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Economic and environmental sustainability and public perceptions of rooftop farm versus extensive garden

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ABSTRACT

Green roofs have become popular in urban areas as a solution to restore green space in cities and mitigate urban problems. In this study, the economic and environmental sustainability of using green roofs for rooftop agriculture (i.e., roof farms) is evaluated and compared with that of using green roofs as extensive gardens of flowers and non-edible plants with low maintenance (i.e., roof gardens) based on these two green roofs that were installed and operated for over five years in a university building in Seoul, Korea. The life cycle cost analysis results show that the total cost of the roof garden is 38.9% lower than the flat roof whereas the total cost of the roof farm is 68.3% higher than the roof garden. The environmental impacts of both the roof garden and farm were 2.4–35 times as high as those of the flat roof. The need to frequently replenish the lightweight soil over its lifetime was the main contributor to both the economic cost and environmental impacts of the roof farm, suggesting a need to develop cost-effective and environmentally benign lightweight soil materials. A survey was also conducted to investigate public preferences and perceptions of these two green roof options. Over 80% of the respondents expressed the necessity for green roofs in urban areas, and 79.3% preferred roof gardens over farms. Our results show that roof farms have several merits in urban areas, especially social benefits, but future research should focus on improving their economic and environmental sustainability.

1. Introduction

Over the past several decades, urbanization has led to the continuous development of infrastructure in cities, and high population densities result in increased demand for energy, water, food, and other resources. With the decreased availability of natural ecosystems, highly dense cities face multiple environmental problems including poor air quality, high volumes of contaminated stormwater runoff, and the loss of natural habitats. Additionally, some cities also experience increased urban temperatures, also known as the urban heat island effect, leading to further increases in energy consumption. These problems will only become more severe as the urban population is projected to increase by a further 3 billion people by 2050 [1].

Green roofs have gained popularity among developers, architects, engineers, and city planners as a sustainable method to aid in resolving urban problems and restore green space in cities. Green roofs consist of plants, a lightweight soil media layer, a waterproofing membrane layer, and a drainage layer on the top of the building's roof, and offer various benefits, such as stormwater runoff reduction [2,3], urban heat island mitigation [4], and an increase in biodiversity [5]. Furthermore, several studies have reported energy savings in the building due to the reduction in the total energy required for air conditioning [6–8] as well as lower environmental footprints due to the reduction in carbon and other pollutant emissions [9].

In addition to the aforementioned environmental benefits, green roofs provide social benefits in cities. Both physical and mental health problems are reportedly linked to a lack of public spaces in cities [10,11]. These negative effects on human health can be minimized with the implementation green roofs, as they improve the availability and access to green space in urban areas [12]. The addition of aesthetic value to the urban landscape has also been suggested as a benefit of green roof installation, although the type of vegetation influenced the extent to which people approved of the visual appearance of the green roofs [13,14].

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The incorporation of green roof technology into urban agriculture has also received some attention [15]. With rapid and continuous urbanization in many countries, urban dwellers are becoming increasingly more vulnerable to the food insecurity risks, especially related to the fresh food availability. Urban agriculture is an attractive method of ensuring food security in highly dense urban areas [16]. Urban agriculture fosters community engagement and reduces the energy associated with food transportation, however, securing space in cities for urban infrastructure is often difficult because land is expensive. Farming on green roofs is an attractive option to solve the space issue for urban agriculture. Furthermore, it also serves as an integrated water-energy-food nexus technology that ensures sustainable agriculture while maximizing the efficiency of rainwater use and minimizing building energy requirements [17].

While the use of green roofs as urban farms is a promising and sustainable solution to urban problems, it is important to determine its potential benefits and trade-offs and compare them to those of other types of green roof (e.g., extensive and intensive garden of flower and non-edible plants) as well as those of more conventional flat roofs (i.e., no green roof). The goal of this study is to evaluate and compare the overall sustainability of three roof options (i.e., rooftop farming, extensive green roof, and flat roof) in urban buildings based on real data obtained from two green roofs installed and operated in Seoul, Korea. The economic and environmental costs for each roof option were evaluated using life cycle cost (LCC) analysis and life cycle assessment (LCA). Furthermore, a survey was conducted to identify which green roof type is preferred by stakeholders and how they perceive the associated trade-offs with economic, environmental, and social costs. The specific objectives of this work are to i) quantify the relative contribution of materials and components to the economic costs and environmental impacts of each option, ii) elucidate the trade-offs of each option from economic and environmental perspectives, iii) understand the key values people associate with green roofs, and iv) identify key areas to improve for the use of rooftop for urban agriculture.

2. Literature review

Over the past decade, numerous studies have investigated the environmental benefits of green roofs in cities. These green roofs were generally categorized into two types, extensive (thin and light soil medium, only shallow-root plants, low maintenance) and intensive (thicker soil medium, a variety of plants and trees, high maintenance) green roofs. Tam et al. [8] had conducted case studies in Hong Kong to evaluate the thermal insulation from the green roof and observed the indoor temperature reduction up to 3.4 °C. A simulation study by Smith and Roeber [18] found that the temperature in Chicago (U.S.A) would be 2–3 °C cooler during evening time when green roofs are installed on all rooftops. Solcerova et al. [19] suggested that extensive sedum-covered green roofs in Utrecht (Netherlands) reduced the temperature at night but increased it at daytime, suggesting that the availability of water in the substrate may play an important role in the cooling behavior of the green roof. Other studies [20,21] demonstrated that plant coverage, floristic composition, and plant and substrate selection on the green roof can also influence its thermal behavior. In addition to the urban heat island mitigation, storm water run-off reductions of 60% and 90% were observed for extensive and intensive green roofs, respectively, in Pittsburgh (U.S.A) [22]. Yang et al. [23] had reported that 19.8 ha of green roofs in Chicago had improved its air quality by removing ca. 1700 kg of air pollutants (including O_3, NO_2, PM_{10}, and SO_2) in one year.

Several studies have also evaluated the economic, environmental, and social costs of green roofs among different types and/or compared to conventional flat roofs [24,25]. Wong et al. [26] compared the life cycle cost of intensive and extensive green roofs and flat roof and found that extensive green roof has a lower life cycle cost than the flat roof. Berto et al. [27] quantified the social benefits of extensive green roof such as aesthetic benefit into monetary terms. Guzmán-Sánchez et al. [28] developed a Multi-Criteria Decision Analysis to compare and support the selection among four roof types including self-protected flat roof and green roof based on multiple matrices consisted of energetic, hydrologic, environmental, social, economic, and structural indicators. The green roof was chosen as the most sustainable option among the four roof types evaluated in the study.

While there is a growing interest in the use of green roofs for urban agriculture, only limited studies to date are available on this topic. Specht et al. [17] and Sanyé-Mengual et al. [29] both conducted survey-based studies to identify stakeholder perceptions on rooftop farming and addressed several opportunities and limitations. For example, some stakeholders consider rooftop farming as false agriculture or more as a socially oriented activity while others consider it more positively to be the potential urban food production site. Tong et al. [30] has investigated the air quality improvement on the rooftop farm in Brooklyn, New York (U.S.A) and observed 7–33% reduction in average $PM_{2.5}$ concentrations. While rooftop farm can be an attractive green roof option, no studies to date have explored the applicability and relative economic and environmental sustainability of rooftop farm in comparison to other available roof options. Therefore, there is a need to conduct a study that objectively compares the relative merits of rooftop farm with other green roof options as well as with flat roof, and to identify what challenges need to be overcome for rooftop farm to become a more sustainable and practical solution for mitigating urban problems.

3. Material and methods

3.1. System description

This study examines the economic and environmental costs of two green roof options and no green roof option based on information obtained from an existing green roof on the Civil and Environmental Engineering Building of Seoul National University. The building originally had no green roof (herein referred to as the **flat roof**), and the green roof was installed in 2012. The original flat roof required a polyurethane waterproofing membrane to be re-coated every five years to prevent water infiltration. There were two parts to the green roof: 1) a 140 m^2 rooftop farm to grow and produce edible vegetables, such as potatoes, tomatoes, and lettuces (herein referred to as the **roof farm**), and 2) a 140 m^2 extensive garden with flowers and other non-edible plants (herein referred to as the **roof garden**).

Both the roof farm and garden were composed of a bituminous waterproofing membrane, a fiberboard for drainage and insulation, wire mesh, and 200 mm of lightweight soil. A 350-mm outer wall constructed from concrete blocks was installed to separate the green roof from the flat roof. The use of lightweight soil minimized the additional load to the building from the green roof; therefore, the structural support of the roof in this building was not modified during green roof installation. For the roof garden, red poppy (*Papaver rhoeas*) was predominantly planted and needed to be seeded every two years. For the roof farm, potatoes (*Solanum tuberosum*) were selected as the primary crop on the Seoul National University building. Maintenance included the annual seeding of potatoes, the addition of compost, and replenishment of lightweight soil.

The system boundary of this study primarily includes the construction, operation, and maintenance, and disposal of the system components directly related to the construction of green roofs on the building, and does not include other parts of the building that would be shared by all roof options evaluated in this study. For instance, the structural support and concrete slabs of the building walls and roof are the same for the two green roof options (i.e., the roof farm and the roof garden), as well as for the flat roof option, and are thus outside of the system boundary. To compare the roof options, a functional unit of 140 m^2 of the roof area with a 40-year lifespan is selected. The same