Hydroponic Planted Roofs as a Tool to Improve Socio-Economical Sustainability and Living Conditions.

A case in middle-income communities.

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Abstract. This study explores the potential of hydroponic systems in addressing climate change by promoting urban food systems, encouraging community involvement, and enhancing thermal comfort. It focuses on middle-class areas in Egypt and uses a comprehensive analysis of literature, defining hydroponic systems, and explaining seeds growing medium. Empirical techniques, including structured interviews with 12 Egyptian hydroponic experts (with 4–15 years of experience), are used to verify the conclusions drawn from the literature, focusing on sustainability, system components, and crop selection criteria. Comparative studies are conducted to assess the socio-environmental advantages of hydroponic case studies. AI simulation techniques were performed using Climate Studio for Rhino, modeling building performance and evaluating the impact of hydroponic systems on indoor thermal comfort and energy consumption. The results demonstrate significant socio-economic and environmental advantages of hydroponic systems, providing useful information for sustainable design guidelines. The research advances urban agriculture techniques tailored to the unique challenges faced by middle-class communities in Egypt, enhancing the resilience of the country against climate change.

1. Problem Definition

Climate change is a global concern due to its rapid environmental changes, leading to an unstable, dangerous future. Families in these communities are in desperate need of new solutions to improve the environment, reduce electricity consumption, support overall health, create new income sources, and engage society in environmental awareness.

While green roofs may not be applicable in Egypt due to its limited support for green roofing loads “as existed Egyptian residential buildings cannot support regular green roofing loads because, it requires approximately 400 kg/m² for 10cm in depth soil thickness and the Egyptian roofs have been designed to withhold a cover load of 200 kg/m²[1], [2], hydroponic planted roofs could be a socio-economical solution for middle-income communities, creating jobs, increasing thermal comfort, and engaging society in environmental awareness[3]. The thesis aims to:

1.1 To identify the urban farming definition, benefits, and challenges.

1.2 To describe the structure of different hydroponic system and the required services to maintain it.

1.3 To identify the guidelines for selecting the crops besides their advantages and disadvantages.

1.4 To study the direct effect of hydroponic system environmentally using AI simulation tools.

1.5 To conduct an economic analysis for implementing hydroponic system.

2. Introduction

Urban farming is a sustainable solution to urban growth and environmental sustainability, combining traditional agricultural knowledge with modern technology. It uses hydroponic systems to transform rooftops into green spaces, reducing greenhouse gas emissions and promoting social and economic sustainability[4].

However, research in Egypt lacks clear guidelines for implementing hydroponic systems. Middle- income communities can benefit from urban farming due to increased motivation, environmental awareness, and financial capability[5]. Proper study of these factors can maximize the benefits and improve overall well-being.

3. Research Methodology

The research methodology will involve collecting a database from literature review, analyzing urban farming's impact on sustainability, understanding its benefits and challenges, and analyzing hydroponic systems. It will also study Egyptian codes and regulations and crop selection criteria. The collected data will provide preliminary guidelines for designing a hydroponic planted roof.

Additional approaches include structured interviews with 12 experts in hydroponic agriculture, where they ranked key criteria to evaluate system components and crop selection. A comparative analysis between three international case studies was conducted, focusing on environmental impact, system design, and technological adaptation. AI-driven simulation techniques using Climate Studio on Rhino software were employed to measure indoor thermal comfort improvements and changes in building energy consumption before and after implementing hydroponic systems.

4. Literature Review

4.1 Urban Farming definition

Urban farming, or urban agriculture, involves growing, processing, and selling food within cities using methods like rooftop gardens, community plots, vertical farms, and hydroponic systems. As urban populations

4.1.1 Benefits Of Urban Farming

Economically, urban farming creates jobs across the agricultural value chain, reduces the need for long-distance food transportation, and repurposes neglected urban spaces, boosting property values and attracting investment[6],[7]. The sale of local produce supports businesses and entrepreneurial ventures, enhancing the economic vitality of urban communities. Environmentally, urban farming lowers the carbon footprint associated with food transportation, mitigates the urban heat island effect by increased green spaces, promotes water conservation and efficient resource use. By utilizing vacant lots and rooftops, it reduces urban sprawl and preserves natural habitats, enhancing biodiversity and air quality[8].

4.1.2 Urban Farming Challenges

However, urban farming faces challenges such as limited space in densely populated areas, soil contamination from industrial activities, water scarcity, and pests and diseases. High initial investment costs and labour-intensive maintenance can deter participation, while regulatory compliance with local land use, water usage, and waste disposal adds complexity.

Urban farms may also be exposed to air and noise pollution from traffic and industrial activities, potentially affecting plant health and posing risks to farmers. Despite these challenges, urban farming plays a crucial role in sustainable urban development, enhancing food security, stimulating local economies, and promoting environmental sustainability[9].

4.2 Hydroponic Systems: Innovating Urban Agriculture

Hydroponic systems represent a transformative approach to agriculture, particularly in urban settings where space and resources are limited. These systems leverage soil-free cultivation, relying on nutrient-rich water solutions to foster plant growth.

By directly supplying essential nutrients to plant roots, hydroponics enhances water efficiency, using significantly less water than traditional farming methods[10]. This efficient use of water is crucial for sustainability, especially in regions facing water scarcity challenges

4.2.1 Types of Hydroponic Systems and System's Key Components

Hydroponic farming offers several systems tailored to different needs and scales. The Wick System is ideal for beginners with its passive, pump-free design, best suited for smaller projects due to nutrient limitations. Water Culture uses floating platforms to support plants with submerged roots in nutrient solution, ideal for leafy greens and herbs[11]. The Ebb and Flow System alternates flooding and draining nutrient solution, offering scalability and high yields. Drip Systems deliver nutrients directly to roots via tubes, ensuring precise control and efficient water use. The Nutrient Film Technique (NFT) provides a shallow, continuous flow of nutrient water over roots, optimizing water use and promoting aerobic conditions. Aeroponic Systems suspend roots in air, misting them with nutrients for maximum oxygenation and absorption. These systems illustrate hydroponics' versatility in enhancing plant growth efficiency and sustainability. In addition, to establish a hydroponic setup, essential components include a reservoir for nutrient solution, growing containers filled with a suitable medium, a water pump for circulation, tubing and fittings for nutrient distribution, optional grow lights for indoor setups, and tools for monitoring pH and nutrient levels. These components ensure optimal conditions for plant growth and efficient resource utilization [12].

4.2.2 Challenges of Hydroponic Farming

Despite its benefits, hydroponic farming faces challenges such as high initial setup costs, technical expertise requirements for nutrient and pH management, and energy consumption from artificial lighting in indoor setups. Disease management and customer acceptance of hydroponically grown produce also pose obstacles [13].

4.2.3 Sustainability Aspects

Hydroponic systems offer significant environmental benefits across several key sustainability metrics. They optimize water usage by recirculating nutrient solutions and delivering them directly to plant roots, thereby reducing water loss by 70-80% compared to traditional agriculture, crucial for sustainable food production in water-scarce regions[14].

Energy consumption in hydroponics, influenced by factors like grow lights and climate control systems, can be mitigated through the integration of renewable energy sources such as solar power, enhancing overall sustainability. [15].

Adopting sustainable practices like composting and recycling can effectively address these challenges. Continued adoption of energy-efficient practices and localized production methods will further reduce greenhouse gas emissions, supporting environmentally friendly agricultural practices for the future.

4.2.4 Growing Medium in Hydroponic Systems

Hydroponic systems utilize specialized growing media such as rockwool and coco peat to support plant growth. Rockwool, made from basalt rock and chalk, offers excellent water retention and nutrient absorption capabilities, providing a stable environment for roots.

Coco peat, derived from coconut husks, is lightweight, pH-neutral, and environmentally sustainable, promoting healthy root development and efficient nutrient uptake. Both media allow for precise control over growing conditions, contributing to the success of hydroponic crops in various climates and settings [16].

4.2.5 Selected Crops for Hydroponics

Lettuce and cherry tomatoes are popular crops grown in hydroponic systems due to their efficient use of space and resources[16]. Lettuce thrives with minimal nutrient requirements and fast growth rates under controlled conditions, requiring pH levels between 5.5-6.5 and specific lighting and temperature conditions.

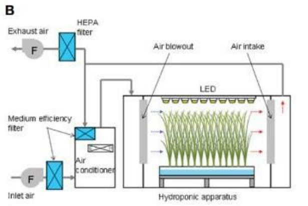
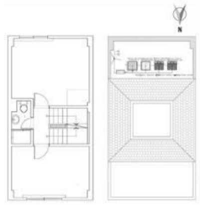
Cherry tomatoes benefit from precise nutrient delivery and environmental control, with pH levels also between 5.5-6.5, appropriate lighting, and structural support to manage fruit[10]. Both crops are chosen for their high yields and suitability for hydroponic cultivation, contributing to sustainable and efficient farming practices.

5. Experimental Work and Main Results

5.1 Case Studies.

The selection of research case studies was guided by rigorous criteria aimed at comprehensive analysis and comparison. Each case study had to be implemented on rooftops to explore the feasibility of urban hydroponics. Variation in hydroponic systems within each case allowed for nuanced comparisons, highlighting system efficiencies and technological adaptations. Different crop selections across cases provided insights into diverse crop requirements and growth dynamics in hydroponic environments. Environmental and economic studies were integral, assessing the systems' sustainability and cost-effectiveness. Each case study focused on distinct aspects or components, facilitating thorough analysis of their impact on system performance and efficiency as shown in table 1

Table 1. Case Studies Comparison (by Author, 2024).

Aspect	Case Study 1	Case Study 2	Case Study 3
Location	Giza, Egypt	Kyoto, Japan	Taichung, Taiwan
Date of Establishment	2020-2021	2017-2018	2016
Picture			
Project Description	A smart hydroponic greenhouse to maximize food production under the challenges of climate change, COVID-19, and natural resource shortages.	Focus on assessing the thermal mitigation effects of hydroponic rooftops on urban buildings during the summer. The study aimed to quantify temperature moderation effects	It targeted the needs of the growing cattle population and aimed to provide an alternative source of income for farmers while enhancing resilience to environmental challenges
System Explanation	utilized NFT and DFT techniques. It incorporated a range of sensors and actuators, enabling precise control. Data collected was transmitted to a web platform for real-time monitoring and analysis.	circulatory system with open pools and tanks on a rooftop. It employed sensors to monitor environmental conditions and ensure optimal growth conditions. minimize water usage.	utilized cement planks with glass tanks placed on a flat rooftop. The setup included multiple stages for testing thermal performance and evaluating different water depths
Type of Crops	Lettuce seeds	Rice	Nephrolepis exaltata &Acorus calamus
Environmental Impact	enhance thermal comfort and reduce electrical consumption.	mitigate urban heat island effects and enhance building energy efficiency.	reduced water usage, lower irrigation needs, and improved land use.
System Efficiency	High energy efficiency with real-time data monitoring allowing optimized resource management.	Moderate efficiency: passive cooling effects observed but limited by system scalability.	Thermal regulation effects noted, but system maintenance and water depth variability posed operational challenges.
Technological Adaptation	High technological integration (IoT sensors, remote data platforms).	Medium technological integration (basic sensors, manual monitoring backups).	Low-to-medium technological adaptation with basic thermal performance monitoring without real-time data systems.

5.2 Interview

The following presents the findings of interviews conducted with Egyptian experts in the field of hydroponic agriculture. The interviews are structured into four sections, each focusing on various aspects of hydroponic practices.

These sections encompassed awareness and outreach efforts, the sustainability of hydroponic systems, the importance of hydroponic system components, and criteria for selecting growing media and crops. Moreover, the aim of these interviews is to gain insights into the perceptions, experiences, and opinions of experts regarding various aspects of hydroponic systems in Egypt. Through their diverse perspectives and expertise, these experts provide valuable insights that can redirect the previously designed guidelines regarding designing a hydroponic system as shown in table 2.

Table 2. Interview Questions Description (by Author, 2024)

Section Number	Description	Aim
1	General Information	Gather general data including gender, age, and years of experience.
2	Awareness and Outreach	Evaluate the effectiveness and accessibility of educational resources on hydroponics.
3	System's Sustainability	Examine the environmental impact and long- term sustainability of hydroponic systems.
4	Importance of System’s Components	Assess the significance of various components in optimizing hydroponic operations.
5	Growing Media and Crop Selection Criteria	Explore criteria for selecting suitable growing media and crops in hydroponic farming

5.2.1 Conclusion and Findings of The Interview:

5.2.1.1 **Demographics** The demographic profile of experts engaged in hydroponic farming interviews in Egypt reflects a predominantly young cohort, with a significant representation between the ages of 25 to 30. Gender distribution skewed heavily towards male participants, indicating a potential gender gap in the sector that warrants attention for fostering greater diversity and inclusion. While the age diversity supports a breadth of experience and viewpoints, efforts to encourage more female participation could enhance sectoral dynamics and insights.

5.2.1.2 **System Sustainability** Perceptions regarding the environmental friendliness of hydroponic systems in Egypt were generally positive, emphasizing benefits such as water conservation and reduced chemical usage. However, concerns were raised about energy consumption and waste generation associated with the systems. There was divergence in opinions about the potential of hydroponics to completely replace traditional agriculture, reflecting varying perspectives on its scalability and long-term sustainability in the Egyptian context.

5.2.1.3 **Importance of System Components** Key components such as grow trays, nutrient delivery systems, lighting, and monitoring equipment were identified as critical for the success of hydroponic systems. The quality and design of these components were highlighted as crucial factors influencing crop yields and system performance. The role of pH and EC monitoring equipment in maintaining optimal nutrient levels was underscored as essential for effective crop management and resource efficiency.

5.2.1.4 **Growing Media and Crop Selection Selecting appropriate** growing media and crops emerged as crucial considerations for hydroponic farming success in Egypt. Experts recognized the importance of media properties like water retention capacity and pH stability in optimizing irrigation practices and enhancing crop growth. Factors such as plant size, growth rate, root system characteristics were identified as significant criteria influencing crop selection, alongside considerations of compatibility with chosen growing media and the ability to mitigate disease risks.

5.3 Environmental simulation

5.3.1 Simulation Introduction

Climate Studio is introduced as a tool for conducting thermal analysis simulations to compare energy use between a regular roof and one with a hydroponic system.

The simulations aim to provide data on thermal dynamics, energy requirements, and economic viability for hydroponic setups.

The simulation used Cairo's TMY weather data in Climate Studio. Building parameters included a wall U-value of 0.57 W/m²·K, a roof U-value of 0.45 W/m²·K, and double-glazed windows with a U-value of 2.7 W/m²·K and SHGC of 0.45. Internal gains were set at 3.5 W/m², and HVAC systems operated at a COP of 3.2. Heating and cooling setpoints were 22°C and 26°C, respectively.

5.3.2 Case Study Selection Criteria

Al Asmarat neighborhood in Cairo was selected as the case study due to several factors: the scarcity of arable land and green spaces, hot and dry weather conditions suitable for hydroponic systems, and the potential benefits for middle-income families, especially those living in apartments, in terms of easier access to fresh produce.

Community involvement was another key consideration, as hydroponic systems offer opportunities for locals to participate in agricultural and urban greening initiatives. The neighborhood's modular structures, with consistent heights and widths, make them ideal for integrating hydroponic systems, ensuring efficient use of urban space while promoting sustainability and community engagement as shown in figure 1

Figure 1. al asmarat neighborhood (Saleh & Gomaa, 2022)

5.3.3 First Scenario "Plain Rooftop"

The rooftop area is approximately 500 m² for a single-story model. Simulation results show that the building's site Energy Use Intensity (EUI) is 203 kWh/m², higher than the baseline of 156 kWh/m², indicating potential inefficiencies. The operational carbon footprint is 92 $kgCO_2/m^2$, and the energy cost is $16/m². Monthly energy consumption patterns reveal high heating demands in winter months, decreased usage in spring, and increased cooling needs in summer, influenced by temperature variations (15°C to 27°C) and relative humidity fluctuations (40% to 80%) as shown in figure 2 and 3

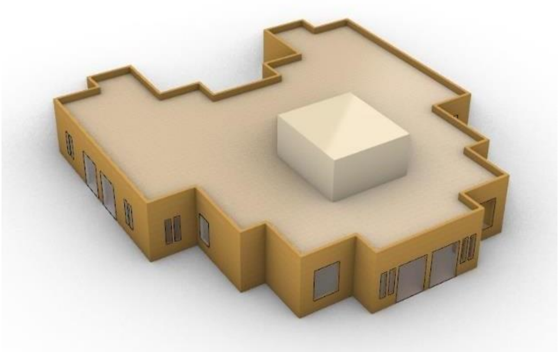


Figure 2. Plain Rooftop (By Author, 2024)

Figure 3. Plain Rooftop Energy Use Intensity (by Author, 2024)

5.3.4 Second Scenario "Hydroponic Planted Rooftop"

Hydroponic System Explanation: The rooftop, totaling approximately 500 m² for a single- story model, accommodates a hydroponic system covering 30% of the area. Each system, occupying 3.75 m², is strategically placed for optimal circulation.

The setup features open grow trays made from recycled plastic crates lined with waterproof plastic sheeting for durability. Coco peat or rockwool serves as the growing medium in net pots, ensuring a uniform layout without complex piping, emphasizing simplicity and adaptability to various environments as shown in figure4. The specific materials and their environmental specifications are detailed in Table 3.

Table 3. Setup Materials Description (by Author, 2024

Material	Description	Specification	Environmental Notes
Recycled Plastic Crates	Used for growing trays	High-density polyethylene (HDPE), UV-resistant	100% recycled material
Waterproof Plastic Sheeting	Lining inside crates	0.5 mm thickness, food-safe polyethylene	Non-toxic, recyclable
Growing Medium	Coco Peat or Rockwool	pH 5.5–6.5, high water retention	Biodegradable (coco peat)
Net Pots	Seedling holders	5 cm diameter, food-grade plastic	Reusable

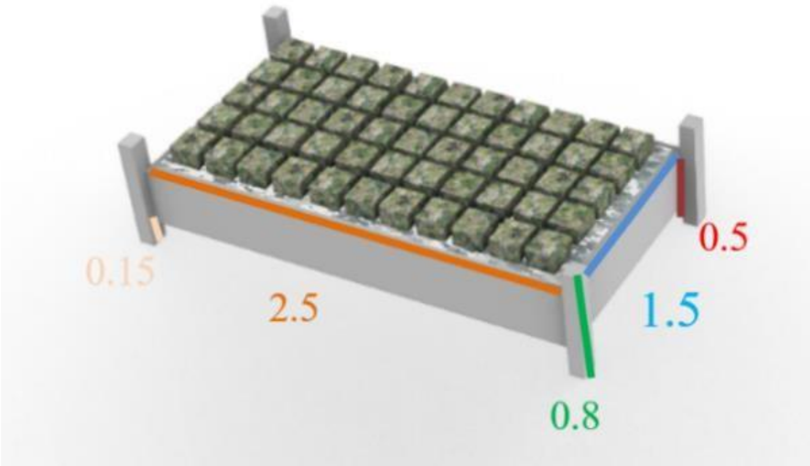


Figure 4. hydroponic system unit (by Author, 2024)

5.3.5 Hydroponic Planted Roof Simulation Results:

Despite covering 30% of the rooftop area, the building's site Energy Use Intensity (EUI) with the hydroponic system is 170 kWh/m², higher than the baseline of 156 kWh/m². The operational carbon footprint improves to 72 $kgCO_2/m^2$, and the energy cost decreases to $12/m². Monthly energy consumption patterns show similar seasonal trends to the plain rooftop scenario, with notable heating demands in winter and increased cooling needs in summer. Temperature ranges and humidity fluctuations also impact energy demands, suggesting opportunities for efficiency improvements to better align with the baseline EUI figure 5 and 6.

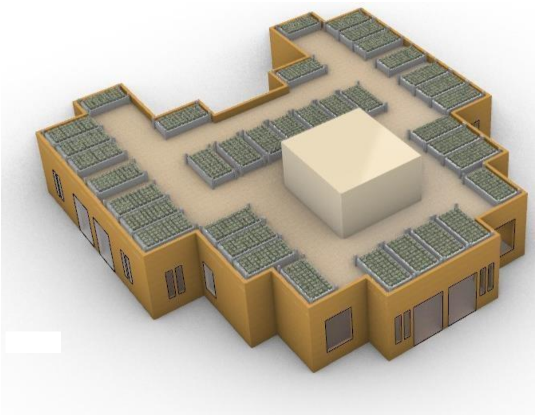


Figure 5. hydroponic planted roof (by Author, 2024)

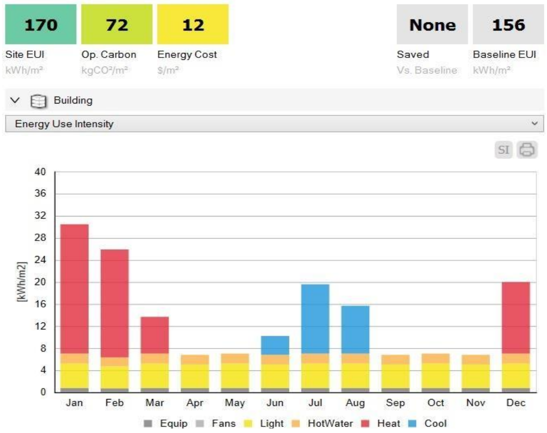


Figure 6. hydroponic planted roof energy use intensity (by Author, 2024)

5.3.6 Simulation Comparison Table

Tables 4 and 5 provide a detailed economic assessment of rooftop hydroponic gardening in residential buildings within a smart city context. Table 4 outlines the initial investment required for setting up a single hydroponic tray, including costs for essential materials such as recycled plastic trays, growing medium, net pots, and necessary equipment like pH and EC meters, water pumps, and timers. It also presents monthly operating costs, covering nutrient solutions, electricity consumption, and water usage. Table 5 extends this analysis by projecting revenue per crop cycle, calculating expected profits based on the yield and market prices of romaine lettuce and cherry tomatoes. The financial evaluation indicates a profit of 3,300 EGP per two-month crop cycle per tray, leading to an estimated annual profit of 19,200 EGP per tray. Scaling up to 40 trays, the model suggests an annual profit potential of 768,000 EGP, demonstrating the economic feasibility and scalability of hydroponic rooftop farming in urban residential settings.

Table 4. Economic Analysis (by Author, 2024}

Aspect	Plain rooftop	Hydroponic rooftop
Site EUI	203 kWh/m²	170 kWh/m²
Baseline EUI	156 kWh/m²	156 kWh/m²
Operational Carbon Footprint	92 $kgCO_2/m^2$	72 $kgCO_2/m^2$
Energy Cost	16 $/m²	12 $/m²
Heating Usage	High in January, February, and November-December; declines March to May.	High in January, February, and December; declines March to May, rises again in November.
Cooling Demand	Increases from June to August.	Increases in July and August.
Relative Humidity	40% to 80%, notable drops in July	40% to 80%, notable drops in July

Table 5 **Economic Analysis with cost (by Author, 2024}**

Aspect	Details	Unit Cost (EGP)	Total Cost (EGP)
Recycled Plastic trays	1 tray	300	300
Waterproof Plastic Sheeting	Area covered: 3.75 m²	180 per m²	675
Coco Peat (or Rockwool)	20 kg	900 per tray	900
Net Pots	55 slots	45 each	2475
Nutrient Solution	5 L	300 per L	1500
pH and EC Meters	1 unit	2250	2250
Water Pump	1 unit	1200	1200
Timer	1 unit	900	900
Support Structure (Tomatoes)	for 1 plant	600	600
Total Initial Cost			**11700**
Operating Costs (Monthly) for 1 Tray			
Nutrient Solution	Monthly supply	300	300
Electricity for Pump	Monthly consumption	600	600
Water Usage (NFT system)	Estimated low consumption	Estimated	50
Replacement of Growing Medium	Quarterly replacement	150	150
Total Monthly Operating Cost			**1100**
Revenue Projection per Crop Cycle (1 Tray, 2 Months)	Expected Yield/Price (EGP)	Amount (EGP)	
Romaine Lettuce	50 heads x 60 EGP per head	3000	
Cherry Tomatoes	20 kg x 120 EGP per kg	2400	
Total Revenue per Crop Cycle			**5400**
Costs vs. Revenue Analysis (2 Months)	Amount (EGP)		
Total Revenue		5400	
Total Operating Costs		2100	
Profit per Crop Cycle			**3300**
Annual Profit Projection (1 Tray)			
Annual Revenue		32400	
Annual Operating Costs		13200	
Annual Profit			**19200**
Annual Profit Projection (40 Trays)			**768000**

6. Finalized Guidelines

The research guidelines for implementing hydroponic planted roofs have evolved significantly from preliminary to updated versions. Initially covering diverse topics like windbreakers and social welfare, the updated guidelines now focus exclusively on core elements crucial for sustainability and hydroponic farming. They delve deeper with specific recommendations informed by case studies and expert evaluations, emphasizing technological integration, environmental controls, and water efficiency. Community involvement, safety regulations, and environmental sustainability are highlighted, reflecting expert input and enhancing relevance to current hydroponic farming practices. The updated guidelines are more adaptable and practical, incorporating real- world insights to benefit practitioners across different environments as shown in figure 7.

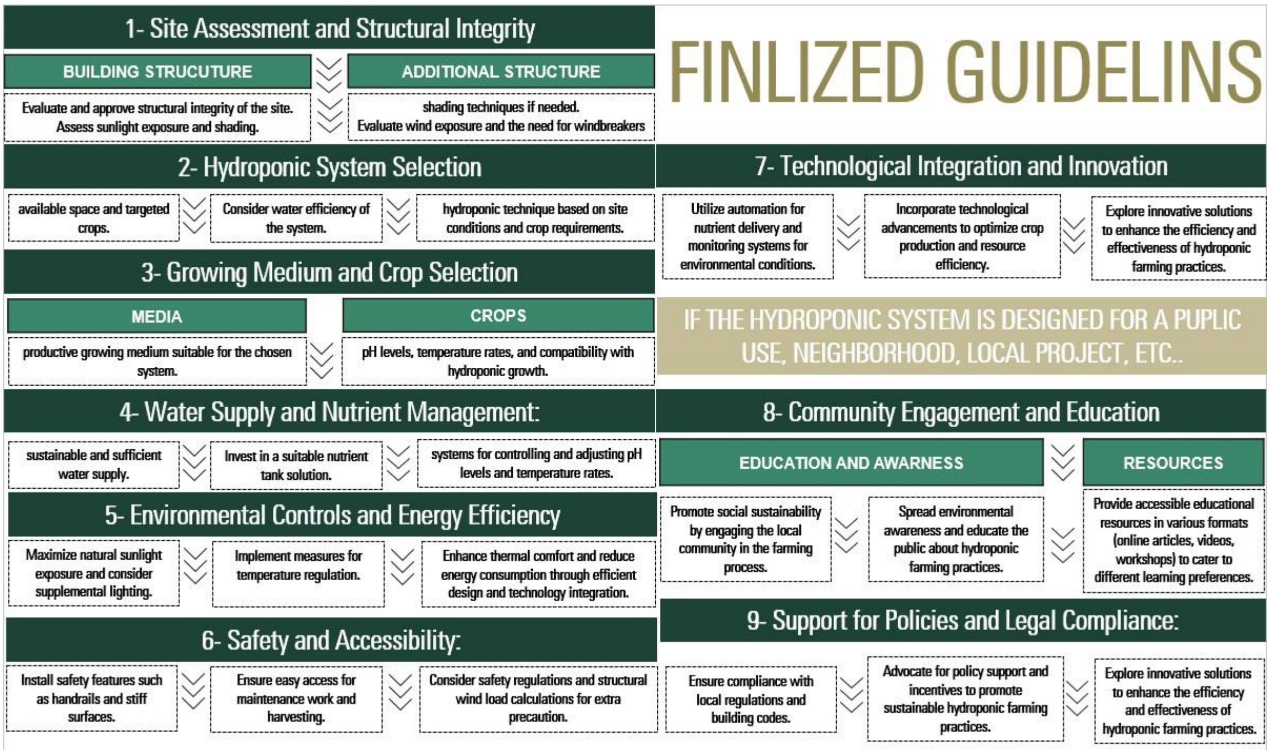


Figure 7. Finalized Guidelines (by Author, 2024)

6.1 Conclusion and Future Development/Improvement

In summary, this study investigates the feasibility and benefits of hydroponic planted roofs in middle-income communities in Egypt. It explores how these systems can enhance socio-economic sustainability and living conditions by:

- Addressing climate change challenges through improved thermal comfort and reduced energy consumption in buildings.
- Creating new economic opportunities through job creation and local food production, thus boosting community resilience.
- Promoting environmental sustainability by conserving water, reducing carbon footprints, and repurposing urban spaces.
- Utilizing AI simulations to optimize system performance and economic viability.

The findings underscore the potential of hydroponic systems to transform urban agriculture, offering a pathway towards sustainable development in Egypt and similar

6.2 Future Recommendation:

- More Studies in Different Tray Materials Effect.
- Study the implementation of hydroponics in terraces.

- Interdisciplinary Collaboration as Foster collaboration between agriculture, environmental, and economics professionals.
- Technology integration by utilizing automation techniques, sensor-based monitoring system and precision in hydroponic farming

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