition over 12 years on the roofs of an eco-settlement in Hannover previously investigated by Ackermann and Vahle (1987).

Shafique, Azam, Rafiq, Ateeq, Luo (2020)

Recently, urbanization is a megatrend around the globe. Continuous urbanization can lead to economic development but also puts enormous pressure on existing infrastructure in cities (Cui and Shi, 2012; Lin and Zhu, 2018). Evidently, excessive urban runoff as a result of enormous urbanization is causing flash flooding and water quality degradation problems (Luo et al., 2018; Samsuri et al., 2018; Muhammad Shafique and Kim, 2017). Moreover, According to (Min et al., 2011) study, climate change is another critical factor, due to which the intensity of rain events will increase in the near future. As a result of this, these extreme rain events will cause a number of problems including flash flooding, water quality degradations, and heatwaves. Under these circumstances, there is a high need for green and sustainable practice which could retrieve the natural hydrology (allowing green spaces like a green roof to allow evapotranspiration) in urban areas.

According to (Hogan and Walbridge, 2007), the demand for new effective strategies for sustainable stormwater management is increasing i.e. Green Infrastrastrture (GI) (Licata, 2012; M. Shafique and Kim, 2017a; Muhammad Shafique and Kim, 2017) all around the world. This is because GI employs a natural process to collect, treat and improve runoff water quality as compared to conventional infrastructure (which only captures and allows water towards the sewer system) (M. Shafique and Kim, 2017a). Typical examples of GI are green roofs (rooftop vegetation to collect and store rainwater), rain gardens (vegetation on the ground surface to restore and infiltrate rainwater), permeable pavement (pavement with voids to allow infiltration of water) (M. Shafique and Kim, 2017a).

In urban areas, roof area is approximately 40e50% of the total impervious urban area (Stovin, 2010). This rooftop area gives enormous opportunities to apply green roofs to promote sustainability and a cleaner environment in urban areas (Berardi et al., 2014; Teotonio et al., 2018). Green roofs (GRs) are also called as vegetated roofs are sustainable and effective stormwater management practices which provide multiple benefits including stormwater management (Sangkakool et al., 2018; Shafique et al., 2016b; M. Shafique et al., 2018a; Stovin et al., 2012), reduce heatwaves (Imran et al., 2018; Lin et al., 2013; Shafique et al., 2016a; M. Shafique and Kim, 2017b), energy savings (Berardi, 2016; Cascone et al., 2018) and biodiversity (Berardi et al., 2014; Muhammad Shafique et al., 2018) on the building scale. However, implementations (including materials extraction, production, and transportation of raw materials, construction, operation, maintenance and recycle/decay) of GRs can bring about several environmental and economic burdens (Law et al., 2017). Consequently, the comprehensive assessment of green roof’s environmental and cost benefits should be conducted to provide a sustainable design in the near future. This will help to adopt more safer and sustainable materials for green roofs construction to promote sustainability around the globe.

Susca, 2019

**1. Background**

*1.1. Building energy use*

In 2007 the majority of the world-wide population became urban [1], and, by 2050, this percentage will continue growing reaching 66% [2], entailing further urbanization [3]—one of the major anthropogenic contributors to climate change [4]—and the potential raise of local warming phenomena: Urban Heat Island (UHI) effect [5]. This latter, in turn, augments cooling energy demand [6–12] and the related Greenhouse Gas (GHG) emissions that feed-back climate change. Nowadays, the building sector is responsible for the use of almost 120 EJ globally and about 30% of global carbon dioxide (CO2) emissions [13]. As in the EU28, between 1990 and 2013, the energy-use in the household sector dropped by just 3.2% [14], a further amelioration of the building sector is mandatory to diminish energy use, contributing to climate stabilization.

*1.2. Green roofs as a mitigation measure*

Among other mitigation and adaptation strategies [15–18], green infrastructures can contribute to urban wastewater management [19,20] and to mitigate urban temperature [5,21–24]. Since in densely urbanized cities residual surfaces convertible into vegetated areas are rarely available, rooftops can provide unexploited urban surfaces [25,26] that can help climate adaptation and mitigation. As, in the last decades, the interest towards climate change mitigation and urban climate resilience is growing, green roofs are gaining importance and a wide body of research has been published to ameliorate their performances and to investigate their benefits in different climates (e.g., Refs. [27–31]).

Green roofs can be mainly clustered into extensive and intensive. Extensive green roofs are usually more economically affordable than intensive green ones and because of their lightweight—typically the growing medium layer is 5–15 cm—they can retrofit existing rooftops [32–34]. Because of their easy installation, green roofs mounted on modular trays are becoming popular, although, they cannot be used for pedestrians or for recreational purposes because of their limited structural resistance. Typically, green roofs are constituted—from top to bottom—by: vegetation layer, growing medium, waterproofing membrane, and insulation layer [35]. Additional layers to their basic configuration are a root barrier and a drainage layer [36]. Usually, growing medium is an artificial light substrate and plants are succulent species because of their resistance, minimal maintenance, and limited or unnecessary irrigation [36,37]. Intensive green roofs, also called roof gardens, are characterized by a 15–120 cm thick growing medium that permits to shrubs, little trees, large plants or lawns to grow, providing urban amenities and recreational areas [35,38]. Because of their weight, intensive green roofs can be exclusively installed on specifically designed flat rooftops. The environmental benefits provided by intensive green roofs are the same or greater than extensive roofs, but the maintenance and irrigation costs are higher [39].

Initial and management costs make green roof wide-deployment unattractive, especially in hot climates, where irrigation is crucial in decreasing cooling loads [40–43], and watering costs can exceed the economic benefits deriving from the decrease in building energy demand.

Green roof installation can be beneficial both at building and urban scale as it can: contribute to energy-saving (e.g., Refs. [44–50]); decrease thermal oscillations on the rooftop surface that, in turn, can prolong the lifespan of the rooftop membrane [36,51,52]; abate noise [53,54], enhance air quality [55–59], contribute to beautification [35], enhance urban biodiversity [58–60], reduce storm water runoff [61–72], and mitigate UHI [73–75].

Karteris, Theodoridou, Mallinis, Tsiros, Karteris (2016) 886 words

Buildings and other engineered structures that form cities are responsible for a significant portion of the local and global impacts of climate change raising the need for an increased and large-scale implementation of energy-efficient and renewable energy technologies [1]. More than 50% of the total world population resides in urban areas and continued urbanisation is also set to define and shape the 21st century, since the level of urbanisation is still rising and is expected to exceed 80% in 2030 in developed countries [2]. This ongoing urbanisation involves an unsustainable use of natural systems and creates numerous problems both within and outside cities, such as the heat island effect and the exacerbated flood risk due to reduced infiltration and consequent enhanced rainwater runoff. In this context, mitigation strategies regarding urban-related environmental problems will be of high priority over the coming decades. Since urban development and growth cannot be stopped, it is desirable to create an environmental friendly city in terms of sustainable development; this city would use efficient energy, circulate natural resources, and provide a comfortable living environment [3].

Strategies to mitigate the negative impacts of impervious surfaces in urban areas take three general forms [4]. The first and most common practice is to treat the symptoms of impervious surface through engineered practices such as storm-water ponds, constructed wetlands, bio-retention areas and sand filters. An alternative strategy for mitigating impervious surface ecological impacts is the identification and prevention of converting any areas containing high ecological value to impervious surface, through the creation of parks or wildlife corridors. More specifically, a variety of policy instruments, such as conservation easements and green space requirements, can help towards this direction The final alternative strategy involves the conversion of impervious surfaces in urban areas into a multifunctional land cover that serves both human demands, for instance transportation and housing as well as ecological functions, such as stormwater retention, energy conversion resulting in primary production, and habitat creation. The transportation network, for example, can use porous pavements to permit both traffic flow on the surface and water flow through the pore spaces, allowing infiltration into the soil. Green roofs, also known as rooftop gardens or

vegetative roofs or even ecoroofs, are another example of this third strategy. Considering that nearly 50% of impervious surface in highly urbanised areas is unused roof spaces [4], green roofs represent an interesting and viable alternative by converting the impervious surface of a rooftop into multifunctional spaces in urban areas using vegetation, growing media and specialised roofing materials [5,6].

They are typically divided into three categories: intensive, semi-intensive and extensive green roofs. Extensive green roofs have thin substrates (5–15 cm), limited plant palates, relatively low costs and minimal weight requirements, while, in contrast, intensive green roofs, sometimes referred to as “rooftop gardens”, have deeper substrates ( 4 15 cm) which allow higher potential for increased plant diversity, but also come with increased weight and higher cost and maintenance requirement [4].

Many cities around the world have undertaken greening programmes (e.g. planting urban trees, adding or enhancing parks, providing incentives for green roofs) to benefit from the amenities of urban green spaces [7].Unfortunately, the high amount of impervious along with the high prices of land in urban regions makes creation or even retention of tree planted areas very expensive if not impossible.

There are several environmental benefits associated with green roofs over urban areas [8,9]. Green roofs in urban and suburban areas act as a green corridor, a stepping stone for wildlife to enter the nearby habitats [10]. In particular, they can connect the fragmented habitats with each other so as to promote the urban biodiversity [10]. They can also prevent and reduce pollution acting as a sink for nitrogen, lead and zinc. Green roofs have been also found to reduce the effects of acid rain by raising the pH value [9]. Plants in green roofs can also absorb air pollutants, for instance carbon dioxide and generate oxygen and reduce the air pollution through the uptake of ozone, NO2, PM10 and SO2 by plants [11].

Green roofs may also have an impact on the heat island effect of urban areas through increasing evapotranspiration of water and reduce the energy cost for cooling and/or heating of buildings. Thanks to their water storing capacity, green roofs may significantly reduce the runoff peak of the most rainfall events, delaying the initial time of runoff due to the absorption of water in the green roof system. This leads to an overall runoff reduction by retaining part of the rainfall and distributing the runoff over a long time period through a relative slow release of the excess water that is temporary stored in the pores of the green roofs' substrates [7]. Overall, the performance and benefits of green roof practices have been shown in numerous studies on laboratory scales, in-situ scales and neighbourhood/community scales [12].

A challenge that environmental managers are facing is the ability to extrapolate related analysis in extended spatial scales and investigate the functions that may be lost or gained in the process [4]. Following such an analysis, green roof installations could be linked with regional green space plans and policies that may be developed to support connected green space throughout the built landscape.

Vijayaraghavan, Kumar Reddy, Yun (2019) 706 words

A vegetative roof implies planting vegetation on a building rooftop through defined engineering methods. It is a modern way of restoring an ecosystem that was earlier destroyed by the rapid expansion of building construction due to the migration of rural people to urban centers (Satterthwaite, McGranahan, & Tacoli, 2010). Vegetative roofs have several benefits, and are widely considered as a practical solution to make buildings more sustainable (Saadatian et al., 2013; Sangkakool, Techato, Zaman, & Brudermann, 2018; Wong, Tay, Wong, Ong, & Sia, 2003), by providing a healthy environment with low energy consumption. Vegetative roofs offer numerous theoretical economic and environmental benefits to the building underneath, as well as to the surrounding environment. Few of these benefits (Oberndorfer et al., 2007; Rowe, 2011) include (i) runoff peak-flow reduction during high storm events (Morgan, Celik, & Retzlaff, 2013; Zhang, Szota, Fletcher, Williams, & Farrell, 2019); (ii) rainwater buffering (Vijayaraghavan, Joshi, & Balasubramanian, 2012); (iii) mitigating urban heat island (Santamouris, 2014); (iv) decreased energy requirements of the building (La Roche & Berardi, 2014; Ziogou, Michopoulos, Voulgari, & Zachariadis, 2018); (v) sound insulation and noise reduction (Connelly & Hodgson, 2015); (vi) improved air quality (Rowe, 2011); (vii) increased aesthetic value of the building (Jungels, Rakow, Allred, & Skelly, 2013); (viii) protection of the roof membrane of the building (Lata et al., 2018); and (ix) ecological preservation in cities (Johnston & Newton, 1995; Teotónio, Silva, & Cruz, 2018). Several developing and developed nations have recognized these unique advantages and started implementing, and in some instances mandating, the vegetative roofs in urban structures. In 2015, France approved a new rule that mandates all establishments that are newly created in commercial places to be partly installed with either vegetative roofs or photovoltaic panels. Other countries, such as Germany, Canada (Toronto), Denmark (Copenhagen), Japan (Tokyo) and Switzerland (Zürich), have already adopted mandatory vegetative roof by law. Vegetative roofs are also extremely popular in several European (Norway, Sweden and the UK), American (USA) and Asian (Singapore, China and Hong Kong) counties. However, the importance and benefits of vegetative roofs are still not recognized by several nations and their respective policy makers. This might be due to the limited or lack of local research in the respective countries.

Here we would like to give a brief introduction to vegetative roofs, including their characteristics and components, for the interest of readers new to this topic. Vegetative roofs are often regarded as eco-roofs, bio-roofs, and living-roofs, and are generally categorized into extensive and intensive vegetative roofs. Extensive vegetative roofs have a thin growth-substrate layer that can accommodate only a few species of plants, whereas intensive vegetative roofs comprise a thick growth-substrate layer and therefore support a wide variety of plant species. Table 1 summarizes important characteristics of different vegetative roof types. We should point out that extensive vegetative roofs are the most common and popular worldwide.

Some research reports have highlighted the possibility of achieving potential benefits of vegetative roofs (Mahdiyar, Tabatabaee, Abdullah, & Marto, 2018; Morgan et al., 2013; Rowe, 2011). However, the focus of commercial developers is often limited to the development of low-weight growth substrate and its subsequent management (fertilization and irrigation) to facilitate plant growth (Berndtsson, 2010). As a result, most commercial vegetative roofing cannot accomplish all of the benefits. This scenario is likely to change once more research reports emerge, and also by close cooperation between academic researchers and commercial developers. It is also important to understand the potential constraint that hinders the positive image of a vegetative roof. Of these, a crucial concern often linked with vegetative roof technology is the runoff quality, and several researchers have pointed out that the runoff quality from vegetative roofs is questionable, as it has been found to contain several pollutants (Berndtsson, 2010; Vijayaraghavan, 2016). It is known that plants and substrate components heavily influence the runoff quality of vegetative roofs (Berndtsson, 2010). However, research performed on these components to possibly improve the quality of runoff is relatively limited (Long, Clark, Berghage, & Baker, 2008; Vijayaraghavan & Joshi, 2015; Vijayaraghavan & Raja, 2015a). Therefore, this review intends to systematically assess the quality of runoff generated from vegetative roofs, and suggest ways to enhance the runoff quality.

Coma, Perez, Sole, Castell & Cabeza (2016) 507 words

During the last two decades, the building sector has experienced an important evolution in terms of quantity of constructed buildings, but less evolution in its energy performance regarding to usage and operational phases. Consequently, 40% of total primary energy consumption in European Union (EU) is due to households and the building sector. For this reason and with the aim to reduce the CO2 emissions, the EU has issued legislations and regulations on energy efficiency of buildings [1] and built environment sustainability [2,3]. Therefore, in the building sector reduction of both energy demand and environmental impact have become important factors to achieve more sustainable buildings and meet the objectives of “20e20e20” in energy efficiency. In addition, the European Energy Directives promote new building processes and construction systems to improve energy efficiency and sustainability in buildings.

New construction systems have become important for the scientific community in the last decade. Within them, green roofs are seen as interesting construction systems because they provide both aesthetic and environmental benefits [4], being one of them energy savings.

Numerous studies in different fields about green roofs have been conducted during the last twenty years. Some authors divide these systems into two categories, “extensive” and “intensive” [5e8], while other authors introduce an intermediate category called “semi-intensive” green roofs, which are a combination of the extensive and intensive [9]. Generally, extensive green roofs have shallower substrates (<200 mm) that do not represent an excessive overweight for conventional roof structures (70e170 kg/m2) [8]. Some advantages are: no additional structural reinforcements, less investment in growing media and plants, and less maintenance. On the other hand, intensive green roofs systems, also called living roofs or roof gardens, implement more heavy vegetation, like trees and shrubs, which require deeper substrates (>200 mm). In addition, roof gardens represent an overweight (290e970 kg/m2) and additional maintenance in plant care [8]. These systems are focused on landscape and aesthetic values to increase living and recreation spaces in densely populated urban areas [7].

After literature review, the main environmental benefits of these systems compared to the traditional flat roofs have been found and listed below: water retention capacity [10e12], reduction of surface runoff in large cities [13,14], water runoff quality [14,15], improvement of urban environment, mitigating the Urban Heat Island effect (UHI) [16e18], reduction of CO2 concentration in the urban environment [19,20], sound absorption [21,22], enhance of internal membranes durability [23,24], aesthetics reactions [25], and enhancement of the biodiversity and reduction of habitat losses [26].

In addition to all the above mentioned advantages, it is known that green roofs are efficient systems to reduce the indooreoutdoor temperature variations and, consequently, to decrease the annual energy consumption [24,27]. However, there are different parameters which influence the final energy performance of a green roof that can be experimentally studied more in detail, such as building insulation characteristics, the climate zone, plant types (Leaf Area Index, stomatal resistance, height, fractional coverage and albedo) [28e30], growing media (thickness, composition, density, moisture content) [28,30,31], and drainage layer properties [28,32,33].

Chen, Kang, Lin (2018) 1011 words

Green roofs can produce many environmental benefits, such as urban hydrology improvements, reduced building energy costs, air and noise pollution mitigation, ecological conservation, and beautiful landscape creation (Dunnett and Kingsbury, 2004; Oberndorfer et al., 2007). In addition, green roofs use existing roof space without requiring extra land, allowing potentially widespread application (Peck, 2003; Villarreal and Bengtsson, 2005; Mentens et al., 2006; Dvorak and Volder, 2010). However, the water quality of leachate from green roofs hinders their widespread acceptance. Several factors are related to the leachate quality of green roofs, including the precipitation composition, substrate properties, plants, fertilization, and the roof itself (Teemusk and Mander, 2007; Mentens et al., 2006; Berndtsson, 2010; Rowe, 2011). In general, green roofs consist of substrate and plants and are therefore more likely to generate pollution than bare roofs (Czemiel Berndtsson et al., 2006 ; Hathaway et al., 2008; Carpenter and

Kaluvakolanu, 2011). Without proper design and maintenance, runoff from green roofs could become a nonpoint pollution source in urban areas (Chen, 2013).

Green roof leachate quality can be improved by optimizing the substrates and plants used. In Rowe’s review paper (2011), high pollution concentrations occur on newly built green roofs, and the concentrations decrease as the plants grow to maturity and the substrates compact with time. Multiple plant species are better at rainwater retention and improving the ecological habitat. Taller plants and plants with deeper roots retain water longer and offer greater runoff reduction (Dunnett et al., 2008; Lundholm et al., 2010). Organic substances are added to the substrates for plant growth but might leach out, causing high organic and sediment loads in the outflow. Many studies have investigated the effects of substrates on leachate quality and have demonstrated that the substrate materials and depth significantly affect it (Teemusk and Mander, 2007; Getter and Rowe, 2009; Alsup et al., 2010).

Substrate components are divided into inorganic and organic substances, both of which can be replaced with recycled materials. For example, compost or green manure can serve as organic nutrients, and abandoned bricks and tiles as inorganic materials. Molineux et al. (2009) used four recycled materials as green roof substrates, including abandoned red bricks, sludge, newspaper, and carbonated limestone. When mixed with certain organic substances, the effects of recycled materials on plant growth vary. These authors concluded that the cost of recycled materials is low, and these materials can be accessed from local markets, benefiting both environmental and economic development. Molineux et al. (2015) subsequently tested 6 recycled lightweight materials and determined the effects of different substrate types and depths on plant growth. The clay substrate supported higher plant coverage and more plant species than other materials. Nagase and Dunnett (2011) tested different ratios of green manures and abandoned red bricks to find the best substrate for plant growth. Graceson et al. (2014) evaluated 9 bricks and 3 tiles with a fixed proportion of 30% green manure to determine their water retention ability and effect on plant growth. Ondono et al. (2014) suggested that the physical, chemical, and biological properties of various artificial materials used in green roofs should be evaluated. These authors tested different ratios of natural loam, bricks, and green manure as substrates and concluded that different substrates affect biological activity, thereby influencing plant growth. Thus, the selection of appropriate substrates is important for green roofs. Bates et al. (2015) tested crushed bricks, building waste, and incinerator bottom ash as substrates and concluded that these materials had the same effect on biomass but that crushed bricks fostered better biodiversity.

Applying recycled materials as substrates is a trend in green roof development. However, previous studies have focused on the effects on plant growth but not the effects on effluent water quality. Substrates have been proven to influence effluent water quality; therefore, the use of recycled materials should consider the effects on not only the plants but also leachate quality. An optimal substrate is expected to benefit plant growth and produce few contaminants. This study aimed to evaluate and compare different substrates, i.e., normal cultivated substrate, special green roof substrate, and mixed recycled glass materials, in terms of their effects on plant growth and water quality. Recycled glass is a lightweight inorganic material that reduces the substrate weight, and its high porosity can provide more space for aeration and water retention. Successful application of recycled materials on green roofs is beneficial for both green roof development and waste resource recycling.

There are two general types of green roofs, extensive and intensive green roofs. The major difference is the depth of the substrate. Extensive green roofs have shallow substrate depths, usually less than 20 cm, whereas intensive green roofs have thicker depths, greater than 20cm. The thin substrates of lightweight extensive green roofs are suitable for shorter plants, such as herbaceous plants. Intensive green roofs can support shrubs and trees or even horticulture (Rowe, 2011). Although the choice of plant species is more diverse for intensive green roofs than for extensive green roofs, the high weight and frequent maintenance limit the application of intensive green roofs, and extensive green roofs have experienced more widespread application (Chen, 2013). Therefore, the experimental design in this study was based on extensive green roofs.

The basic structure of extensive green roofs, from bottom to top, consists of a drainage layer, filtration layer, substrate layer, and plant layer. Between this structure and the building roof, a root barrier and waterproof barrier are optional but suggested layers according to the building roof condition. In this study, an experimental container is designed (Fig. 1) following the basic structure of green roofs. Its length and width were 15 cm, and the height was 13 cm. The substrate depth was fixed at 10 cm. At the bottom was a removable drawer to receive rainwater flow through the plants and substrates. In this study, 3 substrate materials and 3 plant species, each with 3 replicates, were tested, resulting in a total of 27 (3 × 3 × 3) experimental units.

Chaudhary, Sandall, Lazarski (2019) 591 words

Land-system conversion through urbanization represents a major mechanism of global environmental change (Rockstrom et al., 2009). Cities and megacities (greater than 10 million residents) have unique physical, chemical, and biological characteristics (e.g. heat islands, pollution, invasive species) that lead to novel interactions and underexplored frontiers for ecological research. Arbuscular mycorrhizal (AM) fungi form belowground symbioses with the roots of most plants, improving access to soil resources (e.g. phosphorus, nitrogen, water) in exchange for plant-derived photosynthates (Smith and Read, 2008). In cities, AM fungi exist in a variety of different environments including lawns, parks, landscaping, golf courses, urban farms, and green roofs (Cousins et al., 2003; John et al., 2014, 2016), but our knowledge is primarily descriptive and lacks a mechanistic determination of the factors that influence AM fungi abundance in urban ecosystems.

Green roofs, vegetated surfaces on the rooftops of buildings, are increasingly being considered important ecological spaces in urban environments (Oberndorfer et al., 2007). Initially installed to provide ecosystem services such as stormwater absorption, neighborhood cooling, and building insulation, they can also be a place to promote urban plant and wildlife biodiversity conservation (Brenneisen, 2006). In megacities, green roofs potentially play an important role in urban biodiversity conservation as land is limited in densely populated areas (Oberndorfer et al., 2007). Green roofs can be intensive (i.e. deep soil, diverse plant community) or extensive (i.e. shallow soil, low-growing plants) and, in North America, are often planted with non-native plants from the genus Sedum, as they require little maintenance in the hot, dry (yet periodically flooded) environment of green roofs. Sedum species are generally thought to be non-mycorrhizal, but published records suggest variability among species to form mycorrhizas in anthropogenically impacted environments. Sedum rosea (Harley and Harley, 1987), Sedum alfredii (Wu et al., 2007), Sedum adolfii (Wang and Qiu, 2006), Sedum maximum (Kowalczyk and Błaszkowski, 2011) are all highly colonized by AM fungi in environments across a gradient of anthropogenic impacts. Sedum acre forms mycorrhizas in wild dune populations (Harley and Harley, 1987), but was not observed to form mycorrhizas on green roofs (John et al., 2014). The mycorrhizal associations of other Sedum species and horticultural varieties utilized on green roofs have not been studied and it is unclear how urban Sedum populations influence the abundance of urban AM fungi. Green roof plant communities often include native plants to promote biodiversity conservation in urban environments (Lundholm, 2015) as well as other naturalized recruiter plant species. The majority of native and naturalized plant species growing on urban green roofs either planted intentionally or passively recruited form belowground associations with AM fungi (Wang and Qiu, 2006). Green roof soils are typically engineered to be lightweight and shallow (4e20 cm) and contain lower organic matter and nutrient holding capabilities compared to natural soils (Schrader and Bo€ning, 2006). In the United States, green roof companies utilize proprietary substrate blends advertised to meet the guidelines of the German Landscape Research, Development, and Construction Society (Landschaftsbau, 2002); particle size distribution is engineered for a coarse gravelly texture and organic matter is less than 6% prior to installation, though belowground properties likely change rapidly after planting. Throughout this paper, we intentionally use the term “soil” as opposed to “substrate” or “growing medium” because green roof soils (and many urban soils), while heavily anthropogenically impacted, still fall under the conventional definition of soils such that they contain mineral and organic components, are affected by physical, chemical, and biological processes, and support biota (Soil Science Society of America, 2008).

Soulis, Ntoulas, Nektarios & Kargas (2017) 790 words

Green roofs are emerging as one of the most promising management practices aiming to ameliorate the environmental problems and hydrological risks associated with urbanization (Booth and Jackson, 1997; Carbone et al., 2014, 2015; Hilten et al., 2008). One of the most important services provided by green roof systems is related to their ability to retain a portion of the rainfall and to distribute runoff over a longer period of time. In this way, green roofs are considered as an effective methodology for reducing hydrological risks in urban regions.

Green roof systems typically consist of three major components: a vegetation layer, a lightweight substrate medium and a water storage/drainage layer placed on top of a waterproof membrane (Carbone et al., 2015; Carson et al., 2013; Yang et al., 2015). According to the depth of the growing substrate layer, green roofs are commonly classified as extensive or intensive. Generally, green roofs with substrate depth less than 15 cm are classified as extensive and their vegetation consists of shallow rooting, drought resistant plants. In contrast, intensive green roofs have a substrate depth exceeding 15 cm which can support the sustainable growth of deeper rooting plants such as shrubs and trees. Due to the above mentioned characteristics, extensive green roofs are lighter, cheaper, and require less maintenance. Accordingly, they have wider applicability, especially on older building retrofitting where rooftop weight is the outmost limiting factor (Carson et al., 2013; Nektarios et al., 2011, 2015; Yang et al., 2015).

The hydrologic performance of green roof systems is characterized by the rainfall depth retained and the runoff release rate. They both depend on several factors, such as rainfall specific characteristics, anteceded rainfall conditions, substrate depth and its hydraulic characteristics, storage/drainage layer capacity, vegetation cover characteristics, and slope of the green roof (Carbone et al., 2015; Speak et al., 2013; Teemusk and Mander, 2007; Wong and Jim, 2014). Several studies have reported that green roofs can retain up to 90% of the total rainfall depth when individual rainfall events are considered, with the observed retention being reduced as the rainfall depth increased (Carson et al., 2013; Carter and Rasmussen, 2006; Getter et al., 2007; Mentens et al., 2006; Morgan et al., 2013; Simmons et al., 2008; Spolek, 2008; Stovin et al., 2012; Teemusk and Mander, 2007; Van Woert et al., 2005; Wong and Jim, 2014). Furthermore, reductions of 60–80% have been reported in peak flow rates from green roof systems compared with conventional roof tops (Bliss et al., 2009; Carter and Jackson, 2007; Palla et al., 2012; Villarreal et al., 2004). When the total annual rainfall depth is considered, green roofs may significantly reduce runoff generation from 15% to 80% (Bliss et al., 2009; Carter and Jackson, 2007; Palla et al., 2012; Villarreal et al., 2004). However, several studies showed that the observed retention depends on the rainfall pattern (Carter and Rasmussen, 2006; Teemusk and Mander, 2007; Wong and Jim, 2014). More specifically, in larger rainfall events, the maximum green roof storage capacity is reached, resulting in temporary retainment of the remaining rainfall which is then slowly released from the green roof system. Thus, the rainfall surge becomes significantly smoothed compared with the conventional impervious rooftops (Hilten et al., 2008; Wong and Jim, 2014). In addition, the ability of green roofs to reduce runoff is greatly affected by the initial moisture conditions as well as by the total rainfall depth. Consequently, the capacity of green roof systems to reduce runoff when it is mostly needed, namely during wet periods and for large rainfall events, has been questioned.

In practice, water resources planning guidelines necessitate the use of simple methods for estimating runoff volumes and peak flows from green roof systems. For instance, existing regulations often demand hydrologic calculations to be performed using the Soil Conservation Service Curve Number (SCS-CN) method (NRCS, 2009) or by utilizing the runoff coefficient of the rational method. Therefore, several researchers have studied the empirical relationships for green roof runoff based on curve number and runoff coefficient (Alfredo et al., 2010; Carter and Rasmussen, 2006; Fassman-Beck et al., 2016; Getter et al., 2007; Moran et al., 2005). Yang et al. (2015), analyzed the possible runoff generation mechanisms in green roofs, which involve either the runoff resulting from substrate saturation (saturation-excess) or runoff generated when the rainfall intensity is larger than the infiltration rate (infiltration-excess). They suggested that due to the highly conductive substrate materials that are utilized in extensive or semi-intensive green roofs, saturation-excess is the dominant mechanism. Accordingly, they proposed a simple linear relationship between total rainfall depth and total runoff depth based on a simple water balance applied on an event by event basis.

Herrera-Gomez, Quevedo-Nolasco, Perez-Urrestarazu (2017) 887 words

Numerous studies on climate change predict a global rise in temperatures. The consequences of this increase will be more troublesome in urban areas, where the temperatures are already higher than in surrounding rural areas. This heating phenomenon is mostly due to anthropogenic development in the urban area [1] and the increase of building covered areas [2]. The construction materials commonly used absorb most of the radiation and release it as heat. This generates the urban heat island phenomenon, which has direct and indirect impacts on the health and life quality of the citizens [3]. Urban heat islands vary in magnitude and structure according to two main groups of factors: climatological factors (such as climatic region, season, time of day, synoptic conditions and wind regime) and those related to the physical and human nature of the built environment, such as geographic location, topography, urban landscape geometry, type of building materials and intensity of human activities [4]. In fact, a study aiming to identity heat islands at different height levels conducted in Tel-Aviv (Israel) showed that parks and open areas were the coldest elements within the city during day and night [5]. There is a clear correlation between plant cover and land surface temperature [6,7], and consequently, an urban increase in green areas would contribute to mitigate the Heat Island [8]. Nevertheless, in many modern cities, there is a high density of building covered areas which does not allow raising the number of green areas. Thus, in order to increase the presence of urban vegetation, it is necessary to draw on systems implemented on existing buildings. Currently, the sum of all the building roofs represents a high percentage of exposition in urban areas. Estimations for dense cities prove that the fraction of roof area varies between 20 and 25% of the total area [9]. Because of this, the use of these surfaces to increase urban vegetation is an interesting option.

Green roofs are urban greening systems that precisely allow installing plant life in the roofs of buildings through more or less complex elements. They can be extensive, lighter, and with less substrate when establishing smaller species, or more intensive and heavier with greater amount of substrate where small trees and shrubs can be included [2]. Green roofs have existed for more than a thousand years, although their use has become more relevant in modern times and new technical solutions that favor their implementation have appeared. This development has come about since not only do they provide a nice relaxing space or scenery, but also ecosystems services such as microclimate regulation, rainwater management, improved building insulation (with an influence on inner temperature), noise absorption, decrease of air pollution, and biodiversity enhancing [3,10]. Moreover, they contribute to increasing the albedo of urban areas [11].

Many studies on green roofs are oriented to their capability to regulate temperature. However, depending on the climate and the type of green roof (different plant material, substrate, and construction features), their efficiency can vary [12]. The thermal efficacy of a green roof is closely related with the climate, and it becomes more significant when the environmental temperature rises [3]. This efficacy is measured from the point of view of energy savings in warm areas for their capacity to lower temperatures [2] of both the roof surface and the air above it [13]. For example, an analysis of the surface temperature before and after the placement of a green roof in Singapore showed a significant decrease once the green roof was installed, especially for high plant cover, making the maximum temperature difference approximately 18 C [14]. Another study in Hong Kong proved that the heat stored in a bare roof was 75% higher than that of a green roof [15]. In the city of Chicago, the temperatures in summer of the surface of a green roof and a neighboring building were compared. The temperature of the green roof varied from 33 to 48 C, while in the conventional dark roof of the adjacent building the temperature was 76 C. The air temperature near the surface of the green roof was 4 C lower than near the conventional roof [16]. This decrease in temperature happens because, in a green roof, the flux of sensible heat is low due to the high latent heat flux from evaporation, even if the net radiation is high. This works to lower the temperature in a specific area [17]. Also, some simulation studies indicate that green roofs can decrease the mean environmental temperature from 0.3 to 3 C at a city scale, and drastically decrease the heat island effect [2].

Nowadays, in many cities of several countries, such as Germany, the U.S.A., Denmark, and Canada, their governments have developed a variety of norms, incentives, and technical services to promote the naturalizing of roofs [18]. These measures will foster the increase of the area covered by green roofs, which will have favorable consequences on the specific climatic conditions in the urban areas where they are installed. In fact, the mass installment of green roofs might work as a mechanism to decrease the Heat Island effect and counteract the temperature increase due to climate change. In order to do so, the remaining question would be how much surface would be needed to mitigate the effect of climate change.

Liu, Feng, Chen, Wei, Deo (2019) 1044 words

Although rapid urbanization warrants a need to implement sustainable hydrologic structures that limit environmental degradation, it has become apparent that green surfaces, mainly in urban regions, are being replaced by additional buildings and pavements, which in fact, is changing the original permeable conditions to the impervious surfaces (Berndtsson, 2010). Consequently, there has been a considerable increase in the surface stormwater runoff, which has resulted in more frequent flooding and water logging (Al-Rawas et al., 2015; Ellis et al., 2012). To address this issue, a number of alternative options are being proposed to restore the hydrology of urban areas, including but not limited to the maintenance of green areas, and the recovery or restoration of deforested areas (Wilkinson et al., 2014). In reality, conventional rooftops can constitute up to 40–50% of the impervious area in a densely built-up urban center where no space is available for a new infrastructure to be put in place (Dunnett and Kingsbury, 2004). Green roofs, which are a primary focus of this study, utilize the otherwise unused impervious surfaces to restore predevelopment hydrologic functions, such as a better infiltration and retention effect (Razzaghmanesh and Beecham, 2014). Given a natural shortage of land in urban areas, green roofs can therefore be one of the most important options to address issues associated with surface runoffs (Berndtsson, 2010; Palla et al., 2010). Recently, green roofs have received increased recognition in developed countries such as the USA, Japan, Australia and Europe (Berndtsson et al., 2008; Mentens et al., 2006; Vijayaraghavan et al., 2012; Williams et al., 2010). The purpose of adopting such technologies is to use a smart approach that addresses the pertinent issues associated with waterlogging, urban flooding and uncontrolled runoffs that is likely to pose serious environmental impacts.

The increasing premise of a sustainable city promoted by a green roof, also known as an integrated eco and a living roof, is becoming an issue of interest to hydrologists. Typically, a green roof consists of three major components: a vegetation layer, a lightweight substrate medium and a water storage/drainage layer placed on top of a waterproof membrane (Carson et al., 2013; Yang et al., 2015). According to the depth of the growing substrate layer, a green roof is commonly classified into extensive or intensive categories. Generally, a green roof with a substrate depth of less than 15 cm is classified into an extensive green roof and its vegetation consists of a shallow rooting, and drought resistant plant. Rainwater that falls on the green roof can be captured in the substrate or the vegetation and is eventually evaporated from the surface of the soil and released back into the atmosphere by the process of transpiration (Dunnett and Kingsbury, 2008). The benefits of a green roof is, off course, to help retain stormwater (Gregoire and Clausen, 2011; Schroll et al., 2011; Speak et al., 2013), delay the peak discharge time (Carter and Rasmussen, 2006; Spolek, 2008), and to attenuate the peak discharge volume (Carpenter and Kaluvakolanu, 2011; Stovin et al., 2012). These functions clearly outline the major contribution of an urban green roof in the control and moderation of surface hydrology in urban cities where flood-risk management is a crucial determinant of the overall safety of the city dwellers.

Many researchers have investigated the rainfall-runoff behavior of a green roof (Carter and Rasmussen 2006; DeNardo et al., 2005; Moran et al., 2003), primarily to investigate its implications on surface water flow. Pilot scale studies based on elevated test boxes or similar modules (with a watershed area that can range between 0.37 m2 and 12 m2) have been instrumental in helping to identify and quantify relationships associated with runoff retention of green roofs (Carson et al., 2013). Research into the hydrological properties of a green roof has therefore reveal a range of average rainwater retention efficiencies that vary from one design to another. For extensive green roofs (i.e., with a substrate depth < 15 cm), the average rainwater retention efficiency is nominally estimated to be between 45% (DeNardo et al., 2005; Mentens et al., 2006) and 60% (Moran et al., 2003), and the cumulative annual retentions is about 50% (Stovin et al., 2012) and 60% (VanWoert et al., 2005). The water retention capacity of a green roof system is therefore dependent on several causal factors, such as the rainfall specific characteristics, antecedent moisture conditions, substrate depth and its hydraulic characteristics, storage/drainage layer capacity, vegetation cover characteristics, and slope of the green roof (Bengtsson et al., 2005; Carter and Rasmussen, 2006; Getter et al., 2007; Simmons et al., 2008; Speak et al., 2013; Teemusk and Mander, 2007; Villarreal and Bengtsson, 2005; Wong and Jim, 2014). It should be noted that real-time (i.e., field) measurements of these factors can be rather a tedious, if not an impossible task, and a large variation in the above-mentioned conditions and the respective factors in existing literature also make it difficult to compare the water retention from these independent green roof runoff studies. Considering the difficulties encountered in accurately performing real measurements and the inconsistency of information obtained from previous studies, independent experiments that are able to explore the influence of a green roof design on the underlying urban hydrology (and particularly the runoff retention) in a well-controlled manner, is an issue of practical interest. In addition, to the quantification of runoff retention for different rainfall sizes, there is a particular need to understand retention for significant events with large return periods (These events generally overwhelm stormwater management systems and result in flooding).

To concur with the foresaid reviews, the runoff retention capacity of green roof is a result of the combined action of various factors affecting the runoff retention itself, which results in various, and rather inconsistent conclusions. Many research studies focused on the influence of one or two different structural factors on a green roof’s runoff retention. However, multiple structural factors, which are particularly important from a practical viewpoint, have not been considered to assess their integrated contributions to the runoff retention. Therefore, to address these issues from a practical point of view, the primary structural factors must include the substrate material, substrate depth, vegetation types, and slope gradients, as undertaken in the present study.

Agra, Klein, Vasl, Kadas & Blaustein (2017) 316 words

Urban ecosystems are expanding globally, and assessing the ecological consequences of urbanization is critical to understanding the biology of local and global changes related to land use changes (Lambin et al., 2001; Alberti et al., 2003). Green roofs may be “intensive” or “extensive”. Intensive green roofs may include shrubs and trees and appear similar to landscaping found at natural ground level. As such, they require substrate depths greater than 15 cm and have “intense” maintenance needs. In contrast, extensive green roofs consist of herbaceous perennials or annuals, use shallower media depths (less than 15 cm), and require minimal maintenance. Due to building weight restrictions and costs, extensive green roofs are more common than deeper intensive roofs and carbon fixation on extensive green roofs will be the focus of this study. Green roofs are shown to provide many ecosystem services (Sutton 2015). Most of the green roof research until now has been on their role in regulation of building temperatures, reducing urban heat-island effects and rainwater management. Green roofs may also sequester carbon in plants and soils. Photosynthesis removes carbon dioxide from the atmosphere and stores carbon in plant biomass, a process commonly referred to as terrestrial carbon sequestration. Carbon is transferred to the substrate via plant litter and exudates. The length of time that this carbon remains in the soil before decomposition has yet to be quantified for green roofs, but if net primary production exceeds decomposition, this man-made ecosystem will be a net carbon sink, at least in the short term (Getter et al., 2009). Most previous studies of photosynthesis on green roofs concentrated in measuring direct CO2 uptake by the plants and producing models. The ones that measured CO2 directly did so by either studying specific species or plant groups under lab conditions or on the actual green roofs by taking long-time-period samples using permanent sensors with limited repetitions.

Morakinyo, Dahanayake, Ng, Lun Chow (2017)

As a consequence of rapid urbanization, many global cities have been transformed into congested and overpopulated concrete jungles leading to a number of environmental problems such as pollution of its various forms, urban heat island (UHI) and heat stress, among others [1]. The UHI phenomenon basically arises from the heat storage capacity of paved areas, anthropogenic heating and reduction of green spaces leading to higher urban than rural daytime and nighttime air and surface temperatures [2]. In a bid to mitigate or adapt to UHI and heat stress, several countermeasures such as urban greening (i.e. tree-planting, facade greening and roof greening), cool roof, water-retentive materials, modification of urban morphology, insulation of buildings, application of irrigation systems [3,4] have been suggested and are being implemented by urban planners and landscape architects. Urban greening is one of the most effective of these countermeasures as it directly reduces solar gains by surfaces. Of all forms of urban greening, tree-planting is the most efficient and more advocated for ground surface temperature reduction. However, the contribution of roofs’ surfaces cannot be overemphasized as they cover more than 20% of the total urban surface [3]. Hence, cooling roof surfaces’ temperature could significantly contribute to UHI mitigation, indoor air temperature reduction and lowered cooling energy demand [5,6]. This is even more important due to limitation of ground surface area for ground level tree-planting especially in high-density cities. Therefore, green-roofs though ancient practice, are becoming popular as a potential alternative and means of re-establishing the connection between nature and city [7], enhancing the aesthetic appearance of a building [8] and improving environmental quality. Simply put, a green-roof is a roof top used for plantation with the use of a suitable growing medium. In recent years, green-roofs have been getting popular as a suitable technique of introducing greenery into congested cities [9]. Latest technological advancements have enhanced the flexibility and speed of construction of green-roofs enabling them to be integrated into most of the projects. Modern green-roofs are generally consisting with number of layers. These may include vegetation, growth substrate, filter fabric, drainage element, root barrier, insulation and water proofing membrane depending upon the location and the requirements [9–11]. In a broader perspective, green-roofs are classified into intensive and extensive based on the thickness of the substrate layer. Green-roofs with thin substrate layer (<15cm) are considered as extensive green-roofs. On the other hand, if the substrate is thicker (20–200 cm), they are considered as intensive green-roofs. These layers enhance the insulation capacity of a conventional roof by controlling the heat transfer into the building [12]. In addition, these layers block the solar radiation reaching the building surface. Only limited type of vegetation can be grown in extensive green-roofs such as grass. Intensive green-roofs have more flexibility in accommodating shrubs and small trees. However, they require more attention in structural support, maintenance and irrigation [13,14]. Therefore, extensive green-roofs are widely used in practice due to lower cost and maintenance compared to intensive green-roofs [9]. Solar radiation is the main heat source into the buildings. Integration of vegetation to the building surface is an effective way of controlling this heat gain [15,16] as greenery absorb the solar heat and evaporates water through biological functions and metabolism, a process known as evapotranspiration which essentially creates a cooling effect in the surrounding. The evaporative cooling potential of the vegetation layer may depend upon characteristics of vegetation such as foliage density and leaf thickness [17,18].

Green-roofs have a range of benefits: they improve the microclimate, minimize heat island, lowers the building envelope temperature and reduce energy consumption and peak cooling load of the building at both city, neighborhood and building scale [13,18,19]. Besides, they are known for reducing the risk of flooding by retaining rainwater and delaying the peak flow [20,21] and also helps to control the urban sound pollution [22]. Moreover, they are efficient in absorbing gaseous pollutants including greenhouse gas emissions and helps remove of particulate pollutants thereby contributing to improved urban air quality [23,24].

The performance of green-roofs for urban cooling and energy reduction is dependent on several factors based on findings from previous studies. First, building height and urban density: previous studies [25,26] have shown a negligible cooling effect of extensive and intensive green-roof in medium to high density neighborhood. It has also been established that intensive green-roof provides better environmental and energy reduction benefit than their extensive counterparts mainly due to higher soil depth and leaf density implemented in the former [27]. Another important factor is the geographical location on the green-roof installation. While several studies have investigated the benefit of green-roof, most did so under singular climatic condition and as such their conclusion are restricted with the geographical scope of their study.

Reyes, Bustamante, Gironas, Pasten, Rojas, Suarez, Vera, Victorero & Bonilla (2016)

In the last two decades, there has been substantial expansion of green roof technology in humid and temperate climates, providing a wide range of ecological, economic, and social benefits in Western and Central Europe, North America, Japan, and China. Green roofs extend roof life and improve building’s thermal and acoustic insulation (Kosareo and Ries, 2007; Van Renterghem and Botteldooren, 2008; Jim and Tsang, 2011; Jaffal et al., 2012). There are also effects on storm water management by reducing and delaying precipitation runoff (VanWoert et al., 2005; Fioretti et al., 2010), enhancements in urban biodiversity (MacIvor and Lundholm, 2011), mitigation of the so-called urban heat island effect through cooling due to evapotranspiration (Alexandri and Jones, 2008), improvements in air and water quality (Yang et al., 2008; Gregoire and Clausen, 2011) and a psychological benefit for humans because of a more healthy and esthetically pleasing environment (Oberndorfer et al., 2007).

In terms of design, green or living roofs are typically flat and slightly sloped surfaces planned to support the growth of vegetation (Dvorak and Volder, 2010). Green roof structures consist of a series of layers: a waterproofing membrane over the rooftop, a drainage or retainer system, anti-root and filter membranes (if needed) to place under and over the drainage, respectively, a substrate layer, and plants (Oberndorfer et al., 2007; Berndtsson, 2010). The substrate type and depth has an important role in green roofs (Thuring et al., 2010). Substrate is a specific and engineered growing medium that is lighter than topsoil, better drained, primarily inorganic, and capable of supporting plant growth (Morgan et al., 2012). Substrate depth can range from few centimeters up to a meter. Depending on the substrate depth and irrigation requierements, there are two types of green roofs: extensive and intensive. Extensive green roofs, also referred as eco-roofs or lightweight green roofs, have a substrate layer from 2 to 20cm in depth, require minimal or no irrigation, and are usually planted with moss, succulents, grass, and some herbaceous plants (Dunnett and Kingsbury, 2004; Oberndorfer et al., 2007). Intensive green roofs are deeper than 20cm, often designed as gardens for human use, and usually require irrigation and maintenance. They also can support wild shrubs, coppices, small trees, and lawn (Oberndorfer et al., 2007; FLL, 2008).

Up to now, one of the major barriers to increasing the prevalence of extensive green roofs arid environments is the lack of scientific data available to evaluate their applicability to local conditions (Williams et al., 2010). In humid regions, rainfall is usually distributed throughout the year, promoting vegetation growth and reducing irrigation requirements. However, in dry regions, maintaining the vegetation condition through the entire dry season without using a large amount of irrigation water becomes challenging (Dvorak and Volder, 2013). Therefore, relying that experience and technology is problematic due to significant differences in climate, available substrates and plants (Williams et al., 2010), so the number of green roof projects has been limited in arid environments (Nektarios et al., 2011; Issa et al., 2015).

Perini, Rosasco (2016) 1458 words

A wide replication of green envelopes can be a good opportunity to improve urban environment conditions, mitigating urban heat island phenomenon (Fioretti et al., 2010; Onishi et al., 2010; Ottelé et al., 2010; Taha, 1997). The possible integration modalities of green elements in architecture are many, with a major or a minor influence on the project conception and on the formal and functional characteristics (Perini, 2013). Vegetated roofs, traditionally widespread in northern Europe, may use different plant species, for both their influence on architectural aesthetic and the microclimatic improvements obtainable (Dunnett and Kingsbury, 2008; Fioretti et al., 2010). The many products available on the market propose several integrated solutions for proper drainage, waterproofing, and roof protection depending on the vegetation type, such as grass and bigger or smaller shrubs (Bianchini and Hewage, 2012a; Bouvet and Montacchini, 2007). These are commonly classified in: intensive, semi-intensive and extensive solutions and have different uses, stratigraphy and vegetation (Dunnett and Kingsbury, 2008). For every type of green roof substrate thickness (given by the plant species used), maintenance, system weight, obtainable microclimatic benefits, influence on architectural aesthetic, costs, and use are different (Bianchini and Hewage, 2012b; Carter and Keeler, 2008).

Vertical greening systems are made by simple climbing plants, supporting structures for their growth or planter boxes placed at several heights with a shading function; other provide the possibility to cultivate species otherwise not suitable for growing on vertical surfaces, thanks to the disposition of pre-vegetated panels, defined as “living wall systems” (Köhler, 2008; Perini et al., 2012). These systems entail very different initial costs (i.e. in a range of 3–315 D /m2), maintenance (i.e. in a range of 3–27 D /m2/year) and disposal (i.e. in a range of 31–220 D /m2 ) (Perini and Rosasco, 2013).

Studies conducted on green roofs and vertical greening systems demonstrate that systems provide several benefits, both social and personal (Bianchini and Hewage, 2012b; Perini and Rosasco, 2013). A green roof can reduce the energy demand for heating during winter season thanks to its insulation properties; during summer, vertical and horizontal building surfaces covered by plants improve thermal comfort reducing the energy demand for air conditioning (Alexandri and Jones, 2008; Kosareo and Ries, 2007; Perini et al., 2011).

Permpituck and Namprakai (2012) show that green roofs (10 cm and 20 cm substrate thickness) compared to a bare roof reduce the heat transfer (respectively by 59% and 96%) and energy consumption (respectively by 31% and 37%). Similar studies demonstrate that green roofs also reduce the heat flow between 51% and 63% (Morau et al., 2011). During summer a wet green roof can increase the heat dissipation through evapo-transpiratory cooling, reducing the energy demand for air conditioning (Barrio, 1998). With high solar radiation (1400 W/m2 ), a surface temperature differs between a bare roof and a soil roof under a dense vegetation layer by up to 31,4 ◦ C (Wong et al., 2003).

Studies demonstrate that a vertical green layer can contribute to the building envelope performances by creating an extra stagnant air layer, which has an insulating effect (Perini et al., 2011), and reducing the energy demand for air-conditioning up to 40–60% in Mediterranean climate (Alexandri and Jones, 2008; Mazzali et al., 2012).

Another relevant benefit of green roof systems regards stormwater management, with a reduction in stormwater runoff in a range of 60%–100%, depending on system’s characteristics, and climatic conditions (Hashemi et al., 2015; Nawaz et al., 2015; Wong and Jim, 2014), while improving also water quality (Vijayaraghavan and Joshi, 2015; Vijayaraghavan et al., 2012).

Vegetation and other layers of green roofs or vertical greening systems can increase the roof longevity from 20 to 40 years (Clark et al., 2005). Studies demonstrate that green roofs and plants along a facade improve also the aesthetic of a building and its real estate value (Franc ̧ ois et al., 2002; Gao and Asami, 2007; Peck et al., 1999). An intensive or extensive green roof is similar to a green area: Peck et al. (1999) demonstrate that the real estate value of a building can increase from 6 to 15% with the presence of a green roof or green wall.

Studies investigated also the relation between worker productivity and the presence of vegetation: employees in office buildings who had view on green area (garden, etc.) increase their productivity (Kaplan et al., 1988).

Greening systems in dense urban areas provide relevant social benefits, mainly related to air quality improvement, also due to lower greenhouse gas output production, mitigation of urban heat island (UHI) effect, improvement of urban wildlife and plant species biodiversity, increasing also the quality of urban space (Dunnett and Kingsbury, 2008; Goddard et al., 2010; Onishi et al., 2010).

Vegetation improves air quality: gaseous pollutants can be dissolved or sequestrated through stomata on plants and leaves (McPherson et al., 1994). Tan and Sia (Tan and Sia, 2005) sampled roof temperatures and other air quality parameters both pre and post green roof installation in Singapore; using light sensors, volume aerosol samplers and particle counters they found that acid gaseous pollutants, carbon mass levels and ambient green roof surface temperature dropped significantly after the installation of green roofs. A green roof located in the urban dense area of Chicago can absorb up to 52% of O3, 27% of NO2, 14% of PM10 and 7% of SO2 (Yang et al., 2008).

High levels of pollution in the atmosphere and the “cementification” of urban cause the Urban Heat Island (UHI) phenomenon, resulting in the dramatic two to five degree Celsius temperature difference between cities and their surrounding suburban and rural areas (Taha, 1997). Though the UHI phenomenon has regional-scale impacts on energy demand, air quality, and public health, mitigation strategies, such as urban forestry, living (green) roofs, and light colored surfaces, could be implemented at the community level (Rosenzweig et al., 2006). Although UHI can be mitigated with large amount of surfaces with higher albedo (e.g. green areas) (Rizwan

et al., 2008), larger green areas like urban parks may be more effective (Petralli et al., 2006). Akbari (2005) shows that the mitigation of the urban heat island effect with trees, green roofs and green facades can reduce the U.S. national energy consumption for air conditioning up to 20%, saving of more than $10 billion per year in energy costs.

The economic sustainability of green roofs has been investigated by several authors. Wong et al. (2003) evaluate the economic sustainability of intensive and extensive green roofs and demonstrate that only extensive green roofs are economically sustainable, due to higher installation and maintenance costs for intensive green roofs.

Bianchini and Hewage (2012b) evaluated, by means of a Cost Benefit Analysis (CBA), the economic sustainability of intensive and extensive green roofs, demonstrating that both are economically sustainable from social and personal point of view (respectively Net Present Value – NPV of 3606 $/m2 and 5715 $/m2); in their case study the two authors considered a tax incentive of 48 $/m2; so the financial risk for installing any green roofs type is very low. Other studies (Carter and Keeler, 2008; Clark et al., 2008) show the economic sustainability of green roofs compared to traditional roofs calculating the NPV by means of CBA. In a case study located in Flanders, Claus and Rousseau (2012) discovered that an extensive green roof in Flanders is economically sustainable in two case scenarios (base and best, with public subsidies). In the worst scenario or without subsidies, the systems analysed are not economically sustainable.

A study conducted by Perini and Rosasco (2013) demonstrates that in an ordinary scenario of cost and benefit values a direct green facade with a well grown Hedera helix and an indirect green facade with the vegetation supported by a plastic mesh can be economically sustainable, due to the low installation and maintenance costs during a life span of 50 years. For the other systems analysed (indirect green facade with planter box with steel mesh and living wall system) economic indicators show that they are not sustainable even in a best case scenario. The authors suggest that the economic sustainability of such systems can be significantly increased by reducing the initial costs for promoters; this can be achieved through government incentives. For example, the city of New York enhanced installation of green roofs allowing one-time tax abatement of 48,50 $/m2 (up to $100,000 or the building’s tax liability, whichever is less) wherever the green roof covered at least 50% of the total roof area (NYC Energy Efficiency Corporation (NYCEEC), 2015).