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Review of the Benefits of Green Roofs

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ABSTRACT: Green roofs installed on rooftop of buildings in urban communities have multiple environmental, economic, energy and social benefits. They promote the urban sustainability and the well-being of the local residents. The impact of green roofs in buildings, in the environment and in local communities have been studied. Green roofs remove atmospheric pollutants including carbon dioxide, release oxygen, mitigate the urban heat island effect, reduce the energy consumption in buildings, improve the rainwater management, promote urban agriculture, enhance urban green spaces and bring nature closer to local residents. The development of green roofs results in many benefits in the buildings that have been constructed as well as in the broader community. Their construction is financially subsidized in several countries due to their multiple external benefits. In the era of climate change and of sustainable development construction of green roofs in urban environments has multiple positive impacts. Therefore, local and municipal authorities should promote their construction in public and private buildings. The current work emphasizes the benefits of green roofs and it could be useful to policy makers, to public and municipal authorities as well as to architects, construction companies and buildings' owners who should promote their development in urban communities.

KEYWORDS: benefits, climate change mitigation, green roofs, rainwater management, urban agriculture, urban heat island effect

1. INTRODUCTION

Construction of green roofs in urban areas is increasing worldwide due to their multiple benefits including their contribution to climate change mitigation. Green roofs have positive environmental, energy, economic and social impacts including removal of atmospheric pollutants [1], [2] atmospheric carbon sequestration and release of oxygen [3], [4] mitigation of the urban heat island effect [5], [6], [7] reduction of energy consumption in buildings [8], [9] better management of rainwater [10], [11] possibility of food production on rooftops of buildings [12], [13], [14] enhancement of urban green spaces and promotion of ecological balance.

The current work aims in the review of the multiple benefits related with green roofs construction in urban spaces.

The structure of the paper is as follows: After the literature review the multiple environmental, economic, energy and social benefits of green roofs are analyzed including the possibility of using the rooftop of buildings in urban areas for micro-generation of energy. The present work has innovative aspects since it gives a holistic approach to the multiple positive and sustainable impacts of green roofs in urban environments. It could be useful to policy makers and to municipal authorities who are willing to promote the environmental sustainability in urban areas improving the well-being of the local residents.

2. LITERATURE SURVEY

The perceptions, evidence and the future of green roofs have been studied [15]. The authors stated that native plants on green roofs are better adapted and provide greater environmental benefits. They also mentioned that Architects, landscape Architects and biologists are more likely to promote native plants on green roofs. The environmental benefits of green roofs have been analyzed [16]. The authors stated that green roofs have been proposed for sustainable buildings in many countries with different climate conditions. They also mentioned that their benefits include the lower energy consumption in buildings, the mitigation of the urban heat island effect, the improvement of air pollution, the water management and the improvement of ecological preservation. Three ecosystem services provided by green roofs have been studied [17]. The authors stated that according to existing studies green roofs result in cooling at street level by 0.03°C-3°C, removal of small particles PM_{10} in the range of 0.42 - 9.1 gr/m^2/year, and the change in the annual energy consumption in buildings by an increase up to 7% to decrease up to 90%. The contribution of green roofs against air pollution and climate change has been reviewed [1]. The authors stated that green roofs recover green spaces in urban areas providing many environmental, ecological and economic benefits. They mentioned that green roofs reduce stormwater runoff, mitigate the urban heat island effect, absorb dust and smog, sequester carbon dioxide, produce oxygen, create space for food production and provide habitats for animals and plants. The benefits and limitations of green roofs have been studied [18]. The

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author stated that there are numerous benefits of green roofs, which are well established. He also mentioned that a new trend has recently appeared combining green roofs with solar-PV electricity generation. The roof harvested rainwater usage in urban agriculture focusing in Australia and Kenya has been studied [10]. The authors stated that urban agriculture contributes to food and nutrition in developing countries while it receives increasing attention in developed countries. They also mentioned that urban agriculture and greening of cities require sufficient water quantities which can be partly provided by rainwater harvesting in green roofs. The environmental impacts of green roofs have been analyzed [19]. The authors stated that the environmental benefits of green roofs in urban buildings include: a) filtration of air pollution and oxygen production, b) reduction of the volume of rain water discharged from roof surfaces, c) reduction of the urban heat island effect, and d) improvements in roof surface insulation including noise reduction. The benefits of green roofs have been reviewed [20]. The authors stated that the benefits of green roofs include: a) better energy performance in buildings, b) improved air quality, c) air pollution mitigation, d) urban heat island mitigation, e) improved management of runoff water, f) increased roof life time span, g) agricultural production, h) improved physical and mental public health, i) increased aesthetic value of urban areas, j) noise pollution mitigation, k) improved efficiency of solar-PV panels, and l) improved urban wildlife habitat. The urban farming from green roofs in high-density urban cities has been studied [12]. The author stated that installation of green roofs with urban farming achieves environmental, social and economic sustainability for buildings in urban cities. Focusing on green roofs in Hong Kong the author mentioned their weaknesses including: a) the lack of room spaces for farming, b) the consideration of agriculture as decaying industry, c) the lack of research and development. Additionally, he mentioned their strengths including: a) the need for fresh food without transportation from long distances, b) the better use of roof spaces, and c) the multiple environmental and social benefits**.** The vegetables' production in green roofs has been analyzed [13]. The authors stated that green roofs create spaces for production of vegetables in urban communities. They also mentioned that shallow-rooted vegetables (<15 cm depth) which include various salad green crops are the most suited in green roofs. Additionally, they stated that vegetables' production in green roofs can be conceived as a supplement to other sources of food production in urban areas. The global rise of urban rooftop agriculture has been examined [14]. The authors stated that rooftop agriculture is developed in North America in open-air farms and gardens. They also mentioned that commercial cases of rooftop agriculture are scarce while the majority of green roof agriculture is targeting in social-educational goals and in the improvement of urban living quality. The sustainability of food production in buildings has been reviewed [21]. The authors stated that urban agriculture has multiple functions having positive impacts on urban life. It has environmental and social benefits while in economic terms it provides potential public benefits. They also mentioned that food production on rooftop of buildings faces many challenges including the combination of several technologies, the high investment cost and a lack of acceptance. The water uptake in green roofs has been studied [22]. The authors stated that drought resistance is critical for plants' survival on shallow-substrate green roofs. They also mentioned that some plant species have been shown to survive without water for over two years. The impact of green roof technology on water availability in urban areas has been examined [11]. The authors have experimented with the construction of a green roof in a large residential building in Lecce, Italy for wastewater purification and its on-site reuse for sanitary purposes and gardens' irrigation. They mentioned that the green roof could be used as a wetland acting as a CO_2 sink while aromatic and medicinal species could be planted on it. The impacts of soil and water retention characteristics on thermal performance of green roofs have been studied [23]. The authors stated that the artificial soil used in green roofs is lighter than the physical soil while it can provide better temperature decrease with good water content. They also mentioned that the efficient water retention in green roofs sustains plants' growth. The ecological and economic effects of water harvesting from green roofs focusing in Poland have been studied [24]. The authors stated that significant water resources can be recovered by green roofs while the net present value of green roof's investments varies in the range of 4.47 $/m^2-60.77 $/m^2. The use of green roofs for rainwater harvesting and sewage treatment has been studied [25]. The authors stated that both substrate and vegetation play an important role in influencing the sewage treatment of green roofs. They also mentioned that when designing green roofs priority should be given in the stability of the substrate as well as in the suitability and adaptability of the plants to cope with different temperatures and precipitation rates. The effectiveness of green roofs in the mitigation of the urban heat island effect has been studied [26]. The authors stated that reduction of the temperature of the UHI by 1°C the Baltimore-Washington metropolitan area requires the coverage of about 30% of the roofs' area by green roofs, assuming that the soil moisture is satisfactory. The mitigation of the UHI effect with green roofs in the city of Toronto, Canada using simulation techniques has been studied [5]. The authors stated that green roofs covering 5% of the total city area can reduce the temperature of the area by up to 0.5°C. The mitigation of the UHI effect with green roofs has been

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analyzed [6]. The author stated that the effectiveness and benefits of green roofs have been studied extensively and they are well documented. He also mentioned that green roofs are considered as one of the most cost-effective strategies for mitigation of the UHI effect. The impact of green roofs on the mitigation of the UHI effect has been quantified [7]. The authors were focused on Constantine, Algeria characterized by semi-arid climate using simulation techniques in their estimations. They mentioned that 4,971.7 m^2 of green roofs can reduce the average day temperature by 1.24^{o}C. The use of green roof technology for the mitigation of the UHI effect has been studied [27]. The authors compared the indoor and outdoor temperatures during the day in a vegetative and in a non-vegetative roof. They found that the vegetative roof could reduce the indoor temperature by 2.4^{o}C compared to outdoor while the non-vegetative roof by 0.8^{o}C. The bees recorded in green roofs in Asia, Europe and North America have been studied [28]. The authors stated that according to various studies a lot of wild bee species have been recorded in green roofs while the percentage of cavity nesting bees on roofs is higher than on nearby ground. The habitat provided for urban bees in green roofs has been studied [29]. The authors stated that a variety of native bee species can use green roofs as foraging and nesting habitat. They also mentioned that the presence of a diverse bee community is likely crucial to permit green roofs to mimic natural ecosystems in a sustainable manner. The role of local communities in supporting green roofs in Indonesia has been examined [30]. The authors stated that the role of community is related with awareness, knowledge and active participation in maintaining and caring of green roofs. Additionally, the community can promote the productive use of buildings when green roofs are planted with productive species. The development of green roofs in European cities has been studied [31]. The authors stated that several incentives for the promotion of green roofs are used in several countries. They also mentioned that according to the World Health Organization the minimum green areas in cities should be at 50 m^2 per inhabitant. Additionally, they stated that the financial support of the maintenance cost of green roofs in Austria is currently at 0.19 €/m^2. The promotion of urban biodiversity by green roofs has been studied [32]. The authors stated that green roofs like other urban green spaces have ecological significance by attending and supporting urban fauna increasing the biodiversity in urban areas. The effect of green roofs focused in Rome Italy has been studied [33]. The authors experimented in an area of 0.218 Km^2 with 3,000 inhabitants and found a lower temperature of 0.5^{o}C at morning and 0.3^{o}C at night. They also mentioned that green roofs reduce the energy consumption in buildings by 2%. The potential energy generation from solar-PV systems in residential buildings of different typologies in Palestine has been assessed [34]. The authors stated that the annual electricity production in Palestinian cities could reach 250 KWh/m^2/year. They also mentioned that the electricity generation in buildings with 2-4 residential units can surplus their estimated future consumption while in buildings with 4-8 residential units can meet their electricity demand in 2030. The research status of rooftop solar-PV systems has been analyzed [35]. The authors stated that the use of crystal silicon cells in public buildings is still the main type of rooftop solar-PV systems while the maximum installed capacity of a single building has exceeded 10,000 KW_p. The renewable energy applications in existing buildings have been studied [36]. The authors stated that there are many synergies between existing buildings and renewable energy technologies while many existing buildings are candidates for renewable energy technologies. They also mentioned that among renewable energy technologies which can be used in existing buildings are solar-PV systems, solar thermal systems and small wind turbines. The potential of roofs in city centers to be used for photovoltaic micro-installations in two districts in the city Opole, Poland has been assessed [37]. Taking into account that the solar electricity generation in the two districts is 161.96 KWh/m^2/year the authors stated that there is a possibility of producing locally nearly 25% of the electricity consumed in residential buildings in the study area. The building integrated solar energy systems have been reviewed [38]. The authors stated that the solar energy systems integrated into buildings can be categorized as: a) solar thermal systems, b) solar-PV systems, and c) hybrid solar systems integrated into the facades. An experimental study regarding the construction of green roofs in buildings has been realized [39]. The authors stated that green roofs can reduce the heating needs in buildings during the winter and their cooling needs in summer. They mentioned that their experiments in Ujjain, India have shown significant benefits regarding the cooling needs in the summer. The role of green roofs on decreasing the energy consumption in buildings in Mediterranean climate has been analyzed [9]. The authors have experimented with three types of green roofs in Calabria, Italy. They stated that green roofs moderate the roof temperature in the summer and winter while the impacts in summer are more remarkable. Their measurements have shown that the roof temperature under the roof surface was higher from 0.2^{o}C-4.6^{o}C in the winter and lower from 5^{o}C to 11.3^{o}C in the summer. The impact of green roofs on energy demand for cooling in Egyptian buildings has been studied [8]. The authors examined the impact of green roofs with different soil depth and thermal conductivity on energy consumption for cooling in Egyptian school buildings. They mentioned that the green roofs studied saved cooling energy in the buildings in the range of 31.61% to 39.74%. The experimental green roof had depth 0.1 m and thermal conductivity 0.9 W/m/K. The energy saving by green roofs using modelling and simulation techniques with reference six global cities in Africa, Asia, Europe, North and South America has been evaluated [40]. The results indicated that green roofs can lead in substantial annual reduction in energy use at city level up to 65.51% in HVAC consumption by 2100. The use of a solar thermal system for domestic hot water production in a medium-size hospital located in Southern Spain has been studied [41]. The authors stated that the current solar contribution to the total demand for domestic hot water (DHW) is low, at 27%. Using simulation techniques, the authors estimated that an optimum solution could increase the solar energy contribution for DHW production up to 60% by increasing the solar caption area by 43% - 57%. The air pollution removal by green roofs in Chicago, USA has been studied [2]. The authors estimated that 1,675 kg of air pollutants were removed by 19.8 ha of green roofs in one year with O_3 accounting for 52% of the total, NO_2 for 27%, PM_{10} for 14% and SO_2 for 7%. The green roofs as a method for pollution reduction has been examined [42]. The authors stated that green roofs involve growing vegetation on rooftops and they can mitigate the negative effects of pollution. They have reviewed published research on how green roofs can influence air pollution, CO_2 emissions, carbon sequestration, storm water runoff collection as well as economic and policy issues. The air pollution removal by green roof systems has been studied [43]. The authors stated that green roofs can be used supplementary to urban trees in air pollution control especially in communities where land is not available. They mentioned that besides carbon sequestration by plants, green roofs contribute in the reduction of energy consumption in buildings and in the reduction of the UHI effect. A report from the Environmental Protection Agency, USA on the environmental effects of green roofs in Kansas' city, Missouri, USA has been released [44]. The report stated that green roofs integrated into urban landscape can benefit the environment, the public health and the society by: a) reducing stormwater runoff, b) lowering ambient air and surface temperatures and reducing the UHI effect, c) increasing buildings' energy efficiency and reducing energy use for heating and cooling, d) reducing air pollution associated with heating, electric power generation and temperature-dependent formation of ground level ozone, e) achieving health benefits associated with reducing air pollution related with fine particulate matter, and f) improving psychological well-being through access to nature. The use of green roofs for the mitigation of urban atmospheric pollution in semi-arid climates has been studied [45]. The authors were experimented with five plant species to quantify the deposition of particulate material on green roofs. Their results indicated that significant amounts of particles were deposited on green roofs while large differences in deposition were recorded among different species. The impacts of green roofs on carbon sequestration and the building carbon footprint in cold and dry climates have been studied [46]. The authors experimented with three plant species on a green roof in Mashhad, Iran. They estimated that the annual CO_2 absorption of three plants was 0.14, 2.07 and 0.61 Kg CO_2/m^2. They also mentioned that the green roof reduced the building's energy consumption reducing the annual CO_2 emissions by 28.16, 26.48 and 23.44 kg CO_2/m^2 respectively. The use of moss on urban green roofs and the atmospheric CO_2 capture in South Korea has been investigated [3]. The authors estimated that the annual CO_2 capture by green roofs was at 1.24 $KgCO_2/m^2$ - 2.66 $KgCO_2/m^2$. The reduction of CO_2 emissions and energy savings obtained by green roofs in Wuxi, China has been studied [4]. The authors stated that a green roof planted with Buddha grass can absorb annually 1.79 $kgCO_2/m^2$ and release 1.3 kgO_2/m^2. Additionally, the CO_2 reduction due to energy savings in the building was estimated at 9.35 $kgCO_2/m^2$. The carbon sequestration potential of 12 extensive green roofs in Michigan and in Maryland, USA has been estimated [47]. The authors stated that energy reduction in buildings due to green roofs leads to annual carbon emission savings by 702 gC/m^2. They also mentioned that the green roofs have stored 162 gC/m^2/year in above ground biomass. The CO_2 payoff of extensive green roofs with different vegetation species has been evaluated [48]. The authors estimated the CO_2 emissions during the construction of the green roof at 25.2 $kgCO_2/m^2$ while the CO_2 emissions during the annual maintenance at 0.33 $kgCO_2/m^2$/year. They also evaluated the CO_2 sequestration at 2.5 $kgCO_2/m^2$/year and the reduction of CO_2 emissions due to saved energy in the range of 1,703-1,889 $kgCO_2/m^2$/year. The authors concluded that green roofs contribute to atmospheric CO_2 reduction within their life span. The annual net uptake of carbon by urban green roofs in Berlin, Germany has been estimated [49]. The authors estimated that the average net carbon uptake in a period of 5 years is in the range of 125.6 gC/m^2/year - 156.6 gC/m^2/year. They also stated that the annual carbon uptake varies between 189 gC/m^2/year for wet years to 95 gC/m^2/year for dry years. The green roof area in London using aerial imagery has been estimated [50]. The authors found that the proportion of green roofs' area to the total buildings' footprint area in various districts of London varies in the range of 0.5% - 3.9%. They also mentioned that the proportion of green roofs' area to the geographical area in these districts varies in the range 0.1% - 2.1 %. A report on green roofs in Basel, Switzerland has been released [51]. The report stated that the city of Basel has the largest area of green roofs per capita in the world at 5.71 m^2/inhabitant in 2019. The report stated that the city was providing in the past, when the construction cost was at around 100 CHF/m^2, subsidies for the installation of green roofs at 20-40 CHF/m^2 while their expected life time was around 50 years. The cost of constructing green roofs has been substantially reduced nowadays and it is estimated at around 23 CHF/m^2 while the thickness of the soil layer is at 12-15 cm. It is also mentioned that construction of hybrid rooftop systems consisted of solar-PV panels and green roofs in proportion 60% and 40% correspondingly have been proposed increasing the ecological value of buildings' rooftops. The average share of the build-up area of cities that is open space for public use for all, by sex, age and persons with disabilities has been evaluated [52]. The author stated that the share of build-up area occupied by streets in three European cities, Vienna, Antwerp and Madrid is 18%, 13% and 29% correspondingly. A United Nations report regarding the Sustainable Development Goal 11 for making cities and human settlements inclusive, safe, resilient and sustainable has been released [53]. The report stated that a sample of 911 cities from 114 countries shows that the share of urban area allocated to streets and open public spaces averages only 16% globally. It is also mentioned that the % of urban area in streets and open public spaces in Northern America and Europe is 18.4%. The use of solar energy, solid biomass and low enthalpy environmental heat, instead of fossil fuels, in residential buildings in Crete, Greece has been studied [54] The author stated that these energy sources can eliminate all the life-cycle carbon emissions of residential buildings generating additionally the electricity required for re-charging the batteries of electric cars of the buildings' occupants. He also mentioned that the installation of the abovementioned green energy systems in residential buildings is economically affordable. The creation of net-zero carbon-emissions residential buildings due to energy use in Mediterranean region has been investigated [55] The author analyzed a residential building with covered area 120 m^2 stating that it can zero its net-carbon emissions using a) a solar thermal system, b) a solar-PV system, and c) a ground-source heat pump covering all its energy demand. The carbon sequestration from green roofs and the carbon emission savings due to reduced energy consumption in buildings with green roofs is presented in table 1 while the share of urban area allocated to streets and open public spaces in European cities in table 2.

Table 1. Carbon sequestration from green roofs and carbon emission savings due to reduced energy consumption in buildings with green roofs

Author, year, country	CO_2 sequestration from green roofs (kgCO_2/m^2/year)	Carbon emission savings due to reduced energy consumption in buildings with green roofs (kgCO_2/m^2/year)
Reza Segedabadi, 2021, Iran	0.14-2.07	23.44-28.16
Seo et al, 2023, South Korea	1.24-2.66	
Cai et al, 2019, China	1.79	9.35
Getter et al, 2009, USA	0.59	2.57
Kuronuma, 2018, Japan	2.5	1,703-1,889
Konopka, 2020, Germany	0.46-0.57	

Source: various authors

Table 2. Share of urban area allocated to streets and open public spaces in European cities

City	Urban area allocated to streets and open public spaces (%)	Author, year
Vienna	18	Ndugwa, R.P., 2008
Antwerp	13	Ndugwa, R.P., 2008
Madrid	29	Ndugwa, R.P., 2008
Several EU cities	18.4	The sustainable development goals report 2021

Source: [52], [53]

3. FOOD PRODUCTION FROM GREEN ROOFS

Green roofs, or rooftop gardens, represent an innovative and sustainable approach to food production, especially in urban environments where land is scarce. By transforming otherwise unused rooftop spaces into productive areas for growing fruits, vegetables, and herbs, cities can combat some of the challenges posed by urbanization, such as limited access to fresh produce and environmental degradation. One of the main advantages of food production from green roofs is the ability to enhance urban food security. In densely populated cities, access to fresh, locally-grown produce is often limited, leading to dependence on imported food that increases carbon footprints. Green roofs enable residents to grow their own food or source it locally, reducing transportation costs, lowering emissions, and promoting healthier diets.

Additionally, green roofs contribute to environmental sustainability. The plants grown on rooftops help reduce the urban heat island effect, improve air quality by filtering pollutants, and mitigate stormwater runoff by absorbing rainwater. These environmental benefits make rooftop gardens a dual-purpose solution, providing food while addressing urban environmental concerns. Moreover, rooftop food production fosters a sense of community and connection to nature. Urban dwellers, often disconnected from food sources, can gain firsthand experience in gardening, promoting environmental awareness and sustainable practices. Schools, community centers, and residential complexes can integrate rooftop gardens as educational tools and social spaces.

Despite these benefits, there are challenges to scaling green roof food production. These include the cost of installation, structural requirements for rooftop support, and the need for specialized maintenance. However, with increasing awareness and investment in urban sustainability, green roofs are becoming a viable solution for cities seeking to improve food security and environmental resilience. By optimizing underutilized spaces, green roofs offer a promising pathway toward a greener, more food-secure urban future. Green roofs provide an ideal environment for urban beekeeping and honey production. With a variety of flowering plants, rooftop gardens attract bees, offering them a safe habitat in densely populated cities. Beekeeping on green roofs supports pollination and enhances urban biodiversity while allowing for sustainable honey production. By providing bees with access to diverse nectar sources, green roofs contribute to high-quality honey, which can be harvested locally. This practice not only promotes environmental awareness but also strengthens food systems and enhances the role of urban agriculture in supporting healthy ecosystems and local economies.

4. RAINWATER MANAGEMENT FROM GREEN ROOFS

Green roofs, also known as rooftop gardens, offer a sustainable approach to rainwater management, especially in urban areas where impermeable surfaces contribute to flooding and stormwater runoff. By incorporating vegetation and soil layers on building rooftops, green roofs provide a natural system to absorb, retain, and filter rainwater, offering numerous environmental and urban infrastructure benefits. One of the primary advantages of green roofs for rainwater management is their ability to reduce stormwater runoff. In cities, where concrete and asphalt dominate, rainfall typically runs off rapidly into drainage systems, which can overwhelm sewers and lead to flooding. Green roofs act as a sponge, capturing and storing rainwater in their soil and plant layers, significantly decreasing runoff volume and delaying its release. This reduces the strain on urban drainage systems during heavy rainfall events, lowering the risk of flooding.

Moreover, green roofs improve water quality by filtering rainwater. As water passes through the soil and plants, pollutants such as dust, heavy metals, and nutrients are trapped and absorbed, resulting in cleaner water entering the drainage system. This natural filtration process helps protect nearby rivers and water bodies from pollution, enhancing overall urban water quality. Additionally, green roofs contribute to cooling urban environments. By retaining water and evaporating it through plants, they reduce the urban heat island effect, which is the increase in temperature in cities compared to rural areas. This cooling effect can improve the microclimate of cities, making them more comfortable and sustainable. However, successful implementation of rainwater management through green roofs requires careful planning, including considerations of roof structure, plant selection, and ongoing maintenance. Despite these challenges, green roofs present a highly effective solution for sustainable rainwater management in cities, providing both ecological and infrastructural benefits.

5. MITIGATION OF URBAN HEAT ISLAND EFFECT BY GREEN ROOFS

The urban heat island effect refers to the phenomenon where urban areas experience significantly higher temperatures than surrounding rural regions. This is primarily due to the vast expanses of concrete, asphalt, and other impermeable surfaces in cities that absorb and retain heat. Green roofs, or rooftop gardens, offer a sustainable solution to mitigate the UHI effect by transforming these heat-absorbing surfaces into cooler, vegetated spaces. One of the key ways green roofs help the mitigation of UHI effect is by providing natural cooling through evapotranspiration. Plants on green roofs release water vapor during photosynthesis, which cools the surrounding air. Additionally, the vegetation and soil layers act as insulators, preventing heat from penetrating buildings and reducing indoor temperatures. This leads to less heat absorption in urban areas and contributes to a cooler microclimate.

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Green roofs also reflect more sunlight compared to conventional roofing materials. Traditional roofs, often dark in color, absorb sunlight and convert it into heat, exacerbating the UHI effect. In contrast, green roofs reflect a portion of this solar radiation, helping to reduce the amount of heat trapped in cities. This not only lowers overall urban temperatures but also decreases the demand for air conditioning in buildings, leading to energy savings and reduced greenhouse gas emissions. Moreover, the cooling benefits of green roofs can have a broader impact on public health. High urban temperatures can exacerbate heat-related illnesses, particularly during heatwaves. By reducing the UHI effect, green roofs help create more livable urban environments, improving comfort and lowering the risk of heat stress for city residents. Though green roofs require investment in design, structural considerations, and maintenance, their potential to combat the UHI effect makes them a critical tool in creating more sustainable, resilient, and cooler urban areas.

6. ENERGY SAVINGS IN BUILDINGS DUE TO GREEN ROOFS

Green roofs, which involve the installation of vegetation and soil layers on building rooftops, offer a sustainable solution for improving energy efficiency in urban structures. By acting as a natural insulator, green roofs contribute to significant energy savings, especially in cities where temperature extremes often lead to high heating and cooling costs. One of the primary ways green roofs save energy is by regulating indoor temperatures. During summer, traditional roofs absorb large amounts of heat from the sun, causing buildings to overheat and increasing the need for air conditioning. Green roofs, however, provide a cooling effect through evapotranspiration—the process by which plants release water vapor into the air. The vegetation also shades the roof surface, reducing heat absorption and keeping the building cooler. This natural insulation minimizes the need for air conditioning, leading to reduced energy consumption and lower electricity bills.

In winter, green roofs help retain heat within buildings. The soil and plant layers act as an additional barrier, preventing heat from escaping through the roof. This improved thermal performance reduces the need for heating, leading to further energy savings. The dual benefits of green roofs—cooling in the summer and insulation in the winter—make them an effective solution for year-round energy efficiency. Furthermore, by reducing energy demands for heating and cooling, green roofs contribute to a decrease in greenhouse gas emissions associated with energy production. This supports broader efforts to mitigate climate change and transition to more sustainable urban living. While the installation and maintenance of green roofs require an upfront investment, the long-term energy savings they provide can offset these costs. Green roofs not only enhance energy efficiency but also improve building resilience, extend the lifespan of roofing materials, and contribute to healthier, more sustainable urban environments.

7. CO_2 REMOVAL AND O_2 RELEASE FROM GREEN ROOFS

Green roofs, or rooftop gardens, provide a unique and sustainable solution for improving air quality in urban environments. By integrating vegetation on rooftops, these green spaces contribute to the reduction of atmospheric carbon dioxide levels and the release of oxygen, offering significant environmental benefits to cities grappling with pollution and climate change. One of the primary ways green roofs help in CO_2 removal is through the natural process of photosynthesis. During photosynthesis, plants absorb CO_2 from the atmosphere and, with the help of sunlight, convert it into oxygen and glucose. The vegetation on green roofs acts as a carbon sink, capturing and storing CO_2 that would otherwise contribute to global warming. Although the scale of CO_2 removal from individual green roofs is modest, widespread adoption of green roofing across urban areas can have a substantial cumulative impact on reducing atmospheric CO_2 levels.

In addition to removing CO_2, green roofs play a crucial role in oxygen production. The plants on these roofs release O_2 as a byproduct of photosynthesis, helping to replenish the oxygen supply in densely populated cities where air quality can be compromised. By enhancing the availability of oxygen, green roofs contribute to healthier, more breathable urban environments, particularly in areas suffering from pollution. Beyond CO_2 removal and O_2 release, green roofs offer other important environmental benefits. By filtering pollutants and particulate matter from the air, they improve overall air quality. Additionally, green roofs help mitigate the urban heat island effect, where cities experience higher temperatures than surrounding areas due to heat absorption by buildings and infrastructure. Cooler cities require less energy for air conditioning, indirectly reducing CO_2 emissions from power generation. Moreover, green roofs support biodiversity by providing habitat for insects and birds, further enriching urban ecosystems. While individual green roofs may have a limited impact, their collective potential to capture CO_2, release oxygen, and improve air quality is significant. As cities strive to become more sustainable, green roofs offer a promising solution for combating climate change, enhancing public health, and promoting environmental resilience.

8. HOT WATER AND ELECTRICITY GENERATION FROM GREEN ROOFS

Green roofs, known for their environmental and aesthetic benefits, can also be integrated with renewable energy systems to generate hot water and electricity. By combining vegetation with solar energy technologies, green roofs offer an innovative solution for enhancing energy efficiency in urban buildings while promoting sustainability. One effective method of generating hot water from green roofs involves the installation of solar thermal panels alongside the vegetation. Solar thermal systems capture the sun's heat and transfer it to water through collectors. This heated water can then be used for domestic purposes such as showers, heating systems, and other hot water needs. The vegetation on the green roof plays a complementary role by naturally cooling the rooftop, optimizing the efficiency of solar panels by preventing them from overheating and reducing the surrounding ambient temperature. This integration maximizes energy capture while maintaining the cooling benefits of green roofs.

Electricity generation from green roofs is typically achieved through the installation of solar photovoltaic panels, which convert sunlight into electricity. Like solar thermal panels, PV panels work well when combined with green roofs because the vegetation helps regulate rooftop temperatures. By reducing the heat absorbed by traditional roofs, green roofs enhance the performance of PV panels, making them more efficient in converting solar energy into electricity. The electricity generated can be used to power lighting, appliances, or even feed back into the grid, reducing reliance on fossil fuels. The combination of solar technologies with green roofs not only reduces energy costs but also decreases greenhouse gas emissions. By producing renewable energy on-site, buildings can reduce their dependence on non-renewable energy sources, contributing to the fight against climate change. Furthermore, this dual system increases the overall sustainability of urban infrastructure, promoting energy efficiency while providing the ecological benefits of green roofs, such as improved air quality, stormwater management, and urban biodiversity.

9. REMOVAL OF AIR POLLUTANTS BY GREEN ROOFS

Green roofs offer an effective solution for reducing air pollution in urban areas. By integrating vegetation on rooftops, these gardens help absorb and filter pollutants from the air, improving overall air quality and contributing to healthier cities. One of the primary ways green roofs remove air pollutants is through the process of deposition. As air moves over the plants, pollutants like particulate matter, nitrogen oxides, sulfur dioxide, and ozone are trapped on the leaves and soil. Fine particulate matter, in particular, is a major urban pollutant that can cause respiratory and cardiovascular diseases. Green roofs capture these particles, preventing them from being inhaled by city residents. Over time, rain washes the pollutants into the soil, where they are either absorbed or broken down by microorganisms, further reducing pollution levels.

Green roofs also contribute to lowering urban levels of nitrogen dioxide and ozone. These gases are often produced by vehicle emissions and industrial activities, leading to smog and poor air quality. Plants on green roofs absorb these gases during photosynthesis, converting them into less harmful compounds. This natural filtration process helps reduce the overall concentration of harmful pollutants in the atmosphere, making the air cleaner and safer to breathe. Moreover, green roofs mitigate the urban heat island effect, which is the temperature rise in cities due to heat-absorbing materials like concrete. By cooling urban areas, green roofs reduce the demand for air conditioning, thereby lowering energy consumption and the emissions associated with power generation. This indirect reduction in air pollution complements the direct filtering role of green roofs. In summary, green roofs serve as natural air filters, removing pollutants and improving urban air quality. Their environmental and health benefits make them a valuable tool for cities aiming to combat air pollution and promote sustainable living.

10. INCREASING BUILDING VALUE WITH GREEN ROOFS

Green roofs can significantly enhance the value of a building, both financially and environmentally. By adding a green roof, buildings become more attractive to potential buyers and tenants due to the numerous benefits these rooftops provide. Aesthetic appeal is improved, creating a more pleasant and eco-friendly environment that can increase demand in competitive real estate markets. Additionally, green roofs contribute to energy efficiency by insulating the building, reducing heating and cooling costs. They also extend the lifespan of roofing materials by protecting them from weather extremes, decreasing maintenance expenses. Environmental advantages, such as improved air quality, stormwater management, and enhanced biodiversity, further increase a

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building's sustainability profile, making it more appealing to eco-conscious buyers. Incorporating a green roof can thus lead to higher property values, rental rates, and long-term cost savings, offering a solid return on investment while promoting sustainability.

11. INCREASING THE LIFE OF A BUILDING WITH GREEN ROOFS

Green roofs not only offer environmental and aesthetic benefits but also play a crucial role in extending the lifespan of building structures. By integrating vegetation and soil layers on rooftops, green roofs provide multiple protective and maintenance advantages that contribute to the durability and longevity of buildings. One of the primary ways green roofs enhance building longevity is through their insulation properties. The layers of soil and vegetation act as a buffer against temperature fluctuations, reducing thermal stress on roofing materials. This insulation minimizes the expansion and contraction cycles that can cause deterioration in traditional roofing systems, thereby extending their lifespan. By maintaining a more stable temperature on the roof, green roofs help prevent damage from extreme weather conditions.

Additionally, green roofs protect roofing materials from UV radiation and weathering. Traditional roofs exposed to sunlight can suffer from UV degradation, leading to cracks and leaks over time. The plant cover on green roofs shields the roofing membrane from direct sunlight and harsh environmental conditions, preserving its integrity and reducing the need for frequent repairs or replacements. Moreover, green roofs manage stormwater effectively by absorbing and retaining rainwater. This reduces the load on drainage systems and minimizes the risk of water-related damage to the building's structure. By controlling runoff, green roofs help prevent leaks, erosion, and water infiltration that can compromise building foundations and interiors. The reduced need for maintenance and repairs associated with green roofs also contributes to lower overall lifecycle costs. Regular upkeep of traditional roofs can be costly and disruptive, whereas green roofs offer a more resilient and self-sustaining alternative. In summary, green roofs significantly enhance the durability and longevity of buildings by providing insulation, protecting roofing materials from UV damage, and managing stormwater effectively. These benefits not only contribute to the structural integrity of buildings but also offer long-term cost savings and sustainability, making green roofs a wise investment for building owners and urban planners.

12. REDUCTION OF INDOOR NOISE WITH GREEN ROOFS

Green roofs effectively reduce indoor noise levels, enhancing building comfort and privacy. The layers of soil and vegetation on green roofs act as sound insulators, absorbing and dampening external noise, such as traffic and construction sounds. This natural acoustic barrier helps create a quieter indoor environment, improving the quality of life for occupants. By mitigating noise pollution, green roofs contribute to a more serene and productive atmosphere inside buildings, making them a valuable addition for both residential and commercial properties. This noise reduction benefit further underscores the multifunctional advantages of integrating green roofs into urban architecture.

13. CREATING A HEALTHY URBAN ECOSYSTEM WITH GREEN ROOFS

Green roofs play a pivotal role in fostering a healthy urban ecosystem, transforming cityscapes into vibrant, sustainable environments. By integrating layers of vegetation and soil on building rooftops, green roofs create habitats for diverse plant and animal species, contributing to urban biodiversity. These green spaces offer crucial refuges for pollinators like bees and butterflies, which are essential for maintaining ecological balance and enhancing food production. Moreover, green roofs support ecological functions such as air and water purification. Plants on these roofs absorb pollutants and particulate matter from the air, improving urban air quality. They also manage stormwater by capturing rain, which reduces runoff and the risk of flooding, while filtering pollutants before they enter water systems. The cooling effect of green roofs helps combat the urban heat island phenomenon, where cities experience higher temperatures than rural areas. By lowering ambient temperatures, green roofs reduce energy consumption for cooling and improve overall urban climate. Additionally, green roofs offer social and psychological benefits. They provide green spaces in densely built areas, enhancing aesthetic appeal and offering recreational areas that improve mental well-being. In essence, green roofs are integral to creating healthier urban ecosystems, promoting environmental sustainability, and enhancing the quality of life in cities.

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14. ENHANCING WELL-BEING, STRESS RELIEF, AND PSYCHOLOGICAL BENEFITS IN URBAN RESIDENTS

Green roofs, which incorporate layers of vegetation and soil atop buildings, provide more than just environmental benefits; they significantly enhance the well-being, stress relief, and psychological health of urban residents. In densely populated cities, where natural spaces are often limited, green roofs offer a vital connection to nature, contributing to improved mental health and overall quality of life. One of the primary psychological benefits of green roofs is their ability to provide accessible green spaces in urban areas. These natural retreats offer residents a respite from the concrete jungle, fostering a sense of tranquility and connection with nature. The presence of greenery can alleviate feelings of stress and anxiety, promoting relaxation and mental clarity. Studies have shown that exposure to natural environments can lower cortisol levels, the hormone associated with stress, and improve overall mood.

Green roofs also offer opportunities for recreational activities and social interaction. Community gardens and accessible green roof spaces can serve as communal areas where residents gather, socialize, and engage in gardening. These interactions build social cohesion and provide a supportive network, further enhancing emotional well-being. Additionally, the act of tending to plants can be a therapeutic activity, offering a sense of accomplishment and purpose. Furthermore, green roofs contribute to improved air quality and reduced urban heat island effects, creating a more comfortable living environment. Lower temperatures and cleaner air contribute to physical health, which in turn supports psychological well-being. The calming effect of a green roof's natural beauty can be particularly beneficial in high-stress urban settings. In summary, green roofs significantly enhance urban living by providing accessible green spaces that improve mental health, offer stress relief, and foster social connections. Their integration into urban planning not only contributes to environmental sustainability but also supports the holistic well-being of city residents.

15. THE ROLE OF GREEN ROOFS IN ENHANCING URBAN GREEN SPACES

Green roofs play a crucial role in enhancing green space within urban environments, where land is often scarce and natural areas are limited. By transforming rooftops into vibrant, vegetated spaces, green roofs provide much-needed greenery in densely populated cities. These elevated gardens offer a range of ecological benefits, including improved air quality, reduced urban heat island effect, and increased biodiversity. In addition to their environmental contributions, green roofs create accessible green spaces that can be utilized for recreation, relaxation, and community engagement. They help bridge the gap between built and natural environments, offering city residents a respite from the concrete landscape. By integrating green roofs into urban planning, cities can enhance their green infrastructure, improve overall livability, and foster a stronger connection between residents and nature, ultimately contributing to a more sustainable and enjoyable urban experience.

16. THE MULTIPLE ENVIRONMENTAL, ECONOMIC, ENERGY, AND SOCIAL BENEFITS OF GREEN ROOFS

Green roofs, also known as vegetative or living roofs, are increasingly recognized for their wide-ranging benefits, which extend across environmental, economic, energy, and social domains. A green roof is a building's roof partially or completely covered with vegetation, growing on a waterproof membrane. These roofs not only enhance urban aesthetics but also address several critical challenges, making them an attractive option for sustainable urban development.

16.1 Environmental Benefits

Green roofs play a significant role in mitigating the urban heat island effect. By adding vegetation to rooftops, green roofs reduce ambient temperatures and lower energy consumption. They also improve air quality by absorbing pollutants and carbon dioxide, releasing oxygen in the process. Furthermore, green roofs help manage stormwater. In urban settings, rainwater runoff often overwhelms sewer systems, leading to flooding and pollution. Green roofs absorb and filter rainwater, reducing runoff and helping cities manage heavy rainfall more effectively. This can also lead to less pollution entering waterways, contributing to healthier ecosystems.

16.2 Economic Benefits

Green roofs offer long-term economic benefits by extending the lifespan of a roof structure. The vegetation and soil layers shield the waterproofing membrane from harmful ultraviolet radiation, extreme temperature fluctuations, and physical damage, thus reducing maintenance and replacement costs. Additionally, green roofs can increase property values. The aesthetic appeal of a building with a green roof can attract potential buyers or renters, boosting real estate prices. Commercial buildings with green roofs may also see increased leasing potential, as businesses and tenants increasingly value sustainability. Green roofs offer the opportunity for cultivation of various vegetables including green salads as well as for honey production generating a small income.

16.3 Energy Benefits

One of the most immediate benefits of green roofs is energy efficiency. Green roofs provide insulation, reducing the need for heating in winter and cooling in summer. The energy savings achieved in buildings result in lower CO_2 emissions due to energy use. The vegetative layer acts as a thermal barrier, keeping buildings cooler by absorbing sunlight and reducing heat transfer. This lowers air conditioning demand, which translates to significant reductions in energy consumption and costs. For buildings in colder climates, the additional insulation can also reduce heating needs, providing year-round energy savings.

16.4 Social Benefits

Beyond their tangible environmental and economic benefits, green roofs enhance social well-being. They contribute to the creation of green spaces in urban areas, where access to nature is often limited. Green roofs offer opportunities for gardening, relaxation, and even urban agriculture, fostering a sense of community and improving mental health by providing spaces for interaction and stress relief. Green roofs can also contribute to biodiversity by creating habitats for birds, insects, and other wildlife, even in densely built-up areas. This promotes ecological balance and brings nature closer to urban residents, raising environmental awareness and fostering a connection with the natural world. The benefits of green roofs are presented in table 3.

Table 3. Benefits of green roofs

Environmental	Removal of atmospheric CO_2
	Removal of various atmospheric pollutants
	Release of oxygen
	Mitigation of the urban heat island effect
	Reduction of the noise in the building
	Improvement of the management of water runoff
	Creation of a healthy ecosystem attracting birds, insects et cetera increasing the biodiversity in urban areas
Economic	Increase of the life span of the building roof
	Increase of the value of the property
	Creation of the opportunity for cultivation of vegetables and production of honey resulting in an economic benefit
	Reduction of the energy consumption and the energy bill in the building
Energy	Reduction of the heat and cooling requirements in the building
Social	Offering the opportunity for gardening and relaxation
	Improvement of the mental health and stress relief
	Promotion of ecological balance and bringing nature closer to urban residents

Source: own estimations

17. DISCUSSION

The multiple benefits of green roofs have been analyzed indicating that green roofs in urban environments offer many environmental, economic, energy and social benefits. Creation of green spaces on rooftop of buildings in densely populated urban communities with limited public parks and public green spaces improves the quality of life of local residents and increase the sustainability of the community. Due to multiple benefits of green roofs local and municipal authorities should try to promote their construction offering several financial and non-financial incentives. The external benefits of green roofs in the local community including the mitigation of the UHI effect, the mitigation of climate change, the removal of various atmospheric pollutants, the development of urban agriculture et cetera justify their financial support from public funds. Municipal authorities should also try to construct green roofs in municipal buildings as good examples for replication in private buildings. Further work should be focused in the investigation of the nexus between the United Nations Sustainable Development Goals and the construction of green roofs in urban communities.

18. CONCLUSIONS

A review of the multiple benefits related with green roofs construction in urban spaces has been presented. Our findings indicate that green roofs have many environmental, economic, energy and social benefits. These include:

a) The removal of atmospheric pollutants including the CO_2 and the release of oxygen,
b) The mitigation of the UHI effect,
c) The improvement of rainwater management and the creation of a healthy urban ecosystem increasing the urban biodiversity,
d) The development of urban agriculture,
e) The increase of the lifespan of the building roofs and the value of the property,
f) The reduction of the energy consumption in the buildings in heating and cooling as well as the noise reduction,
g) The promotion of ecological balance and the improvement of mental health and stress relief.

Our work indicates that green roofs have many benefits in the buildings that have been constructed as well as in the local community. Their construction should be promoted by local communities while due to their external benefits, they should be financially subsidized.

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