

Hydroponics as a Green Entrepreneurial Model for Sustainable Food Security in Resource-Scarce Environments

Amjad Mized 

Water Technology Program, Islamic University of Gaza, Palestine
Email: amjadmized@gmail.com (A.M.)

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Abstract—This study examines the potential of hydroponic farming as a sustainable agricultural solution and a driver of green entrepreneurship in the Gaza Strip—a region characterized by water scarcity, high urban density, and political instability. Drawing on a qualitative case study and thematic analysis, semi-structured interviews were conducted, including farmers, agricultural engineers, and policy experts. The study explores how hydroponics addresses key environmental challenges, particularly water usage, and assesses its alignment with the Sustainable Development Goals and entrepreneurship frameworks. Findings reveal that hydroponic systems significantly reduce water consumption—using less than 2.2 m³ per ton of produce compared to over 100 m³/ton in traditional farming. Participants emphasized hydroponics’ ability to enable year-round production, minimize pesticide use, and create viable micro-enterprises, particularly for youth and women. However, barriers such as high initial costs, limited access to nutrient solutions, and gaps in technical training persist. A Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis highlighted both the system’s promise and its vulnerabilities, while comparative analysis with existing literature underscored its relevance to fragile settings. The study concludes with policy recommendations aimed at supporting hydroponics through capacity building, donor engagement, and urban agriculture strategies. This research contributes to academic discourse by integrating environmental efficiency, food security, and entrepreneurship, while offering practical insights for replicating hydroponic models in other resource-constrained environments.

Keywords—hydroponics, green entrepreneurship, water footprint, post-war recovery, food security, sustainability

I. INTRODUCTION

Resource-scarce environments across the globe—including arid climates, limited water availability, urban congestion, or fragile ecosystems—are increasingly facing challenges in maintaining food security and supporting sustainable livelihoods [1]. Traditional agriculture, which is heavily dependent on arable land and freshwater, is proving inadequate in the face of population growth, environmental degradation, and the escalating impacts of climate change [2, 3]. These conditions call for innovative, resource-efficient alternatives that can ensure food production while minimizing ecological strain. These global patterns of environmental scarcity find a particularly acute manifestation in post-conflict zones such as the Gaza Strip, where ecological limitations intersect with political instability and repeated conflict [4].

In particular, the Gaza Strip has endured unprecedented levels of destruction during the 2023–2025 war, resulting in the collapse of critical infrastructure and the decimation of vast areas of agricultural land [5]. Water facilities were heavily damaged, access to irrigation was severely disrupted,

and economic activity came to a near standstill. These impacts have further deepened long-standing structural challenges, particularly acute water scarcity, chronic food insecurity, and one of the world’s highest youth unemployment rates [6]. Even prior to the war, Gaza’s agricultural sector was constrained by limited arable land, poor soil quality, and declining water availability [7]. The post-war situation has exacerbated these conditions, rendering traditional farming increasingly unsustainable. With a growing population and diminishing resources, the region faces an urgent need for innovative, resource-efficient solutions for both food production and livelihood restoration [8].

In response to these challenges, hydroponic farming emerges as a transformative approach to sustainable agriculture. By allowing soilless cultivation that delivers nutrient-rich water solutions directly to plant roots, hydroponic achieves efficient water use, spatial requirements, and higher crop yields [9]. Common systems include Nutrient Film Technique (NFT), Deep Water Culture (DWC), and aeroponics. Recent research highlights significant advancements in hydroponic technologies that improve water and nutrient management, making the method increasingly viable for sustainable agriculture in water-scarce regions [10]. Additionally, a global meta-analysis confirms that hydroponic farming outperforms conventional agriculture in crop productivity, especially under controlled environments, with notable yield improvements demonstrated for crops such as spinach [11]. These findings underscore hydroponics’ potential as an innovative solution to enhance food security and resource efficiency in challenging contexts.

Parallel to this, green entrepreneurship combines principles of environmental sustainability with business innovation, focusing on ventures that generate economic value while minimizing ecological harm [12]. It plays a crucial role in achieving the United Nations’ Sustainable Development Goals (SDGs), particularly in areas of climate action, decent work, and responsible consumption [13]. In conflict-affected and ecologically strained contexts, green entrepreneurship offers a pathway for marginalized populations—especially youth—to engage in regenerative economic activities that rebuild livelihoods without exacerbating environmental degradation [14]. Recent research highlights key trends and opportunities within green entrepreneurship in developing countries, emphasizing the circular economy’s role in promoting resource circulation, clean energy adoption, sustainable farming practices, and eco-innovation efforts [15, 16]. Moreover, regulatory frameworks, social entrepreneurship, and technological advancements are increasingly recognized as critical drivers that can accelerate the transition toward environmentally

conscious and sustainable business models [17]. Integrating these elements in Gaza's post-conflict recovery can empower youth to lead green ventures that not only address unemployment but also contribute to environmental resilience and sustainable development.

Another critical lens in evaluating sustainable agriculture is the water footprint framework. The water footprint is a comprehensive metric used to evaluate the total volume of freshwater used directly and indirectly to produce goods and services. In agriculture, this includes green water (rainwater), blue water (irrigation), and grey water (pollution assimilation) [18]. In Gaza, recent studies assessing the blue and green water footprint [19] as well as the grey water footprint [20] of local crops reveal significant water stress, underscoring the urgent need for innovative approaches to reduce water consumption in agriculture. By comparing the water footprint of hydroponic systems to that of traditional farming, researchers can assess the environmental efficiency and sustainability of different agricultural methods. This tool is particularly relevant for water-scarce regions like Gaza, where optimizing water use is not merely an efficiency issue but a survival imperative.

The convergence of hydroponic agriculture, green entrepreneurship, and water footprint analysis presents a novel interdisciplinary framework for addressing the complex realities of food production and economic recovery in resource-scarce environments [21]. While each of these domains has been studied individually, there remains a noticeable gap in research that integrates them into a unified approach tailored to fragile, ecologically stressed regions such as Gaza.

In contexts where conventional farming is no longer viable due to land degradation and acute water scarcity, hydroponics constitutes a technically and economically viable alternative [22]. When positioned within a green entrepreneurial model, it has the potential to transition from a technical intervention into a strategic platform for environmentally responsible enterprise creation. Coupled with the analytical lens of water footprint assessment, this integrated approach enables a more precise evaluation of environmental performance [7], ensuring that proposed solutions are not only economically viable but also ecologically sound.

This study is significant as it provides a rare integrative lens that merges environmental sustainability with youth-centered economic resilience. It contributes to both academic discourse and policy development by proposing a replicable model for sustainable food systems in ecologically and politically vulnerable regions.

This study seeks to bridge the identified research gap by evaluating hydroponic farming as a green entrepreneurial solution to food insecurity and resource depletion. It explores how the synergy between sustainable agriculture, ecological innovation, and youth-led entrepreneurship can support long-term resilience in stressful environments. By focusing on the environmental efficiency of hydroponic systems—particularly through water footprint metrics—the research aims to determine whether this model can offer a scalable, context-sensitive alternative to traditional agriculture. Ultimately, the study proposes a conceptual and practical framework that aligns with the principles of sustainable development and can be adapted to similar

high-stress contexts beyond Gaza. To investigate this model, the following sections present the methodology employed to evaluate hydroponic performance, entrepreneurial feasibility, and environmental impact within the Gaza context.

II. MATERIALS AND METHODS

A. Study Area Context: The Gaza Strip

The Gaza Strip is a small coastal territory of 365 square kilometers, situated along the eastern shore of the Mediterranean Sea. It is bordered by the 1949 Armistice Line to the north and east, Egypt to the south, and the Mediterranean Sea to the west. Home to more than 2 million people, it is among the most densely populated areas in the world [23]. Gaza's water resources are critically strained. The primary source of freshwater—the coastal aquifer—has been severely overexploited, leading to high salinity and contamination levels that render over 95% of the water supply unfit for human consumption. Alternative sources such as desalination and water imports remain limited, intermittent, and vulnerable to infrastructural disruptions. This chronic water stress directly impacts agricultural productivity and public health [5, 24].

The Gaza Strip, a densely populated and resource-deprived region, has experienced severe environmental and infrastructural damage, particularly following the 2023–2025 war [5]. Agriculture in Gaza presented in Fig. 1, has historically been constrained by limited arable land [25], salinized soils, and acute water scarcity. These issues were exacerbated by the destruction of irrigation systems, croplands, and greenhouses during the conflict. Additionally, high youth unemployment and restricted economic activity position Gaza as a critical case for exploring innovative, sustainable livelihood models [26]. The study area, therefore, provides a relevant and urgent context for investigating hydroponic farming as a scalable, green entrepreneurial solution.

B. Research Design and Conceptual Framework

This study adopts a qualitative case study design, supported by secondary data analysis and environmental modeling. The approach aims to explore the potential of hydroponic farming as a green entrepreneurial solution for food insecurity and water scarcity in resource-scarce and conflict-affected environments. The Gaza Strip is selected as a critical case due to its unique convergence of ecological fragility, political instability, and post-war reconstruction imperatives. This design allows for a contextualized understanding of how hydroponics can contribute to sustainable agriculture and youth-led entrepreneurship under extreme constraints.

The study is further guided by an integrated conceptual framework that brings together three interrelated domains: hydroponic agriculture, green entrepreneurship, and water footprint analysis. Hydroponics is examined not only as a technical innovation [11], but also as a socio-economic mechanism for livelihood regeneration. Green entrepreneurship provides the economic and institutional perspective through which youth engagement, circular economy principles, and post-conflict recovery are addressed [15]. Meanwhile, the water footprint methodology provides a

robust quantitative tool to assess the environmental performance of hydroponic systems, particularly in terms of blue, green, and grey water use.

The framework does not treat hydroponics, green entrepreneurship, and water footprint analysis as isolated concepts, but rather generates insights into the synergistic potential of these elements when applied in fragile, resource-depleted settings such as Gaza.

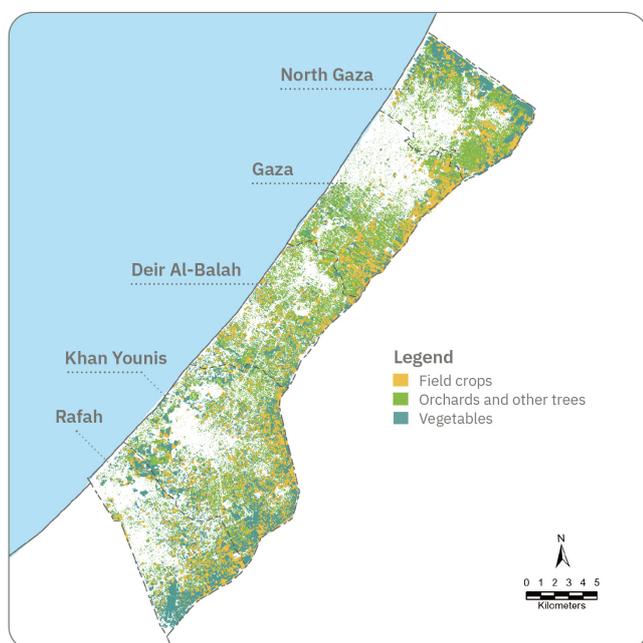


Fig. 1. Cropland category map of the Gaza Strip 2023 [25].

C. Data Collection and Analysis

This research employs a triangulated data collection strategy that combines both primary and secondary sources to enhance validity and contextual depth.

Primary Data

Semi-structured interviews conducted in Arabic with two key stakeholder groups: Agricultural experts and policymakers (e.g., agricultural engineers, university researchers, NGO professionals) and Local farmers and youth entrepreneurs with experience or interest in hydroponic systems.

A total of approximately 16 interviews were conducted (6 expert stakeholders and 10 local practitioners). This sample size is guided by the principle of thematic saturation. Recent empirical syntheses suggest that qualitative thematic saturation often occurs within 9–17 interviews, particularly when the participant group is fairly homogeneous and the research focus is narrowly defined [27]. Participants were purposively selected to represent policy/technical experts, NGO practitioners, local entrepreneurs, and small-scale hydroponic farmers. Recruitment combined sectoral networks and snowballing; inclusion required first-hand hydroponics experience within the past three years.

- Semi-structured interviews followed a brief guide covering four blocks: technical/agronomic aspects of hydroponics, economic/entrepreneurial dynamics (CAPEX/OPEX, markets), environmental performance (water/energy, nutrients, pesticides), and context enablers/constraints (infrastructure, finance, policy,

skills).

- Interview data were transcribed and analyzed using thematic analysis to identify recurring patterns, barriers, and enabling factors. NVivo analysis software is used to ensure systematic coding and categorization. Where appropriate, SWOT analysis was applied to structure key insights into strengths, weaknesses, opportunities, and threats associated with hydroponic adoption in Gaza to ensure trustworthiness, the study applied triangulation, member checking, and peer debriefing where feasible.

All interviews were conducted by two researchers with backgrounds in environmental engineering and sustainable development policy, both fluent in Arabic and English, and experienced in qualitative fieldwork under humanitarian and environmental programs in Gaza. Prior to data collection, both interviewers received refresher training on ethical interviewing and bias minimization. The coding process followed a multi-step workflow: after transcription, the two researchers independently conducted open coding, discussed code convergence, and developed a shared codebook. Inter-coder agreement was assessed through iterative comparison, achieving an average Cohen's Kappa coefficient of 0.82, indicating substantial consistency. Any discrepancies were resolved through discussion and consensus. Analytical reflections were documented in analytic memos throughout the process, allowing the researchers to critically engage with their positionality and potential influence on data interpretation. This reflexive approach ensured that findings reflected both empirical patterns and the authors' contextual understanding of Gaza's environmental and social constraints.

Secondary Data

A comprehensive review of existing reports, peer-reviewed literature, technical manuals, and policy papers relevant to hydroponics, water use efficiency, and green entrepreneurship in Gaza and similar arid regions. Comparative analysis was used to assess hydroponic systems against conventional farming in terms of crop productivity, input requirements, and environmental performance, particularly through the lens of water footprint metrics.

Ethical safeguards include anonymizing interview data, obtaining informed consent, and securing institutional approval prior to fieldwork. Secondary data was used with proper citation and critical evaluation of source credibility.

A visual overview of the methodological sequence—including data sources, collection tools, analysis techniques, and water footprint assessment—is presented in Fig. 2. This flowchart illustrates the integrated design adopted in the study, highlighting the connections between primary and secondary data, analytical frameworks, and contextual constraints.

D. Water Footprint Assessment Approach

To evaluate the environmental efficiency of hydroponic systems, this study applies the Water Footprint Assessment (WFA) framework developed by Hoekstra *et al.* [28], which remains the globally recognized standard for quantifying freshwater use across agricultural practices. WFA figures are expressed as m^3 of blue/grey water per ton. The assessment will focus on three components:

- Blue water footprint: the volume of freshwater used for nutrient solution preparation and system maintenance.
- Green water footprint: negligible in hydroponic systems, but included for comparative purposes.
- Grey water footprint: the volume of water required to assimilate pollutants (e.g., nitrates, phosphates) discharged through hydroponic effluents, calculated based on water quality thresholds.

Hydroponic systems were assessed using input-output models that track water use efficiency per kilogram of produce... Gaza-specific primary metering was not feasible; thus, quantitative values were triangulated from secondary sources. Environmental performance was benchmarked against traditional soil-based farming practices in Gaza. In cases where direct measurements are limited, the study utilized simulation tools such as CROPWAT and reference WaterStat databases to support estimations and ensure methodological robustness.

This approach provides a quantitative lens for comparing agricultural water efficiency, highlighting the potential of hydroponics to reduce freshwater consumption and pollution—an imperative in water-scarce regions like Gaza.

Methodological Framework: Exploring Hydroponics as a Green Entrepreneurial Model in Gaza

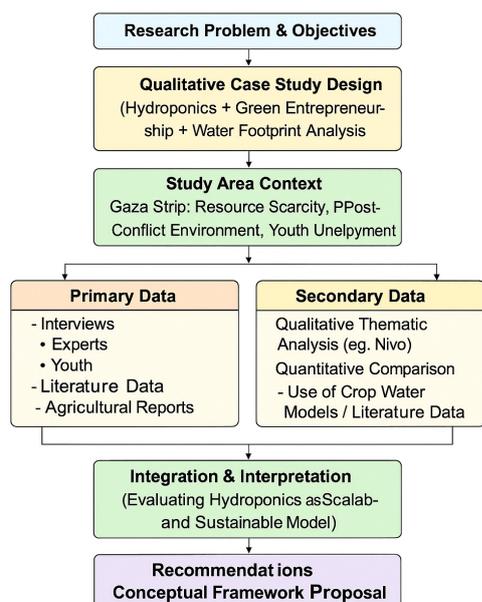


Fig. 2. Flowchart overview the methodological sequence adopted in the study.

III. RESULTS AND EMPIRICAL FINDINGS

A. Participant Profiles

The study engaged a total of 16 participants, equally divided into two key groups: six agricultural experts and ten local hydroponic farmers. The expert group included university academics, agricultural engineers, and senior officials from the Ministry of Agriculture in Gaza, offering a blend of institutional, technical, and policy perspectives on sustainable agriculture.

The farmer group was composed of individuals actively engaged in hydroponic cultivation. Among them were three women and seven young men, all falling within the 25–45 age range, and representing the youth demographic central to

the study’s focus on green entrepreneurship as presented in Fig. 3. Notably, eight of the ten farmers had prior experience in traditional soil-based agriculture, providing a comparative lens on the transition toward hydroponic methods.

Interviews were conducted in person or remotely, depending on logistical feasibility, and ranged in duration from 20 to 40 minutes. All participants provided informed consent, and interviews were carried out in accordance with ethical protocols approved by the relevant institutional review board.

This diverse participant pool was instrumental in capturing a range of experiences and perspectives related to hydroponic farming, sustainability challenges, and the socio-economic conditions shaping post-conflict recovery efforts in Gaza.

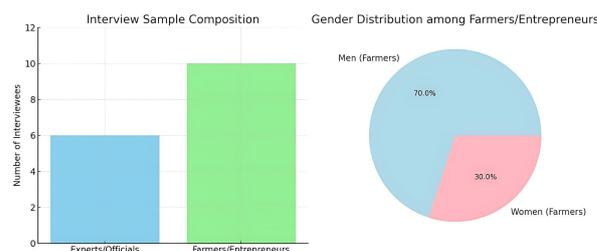


Fig. 3. Distribution of Interview Participants by Role and Gender in the Study.

B. Perceptions of Hydroponics

Interview findings reveal a generally positive perception of hydroponic farming among both practitioners and experts in the Gaza Strip. Participants emphasized that hydroponics, though relatively new in the Palestinian agricultural landscape—first appearing in northern Gaza in 2014—has shown substantial promise due to its resource efficiency, scalability, and suitability for space-constrained environments.

Respondents identified hydroponics as a water-saving innovation, estimating reductions in water use between 75% and 90% compared to conventional soil-based farming. Additionally, the system reportedly reduces pesticide use by over 90%, thereby minimizing environmental contamination and promoting healthier food production. Farmers also reported high yields, with hydroponic systems producing 4 to 6 times more output per unit area than traditional methods. Commonly cultivated crops include lettuce, strawberries, herbs such as mint, and various vegetables (e.g., tomatoes, cucumbers, peppers), with high success rates across all seasons. The method allows for continuous year-round production, even in non-arable or urbanized areas—an advantage underscored in light of Gaza’s severe land degradation and urban encroachment.

Farmers described the technical setup in detail, highlighting the use of nutrient-enriched water, floating polystyrene boards, and recirculation pumps to ensure balanced nutrient distribution. Despite technical constraints—most notably power outages—respondents expressed strong commitment to continuing hydroponic cultivation due to its economic viability and adaptability. Notably, the initial setup costs were cited as a key barrier, especially for youth and small-scale producers. However, many considered these investments recoverable over time through savings on inputs and increased productivity. Interviewees also acknowledged organic alternatives, such as

aquaponic systems utilizing fish waste for nutrient input.

Experts emphasized hydroponics as a strategic response to both environmental degradation and political instability. One expert drew attention to the contamination of Gaza’s soil from military activity, particularly in northern regions, further justifying the shift to soilless cultivation as a safer, more sustainable solution. Overall, hydroponics was perceived not merely as a technical innovation, but as a livelihood-enhancing, space-efficient, and environmentally responsive agricultural system particularly well-suited to Gaza’s constraints. Table 1 provides a synthesized overview of key themes emerging from the interviews, highlighting the multifaceted dimensions of hydroponic farming in Gaza.

Table 1. Summary of key issues identified in interviews on hydroponic farming in Gaza

Analytical Theme	Key Findings from Interviews
Historical Context	Hydroponics introduced in northern Gaza around 2014. Still considered relatively new in the local agricultural scene.
Water Efficiency	Participants reported 75–90% reduction in water use compared to soil farming.
Pesticide Use	Over 90% reduction in pesticide use; minimal environmental contamination and healthier food.
Yield and Productivity	Hydroponics systems yield 4–6 times more output per unit area than traditional farming methods.
Common Crops	Lettuce, mint, strawberries, tomatoes, cucumbers, peppers, and other vegetables; success across seasons.
Production Flexibility	Year-round production possible; systems work in urban, non-arable, or confined spaces—critical in Gaza’s deteriorated land and high urban density.
Technical Setup	Use of nutrient solutions, polystyrene floats, water recirculation pumps. Controlled environments help ensure growth stability.
Environmental Justification	Experts cited soil contamination due to military activity as a major reason to adopt soilless farming systems.
Economic Viability	High initial costs cited as a barrier, particularly for youth and small-scale farmers. However, long-term savings and increased productivity seen as justifying the investment.
Power Challenges	Frequent electricity cuts affect system operation; adaptability and resilience needed.
Gender Inclusion	Both women and men actively participate in hydroponic farming, opening livelihood opportunities.
Scalability & Adaptability	Systems are horizontally and vertically scalable; adaptable to rooftops, balconies, and degraded land.
Alternative Systems	Aquaponics cited as an organic, integrated option using fish waste for nutrient delivery.
Knowledge & Training	Lack of technical know-how and need for training in nutrient management were mentioned as significant challenges.
Social Perception	Overall positive attitude among participants; hydroponics seen as modern, promising, and environmentally aligned.

C. Green Entrepreneurship Opportunities

The interviews revealed a growing recognition of hydroponics as a catalyst for green entrepreneurship in Gaza, particularly in the context of youth and women-led initiatives. Participants highlighted that hydroponic farming presents a viable pathway for income generation, contribution in self-sufficiency, and environmentally responsible production, especially in densely populated or non-arable urban settings.

Several respondents described small-scale, family-based hydroponic projects that began as means of household food security but evolved into micro-enterprises. These were often

promoted through social media platforms and local markets, showing encouraging customer demand for pesticide-free and locally produced vegetables. One female participant reported branding her initiative, expressing aspirations to scale up the project and employ other youth in her community.

The spatial efficiency of hydroponics was viewed as a core enabler of entrepreneurial activity. The ability to grow high-yield crops on rooftops, balconies, or unused urban spaces allows aspiring entrepreneurs to start agricultural ventures without needing access to farmland. Respondents noted that a small greenhouse could be established for under \$1,000 if designed and constructed efficiently by experienced technicians. Experts also pointed to the potential of hydroponic systems to anchor circular or integrated business models. These include aquaponics, animal husbandry, and composting, forming low-waste, vertically integrated systems. This was especially relevant in discussions about urban food security, where such models could support resilient livelihoods under siege conditions.

However, structural barriers remain. Most large-scale hydroponic installations were funded by international donors and NGOs, with limited pathways for independent financing or private investment. Moreover, participants stressed the limited availability of key agricultural inputs, such as nutrient solutions (e.g., iron-rich solution A and calcium nitrate solution B), which are often restricted from entering Gaza. Some farmers resorted to manual workarounds, including hand-perforating containers or improvising irrigation tools, which added labor intensity to their operations.

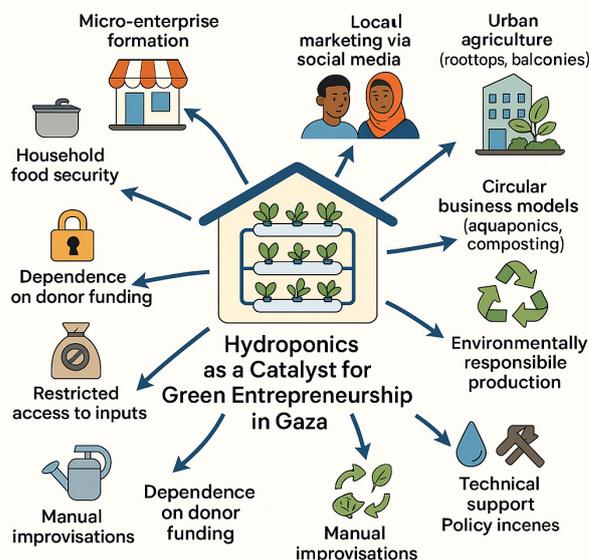


Fig. 4. Hydroponic as a catalyst for green entrepreneurship in Gaza.

Despite these limitations, hydroponics was consistently viewed as a scalable and youth-friendly innovation with considerable entrepreneurial promise—particularly if technical support, input access, and policy incentives can be improved. Fig. 4 presented the role of hydroponic as a catalyst for green entrepreneurship in Gaza.

D. Environmental Efficiency: Water Footprint Comparison

To assess the environmental efficiency of hydroponic

agriculture in Gaza, this study utilizes the Water Footprint Assessment (WFA) framework, with a focus on blue and grey water footprints. The green water footprint is excluded, not due to limited rainfall, but because hydroponic systems are typically implemented in covered or indoor environments (e.g., rooftops, greenhouses), where rainwater does not come into contact with the cultivation system.

Across all interviews, hydroponic farming was identified as a highly water-efficient alternative to traditional agriculture. Respondents estimated that hydroponic systems save up to 90% of water compared to conventional soil-based farming. This perception was consistent across various farming scales—from home gardens to larger donor-supported installations. Interviewees also emphasized the system's low reliance on agrochemicals, further minimizing environmental impact and potential water pollution.

Findings from Gaza resonate with broader regional research. In Saudi Arabia, a study [29] found that hydroponic barley required only 2.83 m³/ton, compared to 117 m³/ton for open-field cultivation. A notable regional example is the Ivvest capsule, a Jordanian-developed hydroponic unit that demonstrates high water-use efficiency. According to operational data, the capsule consumes only 3,000 liters (3 m³) of water per month to produce over 1.35 tons of crops, translating to less than 2.2 m³ per ton. This efficiency is achieved through a closed-loop system, managed by a smart interface (IvvestOS), allowing precise control over pH, nutrient concentration, and water reuse. Sealed reservoirs and controlled environments minimize both evaporation and leakage, reducing blue water usage and maintaining solution balance.

While no formal studies have yet quantified the grey water footprint of hydroponic farming, field interviews and system design features suggest it is nearly negligible. The main reasons include the absence of pesticide use in most hydroponic farms in Gaza; precision nutrient dosing, reducing surplus application; and closed systems that prevent runoff and leaching. These factors align with environmental goals, positioning hydroponics as a low-pollution model, even though more empirical research is needed to establish a definitive grey water footprint value.

In contrast, conventional farming in Gaza demonstrates considerably higher water footprints, particularly in both the blue and grey water categories. According to local data [19], the cultivation of leafy vegetables such as spinach and arugula consumes approximately 112 cubic meters of blue water per ton, along with an estimated 51.5 cubic meters of grey water per ton. Similarly, leguminous crops like beans and peas require around 185 cubic meters of blue water and 166.7 cubic meters of grey water per ton. These figures highlight the substantial water demands associated with traditional agricultural practices in the region and reveal the dual environmental burden of traditional agriculture—excessive water use and high risk of chemical pollution through fertilizer leaching and inefficient irrigation.

Results from Gaza align with broader global research. For instance, Pomoni *et al.* [21] reported water use reductions in high-tech greenhouses to as low as 4 L/kg, compared to 60 L/kg in open-field farming. Similarly, Engler *et al.* [30] confirmed that vertical hydroponics can reduce water

consumption by 70–95%, while Venter (2017) estimated that hydroponic systems require only 10–16% of the water used in conventional agriculture [31]. Table 2 presents a comparative overview of key differences in water use between conventional and hydroponic systems, underscoring the efficiency gains associated with the latter.

Table 2. Overview of key differences in Water Footprint (WF) between conventional and hydroponic systems

Crop Type	System Type	Blue WF (m ³ /ton)	Grey WF (m ³ /ton)	Total WF (m ³ /ton)
Leafy Greens	Traditional	112	51.5	163.5
Legumes	Traditional	185	166.7	351.7
Mixed Crops	Hydroponic Capsule	<2.2	~20-10	<12-22

These results offer strong evidence for the superior water efficiency of hydroponic farming, particularly in environmentally fragile and water-scarce regions like Gaza. With over 95% reduction in blue water use and near-elimination of grey water discharge, hydroponics presents a sustainable and scalable solution aligned with both environmental preservation and food security objectives.

E. SWOT Analysis

The SWOT analysis highlights the multifaceted nature of hydroponic farming in Gaza, reflecting both its transformative potential and its practical constraints. Among its key strengths are its remarkable water efficiency and environmental benefits, making it a viable solution in a region marked by water scarcity and soil degradation. Additionally, hydroponics offers high productivity with reduced labor and chemical input, allowing for safe, high-quality food production that can be managed by both women and youth, thus promoting inclusivity.

However, the system is not without its challenges. The high initial setup cost and technical expertise required pose significant barriers to entry, especially in a context where training resources are limited. Many traditional farmers remain unfamiliar with hydroponic techniques, and access to essential components like nutrient solutions is often hampered by political and logistical constraints.

Despite these weaknesses, the opportunities for green entrepreneurship are considerable. Hydroponics enables small-scale, home-based food production, which can contribute to household food security and create income-generating ventures. Its scalability and adaptability to non-arable spaces further enhance its appeal, especially in dense urban settings. Institutional efforts to support urban agriculture, coupled with youth and women's engagement, can turn hydroponics into a cornerstone of sustainable development in Gaza.

Nonetheless, the success of this model is threatened by broader systemic issues, including the ongoing Israeli blockade, limited infrastructure, and restricted access to materials. The political fragmentation in the region also hinders coordinated agricultural policy and investment.

In sum, while hydroponic farming in Gaza faces tangible limitations, its strengths and opportunities present a compelling case for targeted support and strategic scaling, particularly as part of a broader vision for climate-resilient and socially inclusive agriculture, as shown in Table 3.

Table 3. SWOT analysis of hydroponic farming in Gaza

Strengths	Weaknesses
High water-use efficiency (up to 90–95%)	High initial setup cost
Environmentally friendly: no pesticides or chemical fertilizers	Requires technical expertise to operate and balance pH/nutrients
Labor-saving and manageable by both men and women	Limited awareness and adoption among traditional farmers
Fast growth cycles and higher yields	Limited local availability of critical inputs and replacement parts
Full control over growing environment (pH, EC, nutrient levels)	Dependency on reliable electricity or solar backup systems
Produces safe, hormone-free, clean crops	Limited training programs for new adopters
Opportunities	Threats
Expansion of green entrepreneurship (urban farming, youth-led initiatives)	Israeli blockade restricting import of hydroponic inputs (e.g., nutrient solutions)
Horizontal and vertical scalability in small or confined spaces (balconies, rooftops)	Political fragmentation and weak institutional frameworks
Potential for food self-sufficiency in Gaza (grow food at home, rooftop, wall gardens)	Limited export opportunities due to closed borders
Inclusion of women and youth in agri-startups	Market volatility and dependency on donor-funded pilots
Viable in non-arable or contaminated soils (solution to land scarcity)	
Integration with aquaponics, solar-powered systems, and circular economy models	

IV. INTERPRETATION AND IMPLICATIONS

A. Integrative Discussion: Linking Practice to Framework

The empirical findings of this study reveal a dynamic interplay between hydroponics, green entrepreneurship, and water efficiency, particularly in the fragile and resource-constrained context of Gaza. Participants emphasized hydroponics as a promising alternative to conventional agriculture, particularly due to its significantly lower water footprint and capacity for year-round production in limited spaces. These results directly align with the conceptual premise that hydroponics can serve not only as a sustainable agricultural practice but also as a viable entrepreneurial opportunity, especially for youth and women, in contexts where arable land and clean water are scarce.

Furthermore, the findings corroborate earlier studies that have framed hydroponics as both water-efficient and environmentally friendly [32]. In particular, the local estimates from Gaza revealed that hydroponic systems consumed less than 2.2 m³ of water per ton of leafy vegetable production—markedly lower than the 112 m³/ton required in traditional farming. This substantial reduction validates the theoretical assumption that hydroponics is a water-saving innovation suitable for water-scarce areas.

In terms of green entrepreneurship, the interviews showcased how small-scale hydroponic projects are increasingly being used as platforms for innovation and income generation, particularly when integrated with social

media marketing and household-scale production. These findings support the notion that environmental sustainability and economic opportunity are not mutually exclusive but can be co-developed through creative localized solutions [15].

Beyond these empirical trends, the research process itself offered critical insights into how knowledge is produced under fragile conditions. As researchers based in Gaza, we navigated interruptions due to power cuts, limited mobility, and participants' cautiousness in sharing economic information amid ongoing uncertainty. These contextual barriers shaped not only data collection but also our interpretation of what "resilience" means in practice. The iterative coding sessions and field reflections underscored how hydroponic initiatives represent both a survival mechanism and a quiet form of social innovation. This reflexive engagement reminded us that hydroponics in Gaza cannot be fully understood through technical metrics alone; it is deeply embedded in narratives of persistence, improvisation, and hope. Acknowledging our positionality as local researchers allowed us to remain critically aware of potential biases while interpreting enthusiasm for hydroponics—not merely as optimism, but as an act of agency within structural constraints.

B. Implications for Policy and Practice

The findings of this study hold significant implications for agricultural policy, donor programming, and grassroots development strategies in Gaza and comparable fragile settings.

First, the demonstrated water efficiency of hydroponic systems offers a compelling case for government ministries—especially the Ministry of Agriculture and Water Authority—to formally integrate hydroponic farming into national strategies for food security and climate adaptation. Given Gaza's acute water scarcity, investing in hydroponics could help reduce dependence on groundwater extraction and mitigate agricultural pressure on already-degraded soil resources.

Second, the entrepreneurial potential of hydroponic farming, especially at the household or rooftop level, suggests a strategic entry point for youth employment and women's economic participation. Policy frameworks should thus prioritize the inclusion of hydroponics in vocational training programs and green economy incubation hubs. Pilot projects, if scaled with appropriate technical and financial support, could become anchors for localized food systems and resilient livelihoods.

Third, international donors and development organizations can play a catalytic role by channeling support towards infrastructure (e.g., greenhouses, water filtration units, and solar-powered pumps) and input supplies (e.g., nutrient solutions), while ensuring that interventions include strong components of capacity building and local ownership. Interviewees repeatedly pointed to the need for technical guidance on nutrient management, pH balancing, and system maintenance—areas that can be addressed through tailored extension services.

Finally, the modular and space-efficient nature of hydroponic farming makes it highly transferable to other regions facing similar constraints, such as refugee camps, remote desert communities, or urban areas with land-use

pressures. As such, Gaza's emergent hydroponic initiatives offer valuable lessons for adaptive agriculture in contexts like Yemen, South Sudan, and Jordan's refugee camps. This suggests the potential for policy frameworks to view hydroponics not only as a niche innovation but as a scalable and replicable model of urban and peri-urban agriculture.

C. Limitations and Future Research

While this study provides valuable insights into the potential of hydroponic farming as a pathway for green entrepreneurship and water-efficient agriculture in Gaza, several limitations should be acknowledged.

First, the sample size was limited to 16 participants—ten practitioners (farmers) and six experts (academics, engineers, and policymakers). Although this number allowed for rich qualitative insights, it does not fully capture the diversity of experiences across Gaza's agricultural landscape. Future studies may benefit from broader sampling across multiple regions and socio-economic groups to enhance generalizability.

Second, the data were collected through semi-structured interviews, which, while useful for exploring perceptions and contextual nuances, are subject to response biases and limitations in self-reporting. Some interviewees may have emphasized success stories while underreporting systemic failures or challenges.

Third, logistical and political constraints in Gaza posed challenges to field access, verification of data, and the use of certain measurement tools (e.g., real-time environmental sensors or detailed economic records). These constraints may have influenced the depth and accuracy of some technical assessments, such as precise energy or input consumption across different hydroponic models.

Despite these limitations, the study opens important avenues for future research. Quantitative cost-benefit analyses comparing hydroponic and traditional systems under controlled settings would offer stronger evidence for investment decisions. Additionally, long-term studies tracking the economic viability, employment generation, and gender impact of hydroponic initiatives can help refine support mechanisms and policy frameworks. Moreover, replicating this research in other fragile or water-scarce contexts—such as refugee camps or conflict-affected rural zones—would provide comparative insights into the scalability and adaptability of hydroponic farming as a sustainable solution for food security and climate resilience.

V. CONCLUSION

This study positions hydroponics as a green entrepreneurial model for food security in resource-scarce Gaza by integrating empirical insights with a water-footprint lens. Beyond confirming feasibility, we show how input efficiency, micro-venturing pathways, and context constraints jointly shape adoption.

Findings demonstrated that hydroponics significantly reduces water usage compared to traditional agriculture, supports pesticide-free food production, and enables cultivation in urban or marginal spaces. Despite its high initial cost and technical complexity, the model shows promise for expansion—particularly when supported by donor agencies, local institutions, and entrepreneurial

initiatives. The integration of smart technologies (e.g., automated nutrient systems, water monitoring tools) further enhances its environmental and economic appeal.

From a theoretical standpoint, the results reinforce the literature on sustainable agriculture and green entrepreneurship in constrained environments. They also extend existing frameworks by demonstrating how environmental degradation, resource scarcity, and political instability can act not only as threats but also as drivers of innovation and localized adaptation.

Policy and development actors should therefore consider hydroponics not as a niche or experimental system but as a viable strategy for urban food security, youth employment, and climate resilience in Gaza and similar contexts. Future research should continue to deepen the evidence base through longitudinal studies, comparative regional assessments, and rigorous economic evaluations. Ultimately, hydroponic farming in Gaza is more than a technical solution—it represents a model of adaptation, agency, and forward-thinking amidst crisis.

DATA AVAILABILITY STATEMENT

The qualitative interview data generated and analysed in this study are not publicly available due to confidentiality considerations and the sensitive context of the study area. Anonymized excerpts of the transcripts and the coding framework are available from the corresponding author on reasonable request and subject to institutional ethics approval.

CONFLICT OF INTEREST

The author declares no conflict of interest.

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