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Green roofs and facades: A comprehensive review

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ABSTRACT

Based on United Nations Environment Program (UNEP), building sector accounts for 40% of total energy consumption. In European countries, 36% of total greenhouse gas emissions is attributed to buildings. In this respect, green roofs are considered to be one of the most appropriate sustainable solutions to resolve the urban heat island-related issues. Roofs account for nearly 20–25% of overall urban surface areas. Energy saving, thermal insulation, shading and evapotranspiration features highlight the key role of green roofs in overall thermal performance of buildings and microclimatic conditions of indoor environments. Within the scope of this research, the concept of green roofs and facades is comprehensively analysed in a holistic and thematic way. Following a historical overview of the technology, the research is split into various subfields such as energy saving in buildings through greenery systems, multifunctional thermal benefits including evapotranspiration, thermal insulation, shading and thermal comfort features, evaporative cooling for reducing cooling demand and minimising wind driven convection losses. The results achieved from the literature survey clearly indicate that green roofs and facades are key solutions to mitigate building-related energy consumptions and greenhouse gas emissions. According to the previous works, heat flow through the building roofs in summer can be reduced by approximately 80% via green roofs. The green roofs are reported to consume less energy in the range of 2.2–16.7% than traditional roofs during summer time. A similar tendency is observed for the winter season depending on regional and climatic conditions. The temperature difference between conventional and greens roofs in winter is found to be about 4 °C, which is remarkable. Energy demand of buildings in summer is highly dependent on the plant intensity as it is reported to be 23.6, 12.3 and 8.2 kWh/m^2/year for extensive, semi-intensive and intensive greenery surface, respectively. Greenery systems are also capable of providing thermally comfortable indoor and outdoor conditions. It is underlined that the annual average accumulation of CO_2 reaches the level of 13.41–97.03 kg carbon/m^2 for 98 m^2 of vertical greenery system. The results of this research can be useful for dwellers, builders, architects, engineers and policy makers to have a good understanding about the potential of green roofs and facades to mitigate building-related energy consumptions and carbon emissions in a renewable, sustainable, energy-efficient and cost effective way.

1. Introduction

Today, the majority of the world population lives in cities, and there is a growing tendency to urban life year after year. According to the recent report of United Nations, the population living in cities is expected to increase up to 67%, by 2050 [1]. There is a growing significance of environmental issues at global scale, and urbanisation is of significant relevance. Several environmental problems such as urban heat island, greenhouse gas emissions and reductions of energy sources can be attributed to dense urbanisation. Susca et al. [2] monitor the urban heat island in four areas of New York City, and they observe an average of 2 °C temperature difference between the most and the least vegetated areas, which can be explained by the substitution of greenery areas with man-made building materials. For this reason, effective control of urbanisation and urban heat island through energy-efficient and eco-friendly buildings which use sustainable and recyclable sources is of vital importance.

It is well-documented in literature that the total world energy consumption has drastically increased over the last four decades. It is clearly reported by International Energy Agency that the rise of global energy uses from 1971 to 2014 is about 93% [3]. The greatest part of this increment is related to buildings and according to United Nations Environment Program (UNEP), building sector accounts for 40% of total energy consumption [4]. In European countries, 36% of total greenhouse gas emissions is ascribed to the buildings. Further reports reveal that a significant portion of energy is consumed by commercial buildings for heating, cooling and lightening purposes [5]. Improved comfort conditions of occupants as a consequence of technological developments also play a key role in total energy consumed in building sector. This output can be justified by the case of China as the main

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energy consuming sector is the building sector in the country [6]. In this respect, building sector is in the center of interest to mitigate the role of buildings in total world energy consumption and to minimize the building-related greenhouse gas emissions [7].

In recent years, many policy makers and governments take decisive measures to systematically reduce carbon emissions and energy use in buildings. Some of these measures are directly relevant to building energy regulations which are proposed and implemented by developed and developing countries such as the United States, the European Union countries and China [4,8]. In most cases, building energy regulations in new built applications cover required performance figures for both appliances and building envelope materials. Appliance and equipment standards are related to heating, cooling and water heating devices and lightning Systems. For instance, Energy Star label on an appliance is a sort of performance Standard which is used to address high-efficient electrical devices. Building energy codes essentially deal with energy performance rates of buildings by considering regulations notably for buildings envelopes. Similar to the Energy Star label, Home Energy Rating System (HERS) score is used as building energy label [4]. Current energy consumption figures of the world clearly indicate that drastic measures need to be taken to minimize the role of building sector in total world energy use. As an example, the predictions reveal that energy consumed in buildings in China will reach up to 40% of total energy use in the near future if the government does not adopt appropriate policies with regard to building energy efficiency (BEE) measures on time. In this respect, the improvement in BEE is expected to play a crucial role in mitigating energy consumption rates, and thus in protecting the environment as well as achieving social and economic development. Some essential measures to enhance BEE can be split into five categories: a) improvement of energy codes for new buildings, b) energy labelling and evaluation of buildings, e) heat metering and energy-efficient retrofits, d) increasing the use of renewable energy sources in buildings and e) energy efficiency supervision over large public buildings [6]. In European counties, there are some directives focusing on building energy consumption, such as the Energy Performance of Building Directives (EPBD) 2002/91/EC and 2010/31/EC. According to the said directives, the existing buildings in European countries are evaluated and certified by each member States. These attempts introduce the use of Nearly Zero Energy Buildings (NZEB) recommending low energy demand associated with the renewable energy use [9]. Recently, new regulations called net zero carbon buildings are adopted by the United Kingdom (UK) and other European Union (EU) countries to reduce the environmental impacts of energy use in homes [8]. UNEP addresses five main measures for urgent reduction of carbon emissions such as:

- *Increasing the energy efficiency of new and existing buildings*
- *Increasing the energy efficiency of appliances*
- *Encouraging energy and distribution companies to support emission reductions in buildings*
- *Changing attitudes and behaviour toward energy consumption*
- *Substituting fossil fuels with renewable energies* [10].

As stated above, rising concentrations of greenhouse gas emissions and their negative impacts on environment are taken into consideration by many countries, and developed and developing countries invoke new solutions and designs for buildings to mitigate building-oriented energy consumptions. The concept of green structures is such an attempt that becomes widespread day after day. As reported by United Nations (UN), green buildings enable an opportunity of preventing negative effects of existing buildings on environment [11]. With green building design, eco-friendly structures are expected to engender less carbon emission and natural resource consumption by providing energy saving and increasing the use of recyclable materials [12,13]. Green buildings are multifunctional structures covering different ways of integrating renewable energy solutions into a building concept as well as including architectural approaches such as the design of greenery systems, material selection and site planning [10]. According to the results of a survey research conducted in the USA, green buildings consume approximately 30% less energy compared to traditional buildings [13]. Some standards associated with the concept of green buildings and efficient use of energy in building sector are LEED, Leadership in Energy and Environmental Design, (USA), BREEAM, Building Research Establishment Environmental Assessment Methodology, (UK) and Green Building Label (China) [14]. These standards cover several parameters such as energy, pollution, water, health and well-being, ecology, materials and waste [11]. Green buildings are considered as an ultimate and decisive solution to reduce energy consumed in building sector and to halt greenhouse gas emissions as a consequence of efficient use and control of energy transfer from building envelope [2]. While applying greenery systems on building surface, microclimatic conditions of buildings are controlled without excessive energy consumption [15]. The main goal of this paper is to review the greenery systems to meet the standards of green buildings in terms of thermal, environmental, social and economic aspects.

The paper differs from the previous review works on green roofs and facades in terms of several aspects. First of all, on the contrary to the existing literature focusing on one specific topic only, the concept of green roofs and facades is investigated in a holistic and thematic way in this research. The review starts with a historical overview of the technology following by theoretical fundamentals and brief explanations. Then, the topic is comprehensively analysed by splitting the scope into various subtopics such as energy saving feature of greenery systems, thermal benefits covering thermal insulation, evapotranspiration, shading and thermal comfort features, evaporative cooling for minimising cooling demand and wind blockage impact. Moreover, green roofs and facades are evaluated in terms of cost and environmental benefits such as reduction in carbon emissions and enhancement in indoor and outdoor air quality. The impacts of greenery systems on human health are also considered within the scope of this study.

2. Greenery systems

Rising population living in urban areas due to the welfare level of the big cities results in so many crucial problems such as pollution especially water, air and noise, global warming and urban heat island due to insufficient greenery areas. It can be easily asserted for such regions that the shortage of vegetation causes remarkable increases in surrounding temperatures which affect the thermal comfort conditions of indoor environments [16,17]. In this respect, the greenery systems are considered to be one of the most appropriate sustainable solutions to resolve the urban heat island-related issues.

Greenery systems mainly comprised of green roofs and green walls are initially considered in the architectural style of the buildings. Widening environmental awareness leads to effective exploitation of these systems to enhance the building performance in terms of not only efficient energy use but also desirable indoor and outdoor environments [16,17]. From this point view, the integration of greenery systems to buildings in urban areas has a great potential to increase the quality of urban environment such as providing water and air quality, storm water management, dense vegetation in urban environments, a marked decline in temperature and carbon emissions as well as minimization of heat island effects [18–20]. Besides the profound effects on environment, the greenery systems provide additional benefits to the public such as social and economic aspects. The presence of greenery has a major psychological impact on urban dwellers as well as enhancing the visual aesthetics of the cities, and raising prices of real estate [17,21]. Moreover, greenery systems are capable of being devised as one of the passive design solutions which provide additional benefits such as insulating impact in winter and shading feature in summer. Therefore, it is emphasized that microclimatic conditions of existing buildings can be adjusted in a cost-effective and eco-friendly manner by utilizing