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# Multicriteria decision-making tool for investigating the feasibility of the green roof systems in Egypt

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**Abstract**

Urbanization in Egypt detracts from green spaces, reduces the per capita green ratio, and increases adverse effects such as heat islands, air pollution, and energy consumption. In addition, it affects social human comfort issues. In this context, building rooftops is a potential solution that could reduce the impact of green space scarcity. Such a solution has multiple evidence-based environmental, economic, and social benefits. Consequently, numerous governmental and private initiatives have spread the rooftop greening concept in Egypt. These initiatives have adopted several planting systems, such as soil-based, deep-water culture, and nutrient film technique systems. This manuscript examines these prevalent systems through environmental, economic and social lenses. This paper pioneers a user-centric tool to facilitate the system selection that aligns with individual needs. An analysis was conducted to ascertain the value of various factors influencing system choice, encompassing a literature review, expert opinion solicitation, market survey, and energy simulation. The Analytical Hierarchy Processes methodology was proposed to appraise the factors, aiding in arriving at an informed decision. The paper presents a novel contribution by studying many factors spanning diverse scientific domains. Furthermore, creating an accessible decision-support tool encapsulates a substantial addition to the body of knowledge.

**Keywords** MCDM, AHP, Roof cultivation, Design builder, Energy consumption

## 1 Introduction

Population in Egyptian cities is snowballing, leading to green space demolition. Cairo, for example, lost 910,000 m$^2$ of green spaces between 2017 and 2020, decreasing the ratio from 0.87 to 0.74 m$^2$/individual. World Health Organization (WHO) recommended that 9 m$^2$/individual be the minimum ratio; the ideal is 50 m$^2$/individual. The decline of green space areas leads to various adverse effects such as air pollution crisis, heat island intensity, and increased air temperature, which leads to more energy consumption. Also, water scarcity is a severe challenge facing countries worldwide due to the growing population and climate change affecting green spaces.

In this context, the green roof is a potential solution that could reduce the effect of green space area reduction and have multiple evidence-based benefits. Green roofs have different environmental, economic, and social benefits [1]. Green roofs are designed to adapt to economic and modern social factors to maintain environmental sustainability as they provide great opportunities to improve climate and economy. Green roofs are

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living roofs covered with vegetation, considered growing medium at the top of buildings [2]. The green roof has different benefits; for example, it reduces greenhouse gas emissions, limits urban heat island's impact [3], and improves air quality [4]. Green roofs have many advantages; they enhance the aesthetic value of the urban regions and improve the quality of life for dwellers by creating some activities such as recreational activities [5]. Also, Green rooftop technologies provide a sustainable solution that can help mitigate the water crisis by retaining and reusing rainwater on building rooftops [6, 7].

Furthermore, green roofs enhance energy efficiency, develop efficient strategies for electrical supplies, and boost the building's thermal performance [8]. On the other hand, the green roof fits into modern societal norms, creating comfortable environments for the building's users. This concept is feasible and economical when comparing it with conventional roofs [1].

Recent research about green roofs has shown valuable positive effects and advantages in various locations. Some researchers are capitalizing on numerical modeling to investigate the energy performance of green roofs [9] and other studies based on observation and measurements [10]. Berardi et al. [11] in 2014 reported that green roofs effectively decrease city air temperatures. Also, Czemiel Berndtsson 2010 [12] mentioned that the average air temperature in green roofs is colder than reference roof temperatures. Hashemi et al. 2015 [13] analyzed the effects of green areas on air quality, revealing a significant impact on air quality through the increased dispersion of air pollutants. Also, several studies focused on the benefits of green roofs on urban hydrology and managing stormwater, focusing on minimizing flood risks by reducing water runoff [14]. Green roofs can also reduce sound exposures inside and next to buildings through the mitigation diffraction of the sound waves above roofs and the reduction of sound transmission by different roof systems [15].

According to the recent literature, the performance of energy related to green roofs is still the best and most used advantage for adopting and promoting them [16]. That is why many designers in the field of designing energy are interested in this application, as it reduces the temperature and solar heat for roof surfaces by covering building components and focusing on the overall building thermal performance and the conditions of microclimate in urban areas [17]. Despite the high initial cost, green roofs are an excellent economical solution as it saves energy and helps plant production [18]. Also, as insulation is used on many buildings, green roofs must fulfill the technical requirements, building codes, regulations, and all the energy efficiency standards to meet buildings' performance specifications [19]. Designing an appropriate green roof system is not easy; it is complicated and needs different sustainable aspects, factors related to social encompass, culture, climatic region, and environmental respect. That is why systematically selected methods such as Multicriteria Decision Making (MCDM) are essential to solving all the complexity when using or choosing the appropriate solution [20].

Compared to existing literature, our manuscript delves into a deeper examination of rooftop planting systems within the Egyptian context. Unlike most studies focusing on theoretical hypotheses regarding the cultivation of the entire roof area, our work considers practical aspects such as maintenance, irrigation, and crop collection pathways, offering a more realistic appraisal. Additionally, while most previous studies have considered roof cultivation as part of initial construction, our research extends to exploring locally adaptable methods that can be retrofitted onto existing roofs. Moreover, our manuscript goes beyond elucidating the environmental benefits, delving into the economic, social advantages, and aesthetic value. Prior studies have touched on green roofs' energy efficiency and thermal performance. This manuscript furthers this discourse by providing a comparative decision-making framework to aid in selecting the most suitable system, thus promoting a more practical uptake of rooftop cultivation in Egypt.

### 1.1 Roofs usage in Egypt and local green roof initiatives

The rooftop has the potential to be used in different ways, such as installing solar panels, creating reactional spaces, or cultivating plants. In Egypt, most roofs were not appropriately used and were considered a waste of opportunity [21]. For example, many of the building rooftops in Cairo are not being utilized to their full potential. They often store discarded items, satellite dishes, water tanks, and solar heaters. Green roofs are not yet widely used in Egypt, but researchers have suggested they could solve the shortage of green spaces. However, there are several challenges to the adoption of green roofs in Egypt, including a lack of trained technical personnel to explain and teach the community to use these systems, a lack of media guidance on the topic, and a shortage of fertilizers or fluids needed to sustain crops grown on rooftops [21]. Despite these challenges, green roofs have the potential to provide several benefits in Egypt, such as making up for the shortage of green spaces, increasing the production of vegetables, fruits, and medicinal plants, purifying the air by removing pollutants, improving insulation and energy efficiency on rooftops, and reducing energy consumption [22]. Figure 1 shows the roof situation in Cairo [23].

Several initiatives have been implemented to promote the spread of green roof culture in Egypt. A presidential


**Fig. 1** Rooftops of different buildings in Cairo show rubbish and trash, and satellite dishes [23]

rural development project named Dignified Life was launched in 2020. The project included an initiative to cultivate rooftops in some rural villages in the Gharbiah governorate. This initiative has included ten houses, costing 10,000 EGP per house (1 USD ≈ 31 EGP). Plastic boxes were distributed to the residents to cultivate vegetables and plastic barrels to grow fruits and shrubs with the needed drip irrigation system. Additionally, weekly agronomist supervision was planned [24]. Figure 2 shows an example of the rooftop cultivation system in a rural house [25].

The Cairo governorate launched another initiative to apply in Nasr City, Misr Algadeeda, Zamalek districts, and the Schools in the Sharaabiah district. Different systems of green roofs have been used, including the usual potted plants, plastic boxes, and Nutrient Film Technique (NFT), as shown in Fig. 3 [26].

The grassroots socio-economic program adopted another initiative implemented in Luxor local communities' development clusters (GRASP: a program that aims to support civil society and is funded by the European Union) in Egypt and the Arab Network for Environment and Development [27]. This initiative adopted the soil-based system (SD), using rectangular wooden boxes lined with plastic tarps and a drip irrigation system, as shown in Fig. 4 [28].

Moreover, Shaduf (https://schaduf.com/) is a sustainable green solutions start-up founded in Egypt in 2011. Shaduf has adopted profitable crops to encourage low-income families to rooftop cultivation and has provided agricultural supervising, training, plants, and planting systems. Sakiet Mekky, Ezbet Naser, Maasarah, and Dar El-Salam are neighbourhoods included in the Shaduf

**Fig. 2** Roof cultivating in Sonbat village [25]

**Fig. 3** Roof cultivating in Cairo [26]

**Fig. 4** Roof cultivating in Luxor [28]

initiative. Different systems have been adopted: the deep-water culture (DWC), SD, and NFT [29]. Table 1 summarizes the local initiatives used in cultivation systems, as shown in Fig. 5 [30].

The manuscript undertakes a detailed examination and comparison of different rooftop planting systems in urban areas of Egypt, emphasizing their environmental and economic implications. It presents a user-friendly tool created by a thorough analysis and employing the Analytical Hierarchy Processes (AHP) methodology to help choose appropriate systems aligned with individual preferences. This tool is powered by Python code and has

**Table 1** local green roof Egyptian initiatives summary

| The Initiative Name | Location | Governmental/Private | Used System |
|---|---|---|---|
| Dignified Life | The Sonbat Village | Governmental | Soil-Based Plastic Boxes |
| Cairo Governorate | Cairo Districts | Governmental | NFT Systems |
| GRASP Egypt and RAED | Luxor | Governmental + Private | Soil-Based Wooden Boxes |
| Shaduf | Cairo Districts | Private | DWC + NFT + Soil-Based Pots |


**Fig. 5** The Schaduf initiative used systems [30]

been made available online for the benefit of decision-makers and researchers. The manuscript makes a notable contribution to the current body of knowledge by investigating various factors affecting user choices across multiple domains, providing a pragmatic avenue to further urban greening efforts in Egypt.

## 2 Methodology

In order to achieve the research objectives, several steps have been conducted. This research focuses on investigating the most common rooftop cultivation systems in Egypt. Accordingly, an extensive survey has been conducted for the decade's most used green roof systems. An online search was performed about the news of green roof initiatives in the past ten years. Three types of green roofs have been found repeated in different initiatives. Those systems were SD, NFT, and DWC. After that, criteria were determined based on literature review to compare the selected green roof types. Initial cost, beginner friendly, water saving, ease of maintenance, and heat gain reduction are the comparison selected criteria. In order to fulfil the measurements that reveal the records of each system, different methods have been used. A literature review, expert opinion collection, and design computational simulation using Design Builder software are used. In order to compare the different systems and choose the most suitable one, the AHP method has been used to weigh the different comparison factors, resulting in the relative weight for different systems using different user preference scenarios. Figure 6 illustrates the research framework, including different steps and methods.

### 2.1 Selected green roof systems

A web-based search was conducted to gather information on green roof initiatives over the past decade. Three distinct types of green roofs were identified as common themes across various initiatives to be compared and analyzed. Egypt's most common roof cultivation systems are SD with different materials and potting shapes, NFT, and DWC systems. The following system shows the description and details of each system. The SD is the typical type of green roof that uses soil as the growing medium for plants. SD green roof systems typically include a layer of soil, a layer of drainage material, and a layer of plants. The soil layer is usually about 15 cm deep and comprises a mixture of soil, compost, and other materials suitable for plant growth. The plants used in an SD green roof system are hardy species well-suited to growing in the limited space and exposed conditions of a rooftop environment. Figure 7 shows the details of the SD system and an example photo [28].

The NFT is a type of hydroponic growing system that continuously uses a thin film of nutrient-rich water to flow over plants' roots. It is often used to grow small, fast-growing plants such as lettuce, herbs, and other leafy greens. The NFT system consists of a shallow channel or trough filled with a nutrient solution and a sloping surface to allow the solution to flow over the roots of the plants. The plants are supported by a growing medium, such as perlite or coconut coir, which helps to anchor the plants and provides some additional moisture and nutrients. The main advantage of using an NFT system for a green roof is that it allows for the cultivation of plants in a relatively small space with minimal water and nutrient inputs [26]. NFT is the least stable system and needs intensive monitoring, making it unsuitable for beginners [31]. Figure 8 shows the details of the NFT system and an example photo [26].

DWC is a hydroponic growing system that uses a nutrient-rich water solution to grow plants in a submerged environment. In a DWC system, plants are suspended in airtight containers filled with water and nutrients, and their roots are allowed to grow down into the water. An air stone or other oxygenation device gives the plants the

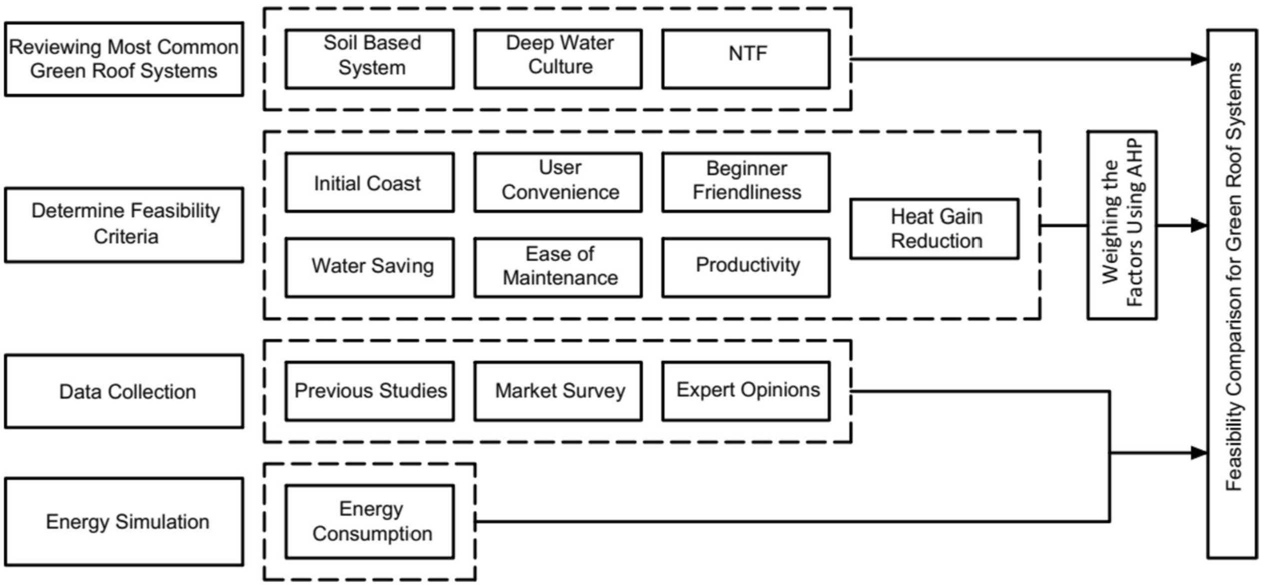


**Fig. 6** Research methodology framework

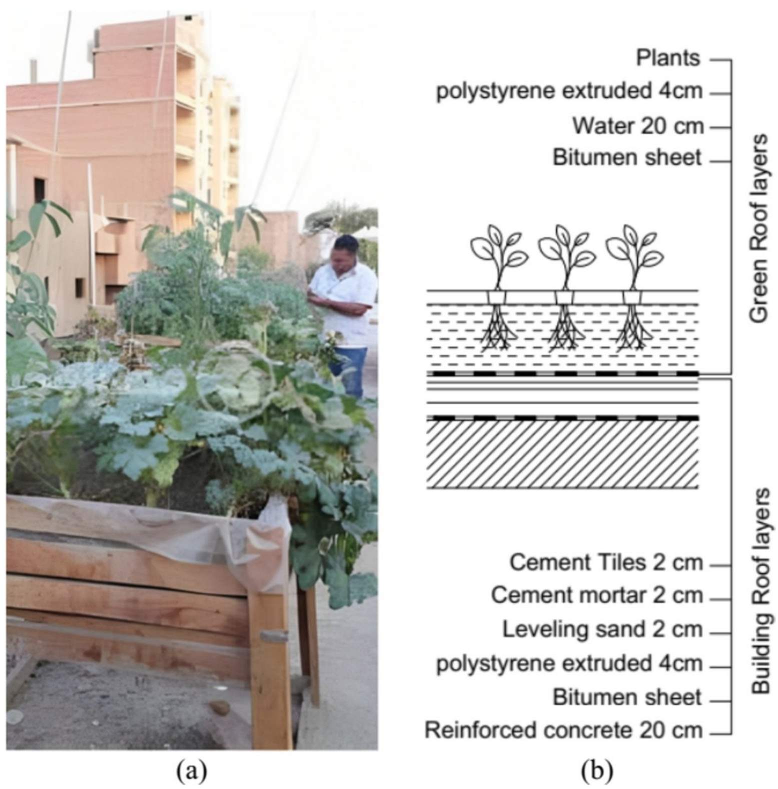


**Fig. 7** **a** Soil-based green roof system [28], **b** Illustrative cross section for SD (authors)

oxygen they need to survive. In a DWC green roof system, the DWC hydroponic system is incorporated into a green roof design to grow plants on the roof of a building. The DWC system consists of a container or trough filled with water and nutrients, and the plants are suspended in the water. The plants are supported by a growing medium, such

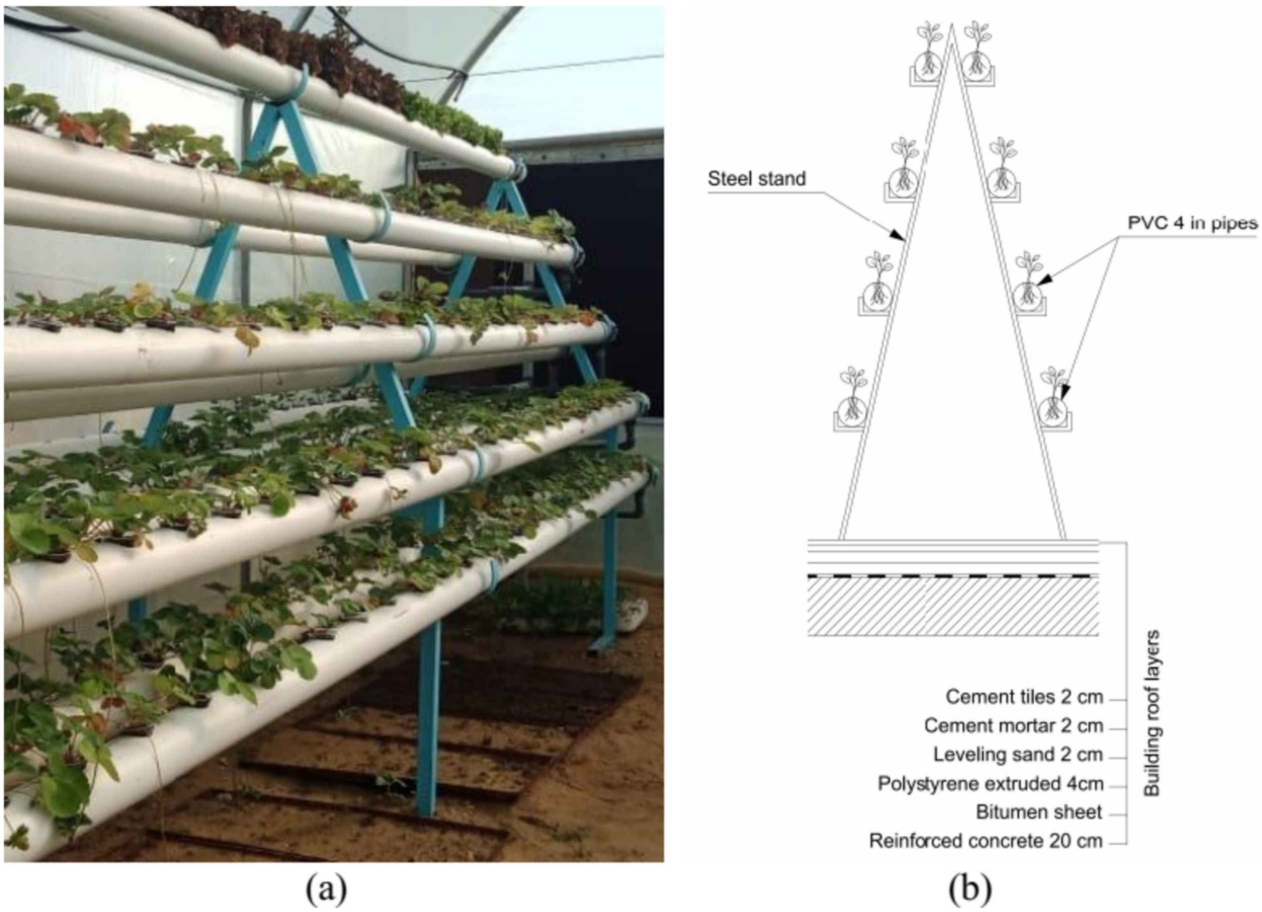


**Fig. 8** **a** The NFT green roof system [26], **b** Illustrative cross section for NFT (authors)

as perlite or coconut coir, which helps to anchor the plants and provides the needed nutrients. The main advantage of using a DWC system for a green roof is that it allows for the cultivation of plants in a relatively small space with minimal water and nutrient inputs. DWC is easy to set up, beginner-friendly, cost-effective, and does not require much monitoring. It is a suitable choice for growing medium-sized vegetables or fruits. Its disadvantage is that the large volume of water could be a hub for mosquitoes to reproduce [32]. Growing a plant in soil is easier and more forgiving than soilless systems, especially for beginners. The plant grows slower, requires less maintenance, and adjusts the soil and gives the plant a better flavor, but on the other hand, it has a longer cycle, less productivity, and more extensive space requirements [33]. Figure 9 shows the details of the DWC system and an example photo [29].

### 2.2 Green roof system analysis criteria

In order to compare those systems in terms of productivity, water saving, beginner-friendly, ease of maintenance, and suitability for retrofitting, an agricultural literature review was performed.

#### *2.2.1 Initial cost*

The initial cost of any procedure is a crucial factor in encouraging to take steps toward its implementation. Although there is a rewarding profit from the green roof, the higher initial cost is considered a barrier that reduces the spread of such initiatives. This research investigates the initial cost of the three systems through the market survey. Price quotations were requested from three companies to implement the three different cultivation systems on a rooftop with an area of 245 $m^2$. The quotations include manufacturing the cultivation units and do not include the plants or the seeds. Also, the irrigation network was considered. Then, the average price per square meter was calculated for the three systems. Table 2 illustrates the initial cost survey for different systems.

#### *2.2.2 Beginner friendliness*

The extent of friendliness and ease of dealing with roof cultivation systems, especially for beginners, is one of the most important factors affecting the spread and continuity of such initiatives. In this study, the level of beginner

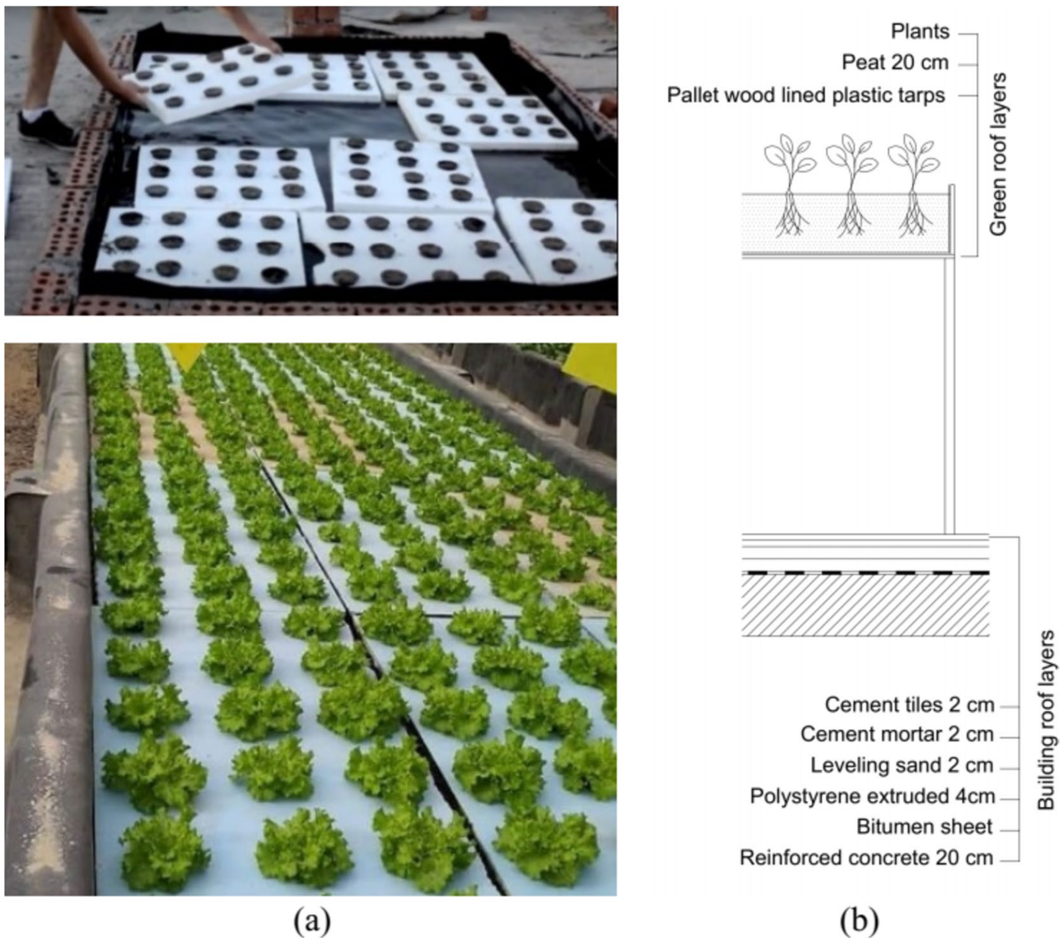


**Fig. 9** **a** The DWC green roof system [29], **b** Illustrative cross section for DWC (authors)

**Table 2** Initial cost survey for different systems

| System | Company 1 | Company 2 | Company 3 | Average Price |
|---|---|---|---|---|
| NFT | 225,000 | 250,000 | 265,000 | 972 EGP $m^{-2}$ |
| DWC | 28,000 | 30,000 | 33,000 | 124 EGP $m^{-2}$ |
| SB | 82,000 | 85,000 | 90,000 | 105 EGP $m^{-2}$ |

**Table 3** Level of beginner friendliness for different systems

| System | SB | DWC | NFT |
|---|---|---|---|
| Beginner Friendliness | Easiest (100%) | Moderate (50%) | Hardest (20%) |

friendliness has been investigated from previous studies. The extent of beginner friendliness depends on experts' and users' opinion surveys. Accordingly, the level of beginner friendliness has been determined, as shown in Table 3. The experts' and users' opinions have adopted a percentage value to be used in the analysis.

#### *2.2.3 Water consumption*

Water consumption is crucial in determining the appropriate cultivation system, especially considering water-deficient conditions [6, 7]. Based on the previous studies, the water consumption in the different systems has been compared. Variables like the planting type, the climatic zone, and seasons may affect the water consumption for the same cultivation system [34, 35]. A research paper established that hydroponics consumes 25% of the conventional cultivation [36]. Another study confirmed that hydroponics could use 10% of traditional cultivation water consumption depending on climatic conditions which go in line with the previous study [31]. Hydroponics not just consume less water compared to soil-based cultivation but also doubles the production of soil-based [37, 38]. In addition to water saving a study have proofed that hydroponics raised carotene contents in tomatoes compared to soil-based [39]. DWC consumes 50% water less than modern systems like Drip Irrigation in Green House and Drip Irrigation in Open Field [40, 41]. Table 4

**Table 4** Water consumption comparison according to literature

| Cultivation System | Relative Water Consumption | Benefits | Reference |
|---|---|---|---|
| Hydroponics | Consumes less than 25%water compared to soil-based cultivation and doubles production | Uses recycled water, can be used in arid regions, produces fish and plants | [37, 38] |
| Deep Water Culture | Consumes 50% less water than drip irrigation systems used in greenhouses and open fields | Water-efficient | [41] |
| Nutrient Film Technique (NFT) | Uses 20–50% less water of conventional cultivation | Water-efficient, can be used in a variety of climates | [40] |

**Table 5** Water consumption for different systems

| System | SB | DWC | NFT |
|---|---|---|---|
| Water Consumption (L $kg^{-1}$ $d^{-1}$) | 3.1 | 3 | 1.1 |

**Table 6** Level of ease of maintenance for different systems

| System | SB | DWC | NFT |
|---|---|---|---|
| Ease of Maintenance | Moderate (50%) | Easy (60%) | Very Easy (90%) |

compares the water consumption in different green roof cultivation systems according to the previous research papers. The current study depended on the results of the previous one as it compares between the three studied systems in term of water consumption. The rest of literature compares two systems, or systems different from the studied ones, or it compares them in terms of elements other than water consumption. Also, Table 5 indicates this research's adapted water consumption rate to compare different systems.

### *2.2.4 Ease of maintenance*

The system that needs more maintenance is the SD system, as gravel increases maintenance and labor costs increase, while the DWC and NFT have a lower level of maintenance [37]. The ease of maintenance has been determined depending on previous research reviews, experts, and users' opinions surveys. Accordingly, the level of maintenance easiness has been determined, as shown in Table 6. Also, a percentage value has been adopted by the experts' and users' opinion survey to be used in the MCDM analysis.

### *2.2.5 Productivity*

Some research has found that the productivity of the NFT system in tomatoes is 23–33% higher than SD system production [42]. Another study proved that DWC and NFT systems had higher production in lettuce than SD systems [40]. NFT and DWC have differed in productivity, so one outperformed the other in some experiments and the other outmatched in others. Table 7 illustrates the production cost and benefit–cost ratio for different systems, which was concluded by Majid et al. 2021 [40]. In order to compare the systems regarding productivity, the benefit–cost ratio has been adopted in this study.

**Table 7** Productivity and benefit–cost ratio for different systems

| System | SB | DWC | NFT |
|---|---|---|---|
| Total Production Cost (USD) | 274 | 236 | 220 |
| Benefit–Cost Ratio | 1.6 | 2.1 | 2.15 |

### *2.2.6 Heat gain reduction*

In order to have a holistic perception of the green roof system use, the effect of each system on the heat gain from the roof has been investigated. The previous studies have proven that using a green roof reduces heat transmission, which affects the energy reduction needed to achieve thermal comfort in the building. In this study, the building was computationally simulated using the three systems conducted by Design Builder software, the most widely used and adopted energy simulation tool [43]. An office building has been chosen to conduct the simulation, and the location has been determined in the new urban extensions of greater Cairo. The area of the office building floor is 3240 $m^2$, including the office area and the horizontal and vertical moving elements, as shown in Fig. 10. The simulation was performed four times to compare the traditional roof (Base case): the roof area is covered by the SD, DWC, and NFT system, respectively. The used material layers sections are indicated in Figs. 7, 8, 9. For the activity schedule, eight hours (From 8 AM to 4 PM) for five days in the week (From Sunday to Thursday) have been assigned. The simulation used a central HVAC system with 24 and 28 °C set points. Simulation measurements were taken for the floor below the rooftop, which is the most affected floor by the green roof system. The simulation result shows that all systems significantly impact energy consumption compared to the base case on the top floor of the building, as shown in Figs. 11 and 12, where the DWC system has a significant record of energy reduction.

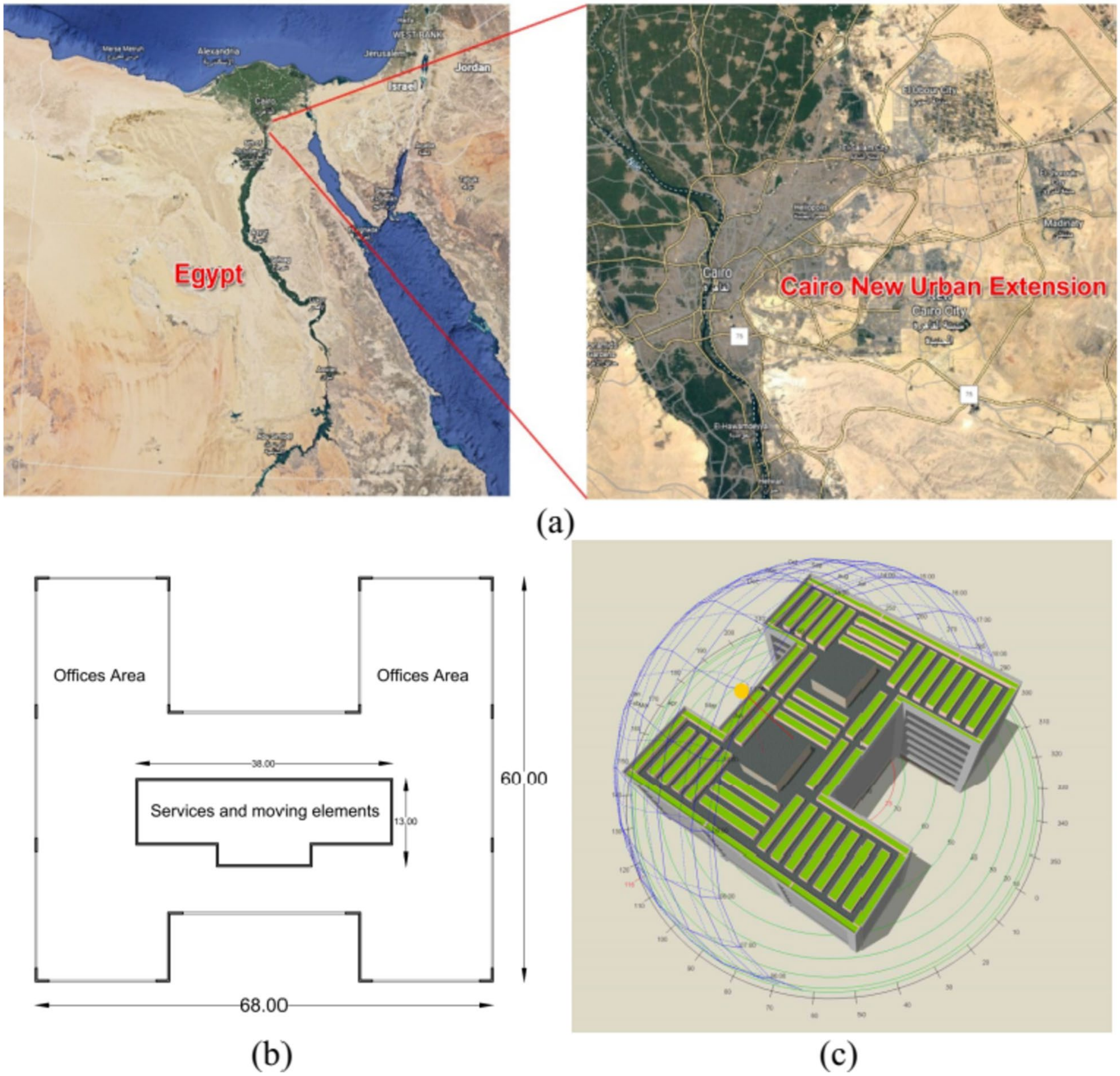


**Fig. 10** **a** Chosen location for simulation (Google map), **b** Building plan, and **c** Building model in DesignBuilder

## 2.3 Analytic AHP

In order to compare, the different values of the various factors were normalized to the percentage scale. After that, the values of the different factors were collected to produce a single reliable value for comparison between the systems. To compile these values, each factor's relative weight must be considered. AHP was used to calculate the relative weight of the factors. AHP is a decision-making method that helps to prioritize complex decisions. This method was developed by Thomas L. Saaty in the 1980s and has since been widely used in various fields, including business, engineering, and public policy. AHP uses a pairwise comparison process to evaluate each component's relative importance, which involves comparing each component to each other at the same hierarchy level and assigning a numerical value to indicate the degree of preference. Once the pairwise comparisons have been completed, AHP uses a mathematical algorithm to calculate a final ranking of the different components based on the preferences that have been assigned. This ranking can decide which option to choose [44]. In this regard, a scale is used to compare the factors pairwise, with 1 representing equal importance,

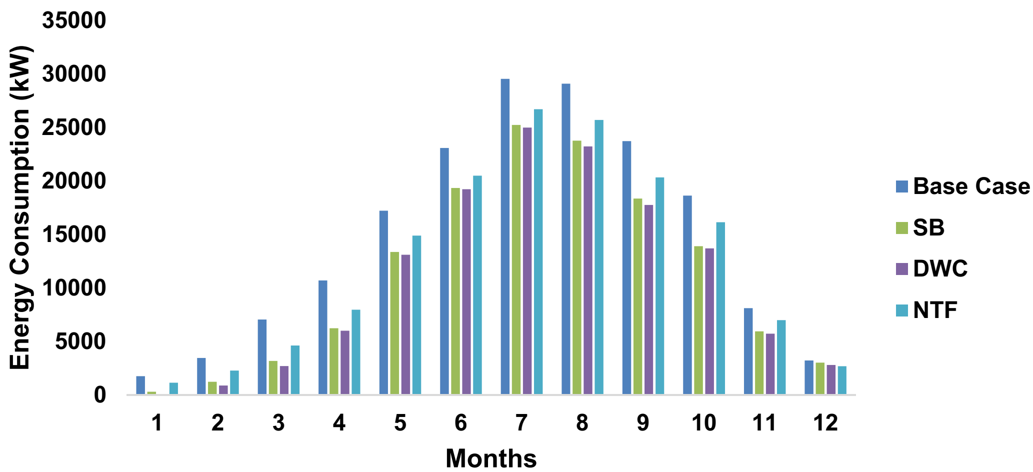


**Fig. 11** The annual energy consumption for different systems

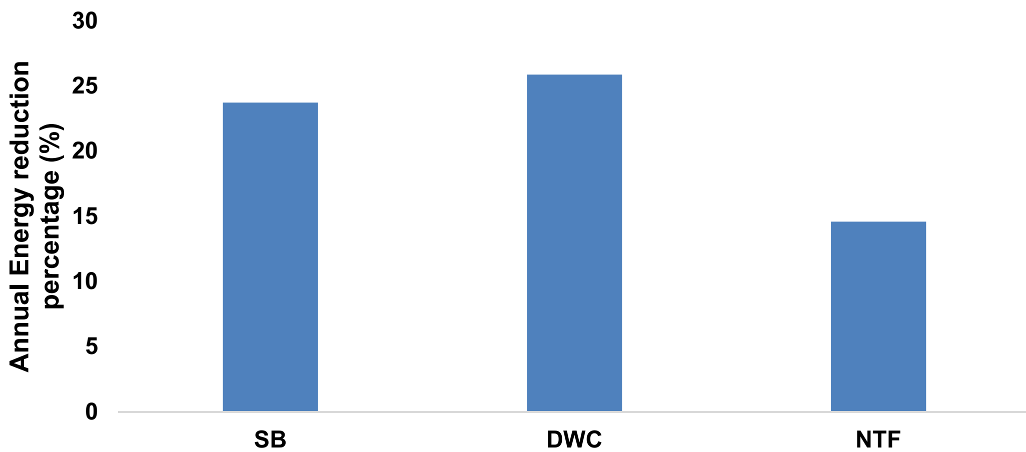


**Fig. 12** The annual energy reduction percentage for different systems

3 representing average importance, 5 representing high importance, 7 representing very high importance, and 9 representing the highest importance. The intermediate values of 2, 4, 6, and 8 reflect compromises between the priority levels. The pairwise comparison matrix is then created, which includes comparing each factor with every other factor. In this matrix, the elements have the characteristics of reciprocity ($E_{ij} = 1/E_{ji}$) where i refers to the elements in raw I, and j refers to elements of column J. The AHP method evaluates the relative importance of each factor in the decision-making process. Then the relative weight of each factor is estimated as the normalized geometric mean of each row to form the conducted matrix. In addition, to measure the consistency of the produced weight, the consistency index has been calculated using Eq. (1):

$$CI = \frac{\lambda_{max} - m}{m - 1} \tag{1}$$

where $m$ is the number of columns or rows, and $\lambda_{max}$ is the largest eigenvalue. Also, the consistency ratio ($CR$), which is used to check the consistency of the pairwise comparison matrix, is represented by Eq. (2):

$$CR = \frac{CI}{RI} \tag{2}$$

where $RI$ is the random consistency index, and the values of the $RI$ for the different number of criteria are given in Table 8. The value of $CR$ has to be less than 0.1, which means that the pairwise comparison matrix is consistent [45].

## 3 Results and discussion

To choose the most appropriate system, considering the differentiation between different projects, owners, and locations concerning the results obtained for

**Table 8** Values of Random consistency index (RI) at different numbers of criteria [45]

| No. of Criteria | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| Random Consistency Index (RI) | 0 | 0 | 0.58 | 0.9 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

```
Rate the importance of Initial cost compared to Ease of maintenance (1-9): 1
Rate the importance of Initial cost compared to Beginner friendliness (1-9): 4
Rate the importance of Initial cost compared to Water saving (1-9): 5
Rate the importance of Initial cost compared to Productivity (1-9): 3
Rate the importance of Initial cost compared to Heat gain reduction (1-9): 4
Rate the importance of Ease of maintenance compared to Beginner friendliness (1-9): 6
Rate the importance of Ease of maintenance compared to Water saving (1-9): 4
Rate the importance of Ease of maintenance compared to Productivity (1-9): 3
Rate the importance of Ease of maintenance compared to Heat gain reduction (1-9): 2
Rate the importance of Beginner friendliness compared to Water saving (1-9): 1
Rate the importance of Beginner friendliness compared to Productivity (1-9): 1
Rate the importance of Beginner friendliness compared to Heat gain reduction (1-9): 1
Rate the importance of Water saving compared to Productivity (1-9): 7
Rate the importance of Water saving compared to Heat gain reduction (1-9): 2
Rate the importance of Productivity compared to Heat gain reduction (1-9): 2
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**Fig. 13** The input process of pairwise comparison

various factors can influence the decision to select the proper system with different weights. In this regard, the AHP method has been used to estimate the importance of various factors. A novel tool was developed to assess and determine the most suitable green roof alternative for locations in Egypt. The tool leverages the Python programming language and employs an AHP methodology that takes into account the preferences and desires of the individual roof owner. To begin the evaluation process, the roof owner must input their priorities and choices for each factor. Figure 13 shows the input process of pairwise comparison.

By comparing the relative importance of each factor from their perspective, the tool can effectively weigh and analyze the significance of each criterion. The evaluation process utilizes a comprehensive scores table meticulously compiled from observed and collected data. These scores have been normalized, as shown in Table 9, ranging from the highest to the lowest, to ensure fair and accurate comparisons between different surface types. This normalization process aids in maintaining objectivity throughout the evaluation, allowing for unbiased and data-driven decision-making.

By combining the input provided by the roof owner with the normalized scores for each factor, the tool can effectively recommend the most optimal green roof alternative tailored to the specific requirements and desires of the individual. This personalized approach ensures that the final green roof selection aligns perfectly with the unique needs and preferences of the roof owner, maximizing their satisfaction and the overall effectiveness of the green roof installation. Then, according to the weighting scenarios for different factors, the suitability of the green roof system has been estimated according to the following Equation:

**Table 9** The Normalized percentage (%) values of different factors for green roof systems

| | SB | DWC | NFT |
|---|---|---|---|
| Initial cost | 89 | 87 | 0 |
| Ease of Maintenance | 50 | 60 | 90 |
| Beginner Friendliness | 100 | 50 | 20 |
| Water Saving | 0 | 4 | 65 |
| Productivity | 74.4 | 97.6 | 100 |
| Heat Gain Reduction | 92 | 100 | 60 |

$$Green\ Roof\ System\ Fesability\ Rank = \sum_{i=1}^{n} w_i * R_i \tag{3}$$

where $i$ is feasibility factors, $n$ is the total number of factors, $w_i$ is the relative weight and $R_i$ represents the factor normalized value. Accordingly, the table shows the final rank of different systems in the different users' scenarios. The conducted tool has been published online in the link following GitHub link (https://github.com/bahaamb/Green_Roof_AHP_Tool.git). To evaluate the effectiveness of the implemented tool, two user preference scenarios were simulated. Interviews were conducted with two individuals to gather insights into their preferences, and the AHP pairwise comparison matrix was then filled based on their responses. The outcome of this process is illustrated in Fig. 14, showcasing the resulting weights assigned to each factor. The final comparison of the green roof system highlights the optimal choice for both simulated scenarios.

The results presented in Fig. 14 indicate that in Scenario A, the DWC green roof system is the most suitable, with a record of 66%, followed by the NFT system. The SB system is not deemed appropriate for this scenario. This outcome can be attributed to the user, in this case, emphasizing factors such as productivity, heat gain reduction, and water saving when evaluating green roof systems. The DWC system typically features high water efficiency and productivity, making it an ideal option for users who highly emphasize these factors. In Scenario B, the SB system is the most suitable, with a record of 68%, followed by the DWC system. The NFT system is not deemed appropriate for this scenario. This result can be attributed to the user placing higher importance on heat gain reduction, as the SB system is known for reducing heat gain in the building.

While full validation of green roof selection models remains challenging due to data limitations in the Egyptian context, we argue that the methodology employed in this study provides a scientifically robust basis for its results. The AHP is a well-established multicriteria decision-making technique widely and successfully used to evaluate complex problems with qualitative and quantitative considerations. By structuring the selection process around the most important criteria identified through previous research, our model transparently and logically integrates both objective performance metrics and subjective stakeholder priorities where data is available. We believe that our evaluation is comprehensive, and the results are reliable, as we have considered all the relevant factors and used a well-established decision-making tool.

Also, the model can be validated using user preference tests which have been made. In scenario A, the user inputs show that they are primarily concerned with water savings and heat gain reduction. They have also assigned a high weight to the "Beginner-friendly" factor, which suggests that they are new to green roofs and want a system that is easy to maintain. The proposed system for the user in scenario A is the DWC system. The reason is that the DWC system is the highest-ranked system regarding water savings and heat gain reduction. The DWC system is also relatively easy to maintain, making it a good choice for beginners. In scenario B, the user inputs show that they are primarily concerned with initial cost and ease of maintenance. They have also assigned a high weight to the "Beginner-friendly" factor, similar to the user in scenario A. The proposed system for scenario B is the SB system. The reason is that the SB system is the highest-ranked system regarding initial cost and ease of maintenance. The SB system is also relatively easy to maintain, making it a good choice for beginners. Overall, the model appears to be a valid tool for selecting green roof systems based on user preferences. However, more testing is needed to validate the model on a larger scale and to ensure that it is accurate for a broader range of users and locations.

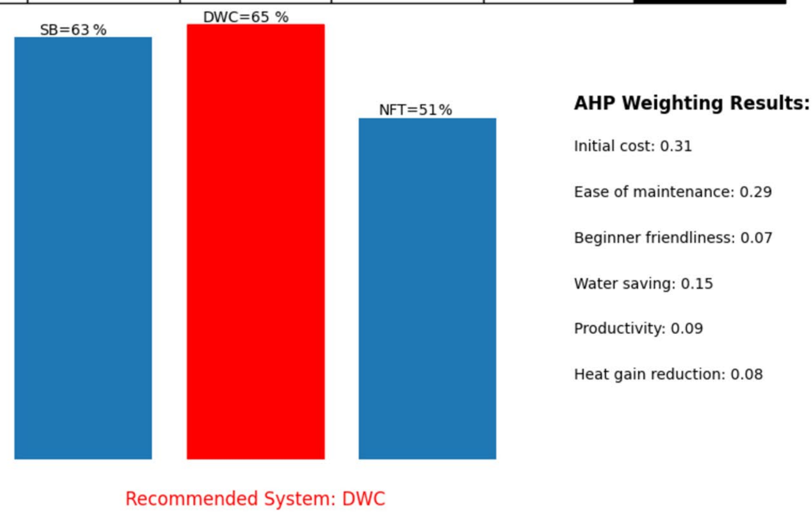
## 4 Conclusions

This research investigated Egypt's most common rooftop cultivation systems and identified the most suitable system based on the criteria: initial cost, beginner friendliness, water saving, ease of maintenance, and heat gain reduction. The research also presented the MCDM framework to help individuals and organizations make informed decisions about the selection of green roof systems based on their specific needs and priorities. The study identified relevant factors and collected relevant data for each system. These factors were weighed using the AHP method to determine their relative importance. The results showed that the DWC green roof system is the most suitable for users who prioritize water savings, heat gain reduction, and beginner friendliness.

The SB green roof system is the most suitable system for users who prioritize initial cost, ease of maintenance, and beginner friendliness. The study has some limitations. First, the data collection was limited to existing green roof projects in Egypt. This means the findings may not be generalizable to all green roof projects in Egypt, especially those in different climatic regions or with different design criteria. Second, the study did not consider green roof systems' long-term performance and maintenance requirements. This is an important consideration, as green roof systems can have a significant lifespan (up to 50 years) and require regular maintenance. This research has some limitations. Future research could address these limitations by expanding the geographical scope of the study to include other regions of Egypt and conducting long-term studies to gain insights into sustainability.

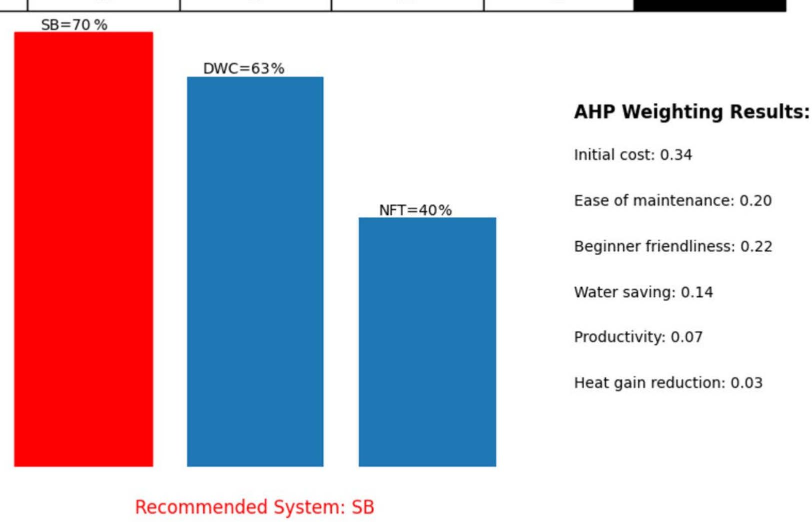
Additionally, future research could explore technological integrations to enhance efficiency and conduct detailed cost–benefit analyses. Overall, this research provides valuable insights into the performance and suitability of different green roof systems in Egypt. The results

| Factors | Initial cost | Ease of maintenance | Beginner friendliness | Water saving | Productivity | Heat gain reduction |
|---|---|---|---|---|---|---|
| Initial cost | | 1.0 | 4.0 | 5.0 | 3.0 | 4.0 |
| Ease of maintenance | 1.0 | | 6.0 | 4.0 | 3.0 | 2.0 |
| Beginner friendliness | 0.2 | 0.2 | | 1.0 | 1.0 | 1.0 |
| Water saving | 0.2 | 0.2 | 1.0 | | 7.0 | 2.0 |
| Productivity | 0.3 | 0.3 | 1.0 | 0.1 | | 2.0 |
| Heat gain reduction | 0.2 | 0.5 | 1.0 | 0.5 | 0.5 | |




Senario A

| Factors | Initial cost | Ease of maintenance | Beginner friendliness | Water saving | Productivity | Heat gain reduction |
|---|---|---|---|---|---|---|
| Initial cost | | 3.0 | 2.0 | 8.0 | 2.0 | 7.0 |
| Ease of maintenance | 0.3 | | 1.0 | 7.0 | 3.0 | 6.0 |
| Beginner friendliness | 0.5 | 1.0 | | 7.0 | 5.0 | 4.0 |
| Water saving | 0.1 | 0.1 | 0.1 | | 7.0 | 9.0 |
| Productivity | 0.5 | 0.3 | 0.2 | 0.1 | | 2.0 |
| Heat gain reduction | 0.1 | 0.2 | 0.2 | 0.1 | 0.5 | |




Senario B

**Fig. 14** The constructed tool results for different users' preferences scenarios can be used by architects, builders, and other stakeholders in the construction industry to make informed decisions about green roof system selection for specific projects. Future research can build on this work to address the limitations and further enhance our understanding of green roof systems in Egypt.

#### Authors' contributions
Mahmoud Desouki: Conceptualization, Methodology, investigation, writing, supervision. Mai Madkour: Validation, formal analysis, writing, supervision. Ahmed Abdeen: Simulation, visualization. Bahaa Elboshy: Conceptualization, Methodology, writing, review and editing, visualization, supervision. All authors have read and agreed to the published version of the manuscript.

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#### Availability of data and materials
The data that supports the findings of this study are available within the article.

## Declarations

#### Competing interests
The authors declare no conflict of interest.

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## Publisher's Note