OXFORD JOURNAL
OF STUDENT
SCHOLARSHIP

Feasibility and Affordability of Renewable Energy-Powered Hydroponics for Small-Scale Farmers

Ahaan Kakad
kakada@asbindia.org

ABSTRACT

The research paper has examined the extent to which renewable-energy-powered hydroponics systems can improve affordability for small-scale farmers. The study has highlighted the relationship between hydroponic systems, renewable energy, financial accessibility and productivity, by comparing hydroponic systems with traditional farming systems. The research has emphasized small-scale adoption of hydroponics and focused on several factors, such as initial setup cost, monthly income for 200 square meters, monthly operational costs, labor, net monthly profit, payback period, sustainability and annual income. Findings from the study have demonstrated that hydroponic farming can generate significantly higher income per square meter in comparison to traditional farming. Whilst renewable energy sources, such as solar power, can reduce long-term operational costs by reducing dependence on grid electricity. However, the research has identified that high initial setup costs and technical barriers remain major limitations for widespread adoption. The findings contribute to a broader understanding of sustainable farming by highlighting how renewable-energy-powered hydroponics could support future food production systems, improve land use efficiency and create more accessible farming opportunities for small-scale farmers and agricultural entrepreneurs.

Keywords: Hydroponics; Renewable energy; Small-scale farmers; Sustainable agriculture; Solar energy; Crop yields; Farm income; Affordability; Food security; Climate change adaptation; Water scarcity; Agricultural technology; Sustainability; Hospitality

INTRODUCTION

1.1 Difficulties that Farmers are Facing Today with Farming and Agriculture

Farmers are facing tremendous pressure in terms of producing more food while conserving soil health and water resources. As a result, there are numerous impacts on farming operations. These include labor shortages, regulatory requirements, and rising input costs (5). Modern farmers are confronting a multitude of agricultural issues, such as addressing challenges that are connected to soil degradation, loss of biodiversity, adapting to extreme weather conditions, and changing growing conditions. These factors can

have an impact on agriculture due to climate change (10). The significant weather-related problems that are faced by farmers include:

Drought: This is especially in water-deficient agricultural regions. It can reduce soil moisture levels. Thus, leading to lower crop yields and reduced fruit quality. Additionally, it can cause issues, such as aborted kernels in staple crops. For example, corn and wheat. In quantitative terms, even moderate drought conditions can reduce wheat yields by 50 to 60% (26).

Hail: This can severely damage crops by bruising fruits, tearing leaves and breaking branches. This increases plants' susceptibility to pests and diseases. In many cases, hailstorms can destroy crops beyond recovery. Therefore, they are a major cause of insurance claims in the agricultural sector (5).

Strong winds: Winds can create both direct and indirect agricultural damage. Direct effects include the loss of leaves and fruits, and indirect impacts occur when farming operations are delayed. Crops that become flattened by strong winds often require additional machinery passes and more time for harvesting (5).

Waterlogging: This issue deteriorates soil quality, restricts nutrient absorption by plants, damages root systems and interferes with essential agricultural activities. In addition, waterlogged soils can increase greenhouse gas emissions. Therefore, further contributes to environmental and climate-related challenges (5).

1.2 Defining Small-Scale Farmers

Small-scale farming includes cultivation techniques where farmers can intervene on relatively small plots of land (4). This is done frequently by using traditional procedures to produce food mainly for local consumption. The farming technique is characterized by lower levels of automation and commonly highlights sustainable practices, community involvement, and the production of varieties of crops (4). Small-scale agriculture includes the functioning of small farms, ranging from 1 to 10 hectares. They are mainly family-owned and focused on sustainability and profits (8). These farms are separated by their environmentally friendly practices, as they rely less on large machines and chemical inputs in comparison to industrial farms (8).

1.3 Understanding Hydroponic System

The phrase ‘Hydroponics’ is derived from the word ‘hydros’ that means water and ‘ponos’ which refers to toil or labor (3). It is used in determining the deficiency indicators of numerous nutrients in plants and to find out about the essential nutrients that are required for the plant’s growth and development (3). It is a farming strategy where plants are grown in a nutrient solution in the absolute absence of soil. In the given context, the soil is replaced by infertile mediums, such as rockwool, vermiculite, sand, gravel, clay pellets, perlite and coco peat, in order to give stability to the roots (3). Nutrients are carried through the roots differently. This is based on the type of hydroponic system that is used. The oxygen is pumped through, pH level is regulated and sufficient light is provided to carry out the process of photosynthesis.

In areas where natural light is not available, artificial lighting is provided (20). It is an innovative method of farming and is widely used now for food production (20).

1.4 Renewable Energy in Agriculture

Renewable energy means the energy which is produced from naturally refreshening resources, which are not lost when used (1). For instance, sunlight, wind, water, biomass and geothermal energy (1). In the context of agriculture specifically, renewable energy refers to on-farm or rural energy systems that tackle natural procedures or biological substances. This is to produce sustainable power whilst reducing the reliance on fossil fuels (1). Unlike coal, oil or natural gases, renewable energy sources can regenerate infinitely and produce significantly lower amounts of greenhouse emissions (13). Thus, in farming or agricultural businesses, renewable energy plays a predominant role in achieving decarbonization, energy security and diversified farm income (13).

1.5 Significance of the Study

The research topic of hydroponics and sustainable farming is significant to several stakeholders. This includes, small-scale farmers, technological businesses which are related to agriculture, urban and rural populations. Hydroponics farming provides ways to overcome challenges, such as scarce water supply, change in climate and limited land, while improving income. This in turn can benefit small-scale farmers, as they can receive higher crop yields. Urban and rural customers can benefit from receiving fresh fruits and vegetables.

Furthermore, technological businesses related to agriculture can gain innovation in terms of food production and business growth. Additionally, this research carries importance at a national and policy level. Governments in countries, such as Singapore and India, have already begun investing in hydroponics and renewable energy integration as part of broader food security and sustainability strategies (14), (18). By examining the affordability of these systems for small-scale farmers specifically, this study contributes to the evidence that can inform how government support is targeted, particularly in regions where land and water scarcity make traditional farming increasingly difficult to sustain (5), (16).

1.6 Aims and Goals of the Paper

This research paper aims to prove hydroponics as a sustainable alternative compared to traditional farming. It will analyse the challenges that are faced by various farmers, compare hydroponics farming with traditional farming and present the financial viability of both methods. The following sections explore how different countries are applying hydroponic systems, along with practical solutions, such as government schemes, subsidies and renewable energy integration.

HOW HYDROPONIC SYSTEMS ARE BEING USED BY DIFFERENT COUNTRIES

Singapore

In Singapore, hydroponics is fulfilling the needs of demographic growth in a highly sustainable way. The Singapore Food Agency (2022) has released articles about the feasibility of hydroponics and examined the benefits of the practice. This is mainly for urban crop development. Singapore imports over 90% of the food necessary to feed its dense population of approximately 5.64 million people. The Singapore Food Agency is an official part of the Ministry of Sustainability and the Environment. It supervises food safety and security in the island country. The agency's main task is to increase the percentage of food that is produced in the city, with a target of 30% of all food consumption coming from local production by the year 2030. It is a hard task - mainly because food farms occupy around 1% of land on the island. This is why it makes sense that the agency has promoted hydroponics as a way for commercial pursuits to meet the necessities of local food consumers. The city's food development contains rooftop gardens and large vertical farms, some of which are located at the apex of skyscrapers (18).

India

According to India's National Sample Survey Office which was conducted in 2003, 2013 and 2019, the average monthly income of a farmer's household is approximately ₹10,218 (US $105.90). A significant portion of this income comes from non-farming sources, such as wages. This proves that farming alone is insufficient to sustain livelihoods. Out of this income, 5 - 10% is usually invested into maintenance. For a five-person household in India, the time required to save a good amount of money to set up a smaller renewable hydroponics farm is heavily dependent on income, which can differ. Numerous households earn between ₹10,000 – ₹20,000 (US $103.60 – $207.45) monthly and are able to save only around ₹2,000 – ₹4,000 (US $20.70 – $41.45), after meeting essential expenses. A basic small-scale hydroponic system for a rooftop or backyard covering approximately 100 square feet could cost around ₹25,000 (US $259.20). Adding a simple renewable energy setup, such as solar panels, increases the total to about ₹40,000 ($414.70). At this savings rate, it could take approximately 10 to 20 months to afford such a system. This refers to earlier discussions about agricultural challenges, as small-scale farmers already have issues, such as climate change, scarce water supply and rising costs. Whilst hydroponics offers an efficient and sustainable alternative by reducing water usage and dependence on soil, the higher initial investment makes it slower to access for lower-income households. This factor highlights a key challenge to adopting modern farming techniques (16).

China

China is one of the most rapidly expanding regions for the cultivation of hydroponics. China has a large population of 1.4 billion people. Due to this, it makes sense for the country to develop independence around the production of food. For such a huge country, China has considerably less land available for agricultural use. In comparison to India, China only has 11.6% of its geography in fertile land. Whereas India's territory is 51.95% fertile land, which is the most in the entire world. With respect to this, China's governing authorities have promoted hydroponics to cultivate highly productive urban farms. Chinese

citizens have continued the trend of moving from the rural areas to the urban regions. Therefore, further pressuring rural food-producing regions (24).

Vietnam

Although poverty levels have decreased from nearly 60% to around 20% over the past 20 years, smaller farmers still face various structural challenges such as scattered plots and limited access to advanced agricultural technologies, such as hydroponics. The World Bank emphasizes that while limited access to hydroponics has enabled agricultural productivity to improve significantly, income inequality is continuing, especially in the rural regions (22).

Kenya

In Kenya, the Food and Agriculture Organization (FAO)'s data implies that several farmers depend on different income streams to reduce risk, such as facing poverty and personal debt. Many smallholder farmers account for a significant amount of agricultural production. Kenya cultivates 1 to 5 acres and produces up to 90% of the local food in the country. Yet, they earn barely 25% of their income, whilst consuming the rest. Their incomes remain lower due to limited food produce, lack of access to financing opportunities and vulnerability to climate variability. After five consecutive failed rainfall seasons, several communities, such as Kenya, were faced with the most severe drought in 40 years. This occurred between late 2020 and early 2023. According to statistics, seven million children under the age of five faced malnourishment and seriously needed nutrition support across Kenya (10), (2). In response to these pressures, hydroponic farming has begun to develop popularity in Kenya. The Ministry of Agriculture offers subsidies covering up to 50% of initial setup costs and organizations are providing training and equipment to smallholder farmers. A World Food Program-funded pilot project in Isiolo County (2024 – 2025) illustrated that hydroponic systems can substantially increase yields on much smaller plots of land (25).

METHODOLOGY

3.1 Purpose of the Methodology

The methodology for this research paper was designed to examine whether renewable-energy-powered hydroponic systems can improve the affordability for small-scale farmers. The methodology focused on comparing hydroponic farming systems with traditional farming systems in terms of income generation, affordability, scalability and operational costs. As the main topic connects agriculture, renewable energy and economics, multiple forms of data collection, such as government reports, academic journal articles and international organization datasets, and analysis related to graphs and other factors, such as setup costs, operational costs and payback periods, were important to create a broader understanding of the topic.

3.2 Modelled Financial Analysis Based on Secondary Data

This study's modelled financial analysis consisted of financial modelling, comparative calculations and graphical analysis, which were developed specifically for this research paper using data drawn from the secondary sources described in Section 3.3. One of the main components of this analysis was a financial comparison between hydroponic farming and traditional farming using a 200-square-meter farming model. This comparison included several factors, such as setup cost, operational costs, annual income, payback period and net monthly profit. Based on this, a graph comparing square meters versus annual income for hydroponics and traditional farming was created. The graph compared the estimated annual income generated by hydroponic systems and traditional farming systems across different farm sizes. These values were scaled using estimates from a 200-square-meter model. This is because, for the majority of small-scale farmers, 200 square meters is the average area required. The unsubsidised hydroponics system in the model generated an annual income of around Rs. 420,000 ($4,410) from 200 square meters, whereas traditional farming generated around Rs. 36,000 ($378) annually from the same land area. To create the graph, annual income per square meter was initially calculated as Rs. 420,000 divided by 200, which resulted in around Rs. 2,700 (around $28) per square meter annually. Traditional farming income per square meter was calculated by dividing Rs. 36,000 by 200, resulting in around Rs. 180 (around $1.89) annually per square meter. Then, these values were multiplied across different square meter values to construct the line graph. The purpose of doing this was to visually view and understand how hydroponics generates significantly higher income than traditional farming, especially for small-scale farmers.

The initial setup cost and monthly operational cost figures used in this model were derived from published cost benchmarks for small-scale hydroponic and protected-cultivation systems in India, rather than being estimated arbitrarily. The setup cost includes the growing structure, irrigation and nutrient-delivery equipment, and the renewable energy (solar) component, benchmarked against guidelines from the National Horticulture Board's Mission for Integrated Development of Horticulture (15) and government reporting on hydroponics initiatives (17). The difference between the subsidised and unsubsidised setup cost reflects the subsidy structure under schemes such as PM-KUSUM, which can cover up to 60% of the renewable energy component of the setup (14), as well as horticulture-specific subsidies covering part of the infrastructure cost. The monthly operational cost figure reflects recurring expenses such as electricity, nutrient solution and equipment upkeep, drawn from the same cost benchmarks. These sources were chosen because they provide standardised, publicly available cost data specific to small-scale hydroponic systems in India, allowing the setup and operational cost estimates to be independently verified rather than treated as fixed assumptions.

This modelled approach was selected because it directly aligned with the research question of this study. This study focuses on affordability. Therefore, it cannot be understood well without comparing costs and income. The graph and financial calculations simplified complex economic relationships and made it easier to visualise scalability and profitability. In addition, the use of a small 200-square-meter plot made the research more realistic and relevant to beginners rather than using larger areas of land for farmers at a wider scale.

3.3 Details about Secondary Data Collection

In addition to the model data, the research relied on secondary data collection. This was collected through reviews, government surveys, academic articles, renewable energy reports, and statistical databases. This included the Food and Agriculture Organization (10), the World Bank (23), the International Renewable Energy Agency (13) and the National Sample Survey Office (16). Additionally, articles from MDPI and university publications, such as The University of The Virgin Islands, The University of Arizona and Cornell University, were used. These provided information related to hydroponic farming, renewable energy costs, agricultural production, farmer income, technology adoption and affordability.

The secondary data included significant information about small-scale hydroponic systems, hydroponic setup costs, solar panel installation costs, farmer income statistics, poverty and affordability data and hydroponic adoption across countries, such as India, Singapore, China and Vietnam. Numerous existing sets of data were examined to identify patterns and support claims which were made throughout the research. For example, studies and reports were used to support the claim that hydroponics is more productive per square meter compared to traditional farming. Furthermore, renewable energy reports were used to explain how decreasing solar panel costs would improve affordability.

The reason behind selecting this particular secondary data was that it was taken from internationally recognized and credible institutions. These organizations collect large-scale agricultural and economic data. Thus, making the information more credible and suitable for academic research. In addition, using secondary data has allowed the research to compare multiple countries and identify patterns related to small farmers, hydroponic adoption and renewable energy access. Since this was an introductory research paper, secondary research provided an effective way to gather large amounts of information.

3.4 Rationale for Selecting the Model, Countries and Financial Formulas

The main model used which was in this research was a comparative financial scaling model. This model compared hydroponic farming income with traditional income across several land sizes. The model was used to examine how annual income differs with farming area, and to understand whether hydroponics farming will provide greater productivity and profitability for small-scale farmers. This model specifically focused on annual income rather than monthly calculations, as it provides a clearer understanding of profits and sustainability than monthly calculations.

It is important to note that the model has strengths and limitations. The positive aspect of the model is that the actual values will not be extremely different from the estimated values, as the model calculates values as per the ongoing trend. In contrast, the model would not be entirely accurate as costs can differ due to inflation rates or supply and demand laws. Additionally, the model does not directly include other factors, such as climate variability which can change costs.

The quantitative financial model developed in this study is based entirely on India-specific data, including setup and operational cost benchmarks, subsidy structures such as PM-KUSUM, and NSSO household income statistics. Kenya and Vietnam were not included in the financial model itself; rather, they were

selected as contextual case studies to illustrate how similar affordability challenges, smallholder farming populations, and drought/climate pressures manifest in other developing-country settings. These countries are discussed qualitatively in Section 2 to broaden the study's relevance, but the cost, income, and payback figures presented in Section 4 apply only to the Indian context. These factors are related to the topic. The sample included multiple academic articles from MDPI, international reports, such as the Food and Agriculture Organization and government data, such as the National Sample Survey Office, and modelled calculations through graphs rather than random data selection. This approach allowed the analysis to reflect consistent and scalable trends rather than isolated data points.

Data was collected through comparative analysis, financial models and statistical interpretation. Existing data and research papers were thoroughly analyzed in order to compare traditional farming systems with hydroponic systems in terms of productivity, setup cost, operational cost and scalability efficiently. Additionally, this involved comparing renewable energy systems, particularly solar energy with traditional electricity usage in order to examine long-term cost reduction.

The financial formulas and calculations that were used in the research included several variables, such as annual farming income, setup costs, operational costs, square meter values, hydroponic revenue estimates and traditional farming revenue estimates. Thus, this study mainly focused on factors that small-scale farmers would in reality consider before adopting hydroponic farming. Operational efficiency and annual income were highly important, as they help determine whether a farming system can be financially sustainable over time or not.

3.5 Inclusion and Exclusion Criteria

The financial model included core and directly measurable variables that were needed to assess affordability for small-scale farmers. The variables were initial setup cost, monthly operational cost, labor requirements, net monthly profit, payback period and annual income. Each of the factors were calculated for a standardized 200 square meter farm. Data sources were limited to internationally recognized institutions, such as the Food and Agriculture Organization, the World Bank and the International Renewable Energy Agency, to ensure the model was built on credible and comparable figures.

Several factors were excluded from the financial model. For example, inflation, climate variability, crop failure risk, maintenance breakdowns, transportation costs, labor variation across countries and fluctuating market prices. These factors were intentionally excluded as they can vary significantly across different countries. They would make the model very complex for a study that focused on introductory affordability for small-scaled farmers. Furthermore, the purpose of the graph was to create a concrete analysis and construct a simplified comparison between hydroponic and traditional farming.

FINDINGS

4.1 Cost Implications

Factor	Subsidised Farmers	Unsubsidised Farmers	Traditional Farming
Initial Setup cost	Rs. 179,000 ($1,879)	Rs. 370,000 ($3,885)	Rs. 20,000 ($210)
Monthly income for 200 sqm	40 kg/sqm 40 x 200 = 8000kg per year 8000/12 = 667kg Sells for ~~100/kg 100x 667 = ~~ Rs. 67,000 ($704)	Rs. 65,000 ($682)	Rs. 7,000 ($73)
Monthly operational costs	Rs. 30,000 ($315)	Rs. 30,000 ($315)	Rs. 4,000 ($42)
Labor	Requires manual labor for planting, harvesting, and monitoring nutrient levels/pH; pumping is automated	Requires manual labor for planting, harvesting, and monitoring nutrient levels/pH; pumping is automated	Traditional farming requires manual labor through harvesting and farming
Net monthly profit	Rs. 37,000 ($388)	Rs. 35,000 ($367)	Rs. 3,000 ($31)
Payback period in months	4 months	8 months	7 months
Annual income	Rs. 444,000 ($4,662)	Rs. 420,000 ($4,410)	Rs. 36,000 ($378)

(10), (13), (16)

Figure 1: Table Comparing Subsidised Farmers, Unsubsidised farmers and Traditional Farmers

The table above portrays the comparison between several factors for subsidised farmers, unsubsidised farmers and traditional farmers. It is observed that unsubsidised and subsidised farmers have a similar annual income. However, both have an annual income which is significantly larger compared to traditional farming. The differences between subsidised and unsubsidised farmers are:

The initial setup cost: In the table, the data highlights that unsubsidised farmers have significantly higher setup costs.

Monthly income for 200 sqm: The monthly income is slightly lesser for unsubsidised farmers.

Net monthly profit: The monthly incomes of unsubsidised and subsidised farmers are different. Consequently, the net monthly profit is also different. Due to this, the subsidised farmers have a higher net monthly profit.

Payback Period: The unsubsidised farmers require significantly more time to earn back their investment, as the initial setup cost is considerably higher.

Annual Income: As there is a difference in the net monthly profit, the final annual income differs. Thereby, making subsidised farming a better choice.

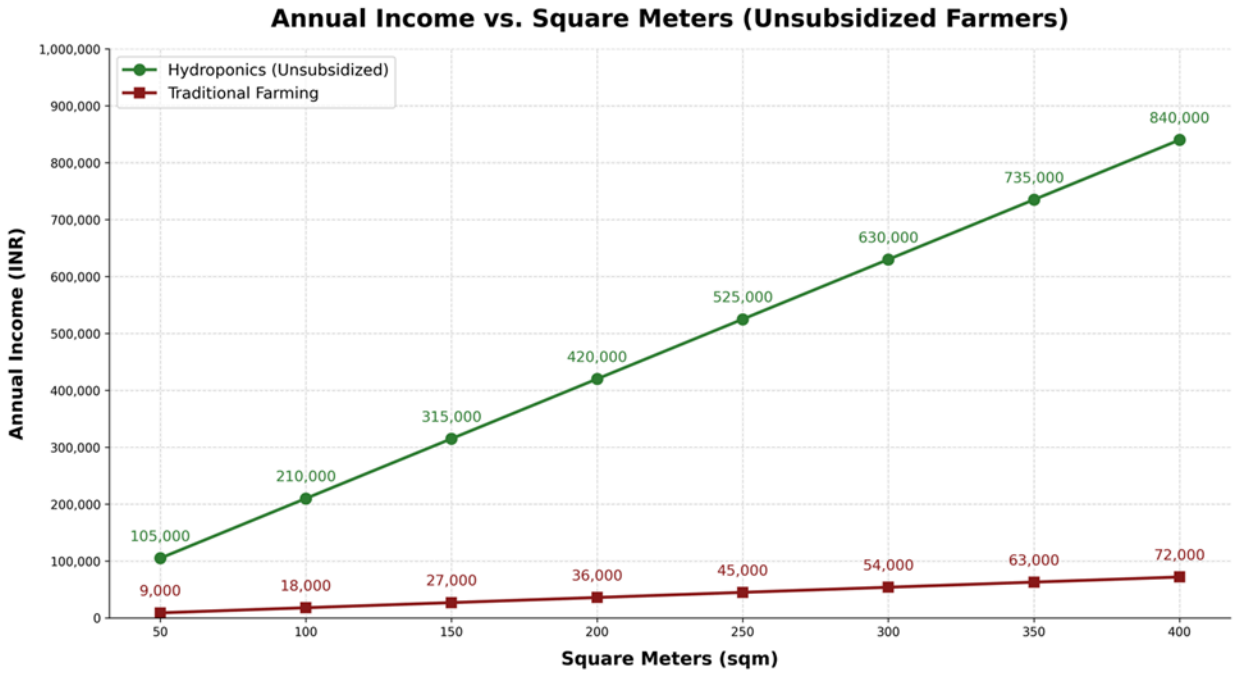


Figure 2: Graph of Annual Income Per 50 Square Meters for Unsubsidised Hydroponics Farmers and Traditional Farmers

The above graph exhibits a comparison between the annual income per 50 square meters for unsubsidised farmers. It is evident that there is a substantial difference in the annual income for an unsubsidised hydroponics farmer and a traditional farmer. It is clear that the maximum annual income a traditional farmer can earn from a farm of approximately 400 square meters is less than Rs. 75,000 ($787.40). Whereas, the maximum annual income an unsubsidised hydroponic farmer can earn from a farm of the same size is approximately Rs. 1,080,000 ($11,221). This is because the graph was constructed using a fixed rate of around Rs. 2,700 (around $28) of annual income per square meter for unsubsidised hydroponics, compared to only around Rs. 180 (around $1.87) per square meter for traditional farming. Thus, the gap between the two lines widens sharply as farm size increases. Even at the smallest farm sizes shown on the graph, hydroponics still produces a noticeably higher income compared to traditional farming. This pinpoints that the income advantage is not limited to larger farms and would benefit small-scale farmers working with limited land. This supports the overall claim of the study that hydroponic systems are considerably more productive per square meter than traditional farming, and that this advantage becomes even more pronounced as farm size increases.

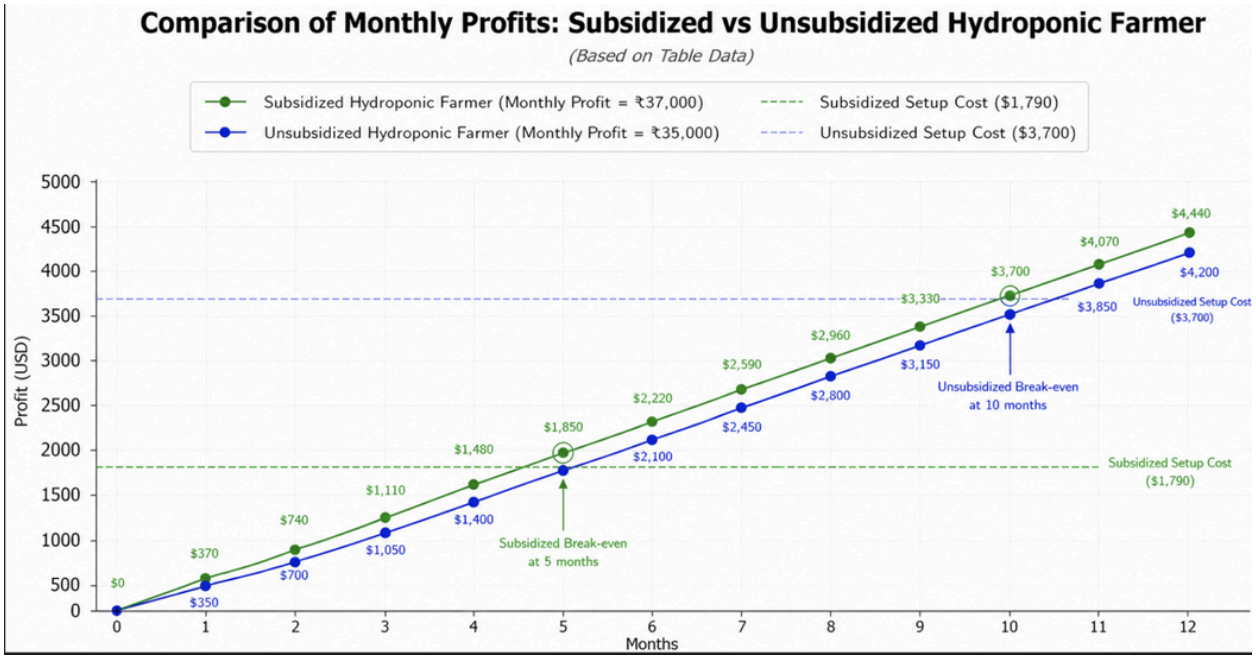


Figure 3: Graph of Monthly Profits for Unsubsidised Hydroponics Farmers and Subsidised Hydroponics Farmer

The above graph displays a comparison between the monthly profits in a year for a subsidised hydroponics farmer and an unsubsidised hydroponics farmer. There is a small difference between both

profits, and the subsidised hydroponics farmers have a higher profit. Furthermore, the above graph highlights the break-even point for both hydroponics farmers and the setup cost, which allows for a more thorough analysis. The above figure demonstrates that subsidised hydroponic farmers can have a higher monthly profit than unsubsidised hydroponics farmers. The graph pinpoints that the subsidised farmers break even at 5 months and the initial setup cost is around $1,790. Whereas, the unsubsidised farmers break even at around 10 months and the initial setup cost is around $3,700.

DISCUSSION

The financial model comparison has demonstrated that hydroponic systems are significantly better than traditional farming in terms of productivity and long-term earning potential despite the higher setup costs. Furthermore, the research proved that small-scale hydroponics systems are more accessible and manageable than large commercial systems. Therefore, making them more suitable for beginner farmers and small entrepreneurs. Renewable energy, specifically solar power, was found to reduce the long-term operational costs by decreasing dependence on grid electricity. In saying that, the research has also identified that the largest challenge to adoption of hydroponics is the high initial setup cost of hydroponics and renewable energy systems. Overall, the modelled financial analysis was combined with the secondary research in order to evaluate the relationship between hydroponics, renewable energy and affordability. By integrating the economic models, comparative analysis and the existing research datasets, a structured framework for understanding whether renewable-energy-powered hydroponics can become a viable solution for small-scale farmers in the future was provided.

These findings connect closely to the secondary data discussed in section 2. The income gap identified in the financial model reflects the affordability challenges which were reported by India's National Sample Survey Office (2019), where many farming households earn between Rs. 10,000 (around $105) and Rs. 20,000 (around $210) monthly and can save only Rs. 2,000 (around $21) to Rs. 4,000 (around $42) after essential expenses (16). This helps explain why the high initial setup cost which was identified in the model, particularly for unsubsidised hydroponics, is such a significant barrier for the majority of small-scale farmers. Similarly, the emphasis on subsidies and renewable energy support in the findings mirrors patterns seen in Singapore, where the Singapore Food Agency actively funds and promotes hydroponics to meet food security targets (18). In India, schemes, such as PM-KUSUM, provide subsidies covering up to 60% of setup costs: 30% from the central government and 30% from the state government). This could reduce the cost of the renewable energy setup which has been discussed earlier from around Rs. 40,000 (around $414.30) to approximately Rs. 16,000 (around $168) (14).

In practical terms, the annual income difference between hydroponic and traditional farming, is around Rs. 420,000 (around $4,410) compared to Rs. 36,000 (around $378) for an unsubsidised 200 square meter farm. This indicates that once the initial setup cost is paid off, hydroponics could create a meaningful and lasting increase in household income for small-scale farmers. The shorter payback period for subsidised farmers, roughly 4 months compared to 8 months for unsubsidised farmers pinpoints that subsidies and low interest financing could substantially accelerate adoption, by lowering the barrier of the initial investment. This effect would be most significant for farmers who are currently in the lower income

brackets identified in the secondary data. This is because they are the ones least able to absorb a high upfront cost, without receiving external support.

There are several limitations to these findings. The financial model relies on modelled and secondary data rather than data collected directly from operating hydroponic farms. Thus, actual costs and returns experienced by real farmers may differ from the estimates that were used here. In addition, the model excludes variables, such as inflation, currency fluctuations, crop failure risk and regional labor costs. These aspects could affect real world profitability. Additionally, because the model is based on a standardized 200 square meter farm, the findings may not generalize well to smaller rooftop systems or larger commercial operations, as the cost structure could be very different.

The generalizability of these findings across different contexts is also limited by the fact that the secondary data used was drawn primarily from a small number of countries, including India, Singapore, China, Vietnam and Kenya. While these countries share common challenges, such as land scarcity and climate vulnerability, other regions may face different regulatory, economic or environmental conditions that would change how feasible hydroponics is in practice. Future research using primary data which is collected directly from small-scale hydroponic farmers across a wider range of countries would help to test whether the affordability patterns identified in this study hold more broadly.

CONCLUSION

The findings of the research have demonstrated that renewable-energy-powered hydroponics systems have a strong potential to improve affordability and productivity for the majority of small-scale farmers. The evidence collected from academic websites, articles, international organizations and government reports have stressed that hydroponics can offer greater land use efficiency and higher productivity, especially for farmers with limited available land (10), (21). The graph which was developed in this study illustrated that a 200 square meter unsubsidised hydroponic system could generate Rs 420,000 annually. Whilst a 200 square meter traditional farming system can generate around Rs 36,000 annually. The line graph that compares annual income per 50 square meters effectively supports the claim that hydroponic systems can produce a substantially higher income compared to traditional farming systems. This supports the hypothesis that hydroponics can improve the economic gain for small-scale farmers when it is implemented well.

While solar panels could increase initial setup costs, long-term energy expenses would be reduced. This in turn would improve sustainability and efficiency over time. Additionally, there are subsidies that could help reduce costs for solar panels. The research has illustrated that modern agriculture is rapidly shifting towards technology driven and resource efficient systems. Hydroponics demonstrates that agricultural productivity does not require large land holdings. This makes it relevant for urban farming, small-scale entrepreneurship and countries who are facing water scarcity. Moreover, the research has highlighted how small-scale hydroponic systems can create several opportunities for younger entrepreneurs and future sustainable food businesses (13) (19).

However, the research paper has identified important limitations. One of these is the high setup cost which remains the largest barrier, as it is preventing widespread adoption among small-scale farmers. In addition, technical knowledge, maintenance requirements, and access to infrastructure and technological knowledge can limit accessibility in several regions. Therefore, while hydroponics offers strong long-term benefits, affordability challenges still exist during early stages in different countries.

The implications of this research are important for governments and policymakers. Governments might consider increasing support for small-scale hydroponic systems by providing subsidies, renewable energy, low interest loans and technical training programs for farmers. Additionally, many educational institutions and agricultural organizations could invest in research and awareness programs which are related to sustainable farming technologies.

Future research could expand on this study by collecting long-term operational data from active hydroponic farms and comparing different renewable energy systems within hydroponic systems. Another connected area of research can examine how hydroponics can support hospitality through food supply systems for hotels and restaurants around the world. As the hospitality industry increasingly prioritizes fresh and locally sourced ingredients, small-scale hydroponic systems could offer hotels and restaurants a reliable and sustainable supply of produce. This is applicable in land- and water-scarce regions. Therefore, future studies could examine partnerships between hydroponic farmers and hospitality businesses to determine whether such supply chains are commercially viable and mutually beneficial. Lastly, another expansion to this research topic could be to find affordability for different crops in order to have data about income from various hydroponic farms.

Overall, this research has supported the conclusion that renewable-energy-powered hydroponics have strong potential to become a more sustainable and affordable farming solution for small-scale farmers in the future.

REFERENCES

[1] ARS. n.d.. *Renewable energy*. https://www.agrirs.co.uk/key-terms/renewable-energy
[2] Al Jazeera. (2023). *Adapting in the face of climate change in rural Kenya*. https://www.aljazeera.com/gallery/2023/12/15/adapting-in-the-face-of-climate-change-in-rural-kenya
[3] Shrestha, A., & Dunn, B. (n.d.). *Hydroponics*. Oklahoma State University Extension. https://extension.okstate.edu/fact-sheets/hydroponics.html
[4] EBSCO Information Services. (n.d.). *Small-scale agriculture.* EBSCO Research Starters. https://www.ebsco.com/research-starters/agriculture-and-agribusiness/small-scale-agriculture
[5] EOS Data Analytics. (2024). *Agriculture problems farmers face today*. https://eos.com/blog/agriculture-problems/
[6] Food and Agriculture Organization. (2014). *The State of Food and Agriculture: Innovation in Family Farming*. FAO. https://www.fao.org/3/i4021e/i4021e.pdf
[7] Food and Agriculture Organization. (2017). *The State of Food and Agriculture 2017: Leveraging Food Systems for Inclusive Rural Transformation*. FAO. https://www.fao.org/3/i7658e/i7658e.pdf

[8] Food and Agriculture Organization. (2018). *Family farming knowledge platform*. FAO. https://www.fao.org/family-farming/detail/en/c/1045935/
[9] Food and Agriculture Organization. (2019). *The State of Food and Agriculture 2019*. FAO. https://www.fao.org/3/ca6416en/ca6416en.pdf
[10] Food and Agriculture Organization. (2021). *The State of Food and Agriculture 2021*. FAO. https://www.fao.org/3/cb8061en/cb8061en.pdf
[11] Government of India, Ministry of Agriculture & Farmers Welfare. (n.d.). *Department of Agriculture and Farmers Welfare*. https://agricoop.nic.in/en
[12] Haryanto, L. I., Hendrawati, T. Y., Darto, D., Yani, F., Listanto, F. A., & Pratama, D. Y. P. (2024). *Utilization of solar energy in hydroponic systems for enhancing energy independence in farming communities*. ResearchGate. https://www.researchgate.net/publication/388698333_Utilization_of_solar_energy_in_hydroponic_systems_for_enhancing_energy_independence_in_farming_communities
[13] International Renewable Energy Agency. (2023). *Renewable power generation costs in 2022*. IRENA. https://www.irena.org/publications/2023/Jun/Renewable-Power-Generation-Costs-2022
[14] Ministry of New and Renewable Energy. (2024). *PM-KUSUM Scheme*. Government of India. https://mnre.gov.in/en/pm-kusum/
[15] National Horticulture Board. (2020). *Mission for Integrated Development of Horticulture Guidelines*. Government of India. https://hortnet.gov.in/Guidelines/midh_Guidelines.pdf
[16] National Sample Survey Office. (2019). *Situation assessment of agricultural households and land holdings of households in rural India*. Ministry of Statistics and Programme Implementation, Government of India. https://mospi.gov.in/sites/default/files/publication_reports/Report_587m_0.pdf
[17] Press Information Bureau. (2023). *Government initiatives for hydroponics and protected cultivation*. Government of India. https://www.pib.gov.in/PressReleaseIframePage.aspx?PRID=1896134
[18] Wood, J., Wong, C., & Paturi, S. (2020). Vertical farming: An assessment of Singapore City. eTropic: Electronic Journal of Studies in the Tropics, 19(2), 228–248. https://doi.org/10.25120/etropic.19.2.2020.3745
[19] Rana, A., Kaushal, S., & Kanwar, A. (2025). *Renewable-powered off-grid hydroponic systems for resource-efficient agriculture: A comprehensive review*. International Journal of Environment and Climate Change. https://journalijecc.com/index.php/IJECC/article/view/5145
[20] Sharma, N., Acharya, S., Kumar, K., Singh, N., & Chaurasia, O. P. (2018). *Hydroponics as an advanced technique for vegetable production*. Journal of Soil and Water Conservation. https://www.agriculturejournal.org/volume6number2/hydroponics-a-technique-for-cultivation-of-vegetables-and-medicinal-plants/
[21] University of the Virgin Islands. (n.d.). *Hydroponics research program*. University of the Virgin Islands Agricultural Experiment Station https://www.uvi.edu/research/agricultural-experiment-station/aquaculture-home/aquaponic-systems/index.html
[22] World Bank. (2016). Transforming Vietnamese agriculture*: Gaining more from less*. World Bank Group. https://openknowledge.worldbank.org/handle/10986/31037
[23] World Bank. (2020). *Solar photovoltaic power potential by country*. World Bank Group. https://www.worldbank.org/en/topic/energy/publication/solar-photovoltaic-power-potential-by-country

[24] Li, Q., Yu, Z., Li, M., Zhang, G., Lu, T., Li, Y., Yu, H., & Jiang, W. (2023). Urban vegetable production in Beijing, China: Current progress, sustainability, and challenges. Frontiers in Sustainable Food Systems, 7. https://doi.org/10.3389/fsufs.2023.1191561
[25] Self Help Africa. (2025). *Hydroponics Boosts Yields for Kenyan Farmers.* https://selfhelpafrica.org/us/hydroponic-farming-kenya/