Economic Viability of Cucumber Farming: Hydroponic Systems VS Traditional Soil Methods

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Abstract

Protective cultivation, in both soil-based and soilless systems, provides a controlled environment that enhances crop productivity, particularly for greenhouse cucumber production. However, various dynamic factors significantly influence production outcomes, including temperature, humidity, radiation, irrigation, fertigation, disease incidence, and operational costs (e.g., electricity, diesel, and labor). While soilless cultivation effectively manages soil-borne diseases and improves yield and quality, it also raises production costs, posing challenges for marginal farmers in developing countries due to high initial investments and limited access to information. Economic analyses confirm that greenhouse production is more profitable than open-field cultivation, although costs associated with artificial heating and cooling for microclimate control remain limited. Hydroponic systems, for instance, yield Rs. 815,000 per acre compared to Rs. 42,748.5 for soil-based systems and demonstrate superior production efficiency (200,000 kg/acre versus 9,000 kg/acre). Despite this, progressive farming systems outperform hydroponics in return on investment (ROI: 7.07 vs. 1.40), cost efficiency, and investment turnover. Results from MANOVA analysis reveal the statistically significant impact of operational and cost factors on greenhouse profitability (Wilks' Lambda: F = 649.62, p < 0.01). Protective cultivation facilitates off-season vegetable production and yields higher, particularly in favorable hilly regions. To promote wider adoption, government agencies must offer subsidies for infrastructure and technology while providing marginal farmers with real-time meteorological data for improved crop planning and environmental management.

Keywords: Hydroponic Cucumber, Economic Analysis of Cucumber, Soil-based Cucumber, Comparison between Soil-based and Soil Fewer Cucumber.

Introduction

As the global population continues to rise, the demand for various products, particularly food, is increasing rapidly. This growing demand raises concerns about a potential food crisis in the coming years. Adopting alternative farming methods and exploring new food production sources is crucial to mitigating such crises. This paper compares two farming systems—traditional soil-based and hydroponic—to determine which is more effective in meeting current and future food demands while minimizing costs and resource consumption.

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Production risks are inherent in greenhouse agriculture, as growers have limited and costly solutions for managing pest or disease outbreaks. The restricted availability of chemical control options has prompted some growers to explore organic production methods. However, managing organic production in a controlled environment remains challenging (Tüzel et al., 2004). Despite these challenges, organic greenhouse production is appealing because many greenhouses operate without pesticides. The primary difficulty lies in developing fertility practices that meet certification standards while maintaining yields (Miles & Peet, 2000). Additionally, consumer preference for quality over price has been noted; buyers are often willing to pay more for visually appealing, packaged organic cucumbers due to perceived health benefits, improved nutrition, better flavour, and reduced cancer risks (Estes et al., 1999; Greer & Diver, 2000).

Engindeniz (2004) conducted an economic analysis of greenhouse cucumber production using soilless systems in Turkey, emphasizing the need for local-level cost and return assessments. Similarly, Engindeniz et al. (2009) compared the economics of soilless and soil-based cucumber production in Turkey to evaluate their respective costs and profitability. Delannay et al. (2010) investigated inbred backcross lines of European cucumbers grown in both soil and soilless systems, highlighting the importance of genetic diversity in improving cucumber production. Zhang et al. (2012) explored how Trichoderma harzianum mutants enhance cucumber growth in greenhouse settings by improving plant colonization and indole acetic acid production. Hedau et al. (2014) examined energy efficiency and the economic viability of various vegetable cropping sequences under greenhouse conditions, recommending a tomato-cucumber sequence for optimal results. In Kenya, Croft et al. (2017) assessed the nutritional density and economic feasibility of hydroponic vegetable amaranth production, demonstrating the benefits of hydroponic systems. Balqiah et al. (2020) analyzed consumer purchase intentions to enhance hydroponic adoption, identifying key influencing factors. Hesampour et al. (2022) conducted a comprehensive energy-economic-environmental assessment of polyethene and polycarbonate greenhouses for cucumber production, considering the entire production-to-distribution process. These studies emphasize the growing interest in hydroponic and soil-based systems, focusing on economic viability, energy efficiency, growth promotion, and environmental sustainability.

Hydroponics is an advanced technology that enables plant growth in nutrient-rich solutions (water and fertilizers) with or without artificial growing mediums, such as sand, gravel, rock wool, peat, and coir, which provide mechanical support. Hydroponic systems are generally enclosed in greenhouse structures in temperate regions to regulate temperature, reduce water loss, and minimize pest and disease infestations. Controlled Environment Agriculture (CEA) using hydroponics offers numerous benefits, including high crop density, maximum yields, the ability to grow crops where soil quality is poor, and reduced dependence on temperature and seasonal changes. Hydroponics also optimizes water and fertilizer usage, minimizes land requirements, and supports mechanization. Hydroponics isolates crops from soil-related issues, such as pests, diseases, salinity, and poor drainage. However, hydroponics also has drawbacks, including high capital and energy costs and the need for advanced management skills. These challenges are particularly pronounced when artificial heating and cooling are required for greenhouse operations.

Traditional soil-based farming involves cultivating crops directly in natural soil with pesticides, herbicides, and irrigation water. Soil can vary in structure and texture, with the main types being:

1. Clay
2. Sand and gravel
3. Silt

4. Loam, and
5. Organic soil (less common).

Soil-based farming is defined as growing crops in natural soil under open-air conditions. However, it often requires large land areas and inefficient water usage, posing significant environmental challenges.

Enhancing agricultural productivity remains a global priority, directly influencing trade and economic growth. Productivity improvements rely on technological advancements and innovations most prevalent in developed nations. Developing countries, such as Pakistan, are also striving to increase productivity. Pakistan has a population of approximately 188 million, with 67% of its people relying on agriculture, which employs 43.7% of the national labour force (GoP, 2014). Horticulture contributes 11% to the agricultural economy, yet crop yields remain stagnant except for major staple crops. Enhancing productivity requires addressing technological, marketing, and policy-related challenges at both micro and macro levels.

Cucumber (Cucumis sativus L.) is one of the most widely grown vegetables worldwide (Soleimani et al., 2009). It thrives under warm conditions with temperatures above 20°C, high light, humidity, soil moisture, and fertilizer availability in greenhouse settings (Engindeniz & Gül, 2009). Cucumbers can be grown through direct seeding or transplantation, with row spacing of 120-150 cm and plant spacing of 30-45 cm. Cucumbers are valued for their tender fruits, consumed raw as salads, cooked, or pickled. Key quality parameters include fruit firmness, which depends on water retention, and a dark green color achieved through chlorophyll in the epidermis. Chlorophyll breakdown leads to the de-greening of cucumber fruit.

The cultivation of off-season cucumbers is increasingly popular alongside conventional vegetable production. A Punjab, Pakistan study aimed to evaluate off-season cucumber production's technical, allocative, and economic efficiency. Data were collected from 70 growers through random sampling in 2014. Results from Data Envelopment Analysis (DEA) showed average technical efficiency at 87.4%, allocative efficiency at 42.0%, and economic efficiency at 37.2%. These findings suggest a potential 12.6% reduction in input use and a 58.0% reduction in production costs while maintaining the same output levels. The lowest efficiencies recorded were 60.7% (technical), 13.7% (allocative), and 9.9% (economic). Medium-sized farms demonstrated the highest technical (96.7%) and financial (46.5%) efficiency, whereas small farms achieved the highest allocative efficiency (49.0%). Factors such as education, farming experience, and interactions with extension staff significantly reduced inefficiency, while family size, cultivated area, and distance to markets increased inefficiency. To address these issues, the government should improve education, provide technical support, and subsidize tunnel materials for small farmers.

This research highlights the need for sustainable and efficient cucumber production methods to meet growing demand. By comparing soil-based and hydroponic systems, this study provides insights into modern agriculture's economic, technical, and environmental aspects, particularly in developing regions like Pakistan.

Data and Methodology

Functional Form of the Model

In cucumber production, the hydroponic approach requires a comprehensive assessment of costs and benefits. Costs reflect system investments, while profits represent the returns generated. Expenditures as investments are necessary for any production system to achieve potential benefits. This structured framework facilitates an evaluation of various production systems' economic feasibility and sustainability. The costs involved in hydroponic cucumber production are categorized as follows:

Fixed Cost (FC) or Capital Cost

Fixed costs are one-time expenses incurred for constructing and setting up the hydroponic production system, including machinery, equipment, and infrastructure. These costs are critical to determining the initial financial barrier to adopting the hydroponic system.

Variable Cost (VC) or Operational Cost

Variable costs are recurring expenses that fluctuate based on the operational intensity of the hydroponic production system, such as nutrient solutions, labour, electricity, and maintenance. These costs are pivotal in determining the system's scalability and profitability.

The profit (P) from hydroponic cucumber production is calculated using the following equation:

$$P(S, H) = R(S, H) - C(S, H) \qquad (1)$$

Where:
P = Profit (PKR)
S = Type of cucumber production system (Soil-based or Hydroponic)
H = Farming system (Hydroponic)
R = Revenue generated from cucumber sales
C = Total cost of cucumber production, including fixed and variable costs

For further analysis, total production costs (C) are divided into two components:

$$C = FC + VC \qquad (2)$$

Production Methodology for Traditional Farming Systems

The conventional soil-based farming approach is included for comparative analysis to highlight the relative advantages and limitations of hydroponic systems. In traditional systems, plant growth depends heavily on environmental and soil conditions. Water constraints during the production cycle often reduce productivity, particularly in regions where high temperatures and limited water availability slow plant development. Other factors, such as poor water quality, high pH levels, and excessive electrical conductivity, further impact overall output.

In contrast, hydroponic systems allow precise control over critical growth factors such as water volume, quality, and temperature, enhancing plant characteristics like height, leaf length, inflorescence, number of leaves, fruit set, and head thickness. This controlled environment minimizes external dependencies and ensures consistent yields.

Methodology

This study considers multiple farming systems based on their technological applications, cultivation practices, and outcomes. The three systems analyzed are:

Progressive Farming

Progressive farmers adopt advanced technologies and reduce risks through intensive training programs. Modern innovations such as drip or spray irrigation are employed to improve water use efficiency and crop productivity.

Soil-Based Farming

This traditional approach relies on cultivating crops in natural soil using conventional practices, including composting and pesticide applications. While cost-effective, it is more vulnerable to environmental and soil-borne challenges.

Hydroponic Farming

Hydroponic farming grows crops in nutrient-rich solutions, eliminating soil-related issues. The plants are supported on an inert substrate, such as coir, which ensures optimal root health and nutrient uptake.

Data Collection

Primary data were collected from farms across the Bahawalpur district for the year 2020. This region was selected for its diverse farming practices and accessibility to different systems. Data collection methods included farmer interviews and field observations. Hydroponic farms, being fewer in number and geographically dispersed, presented sampling challenges, but sufficient data were gathered to ensure robust analysis.

Financial Measures

To evaluate financial performance, the following measures were selected based on prior studies (Hyblova and Skalicky, 2018; Zorn et al., 2018):

Return on Sales (ROS)

Ratio of revenue to production.

$$ROS = R / P \quad (3)$$

ROS indicates how effectively the farming system converts sales revenue into profit, helping assess operational efficiency.

Return on Investment (ROI)

Ratio of revenue to investment.

$$ROI = R / I \quad (4)$$

ROI measures the profitability of investments, allowing comparison of different systems' economic viability.

Operating Ratio (OR)

Ratio of investment to production.

$$OR = I / P \quad (5)$$

OR evaluates cost efficiency, helping identify areas to optimize resource utilization.

Personnel Cost Ratio (PCR)

Ratio of fixed costs to production.

$$PCR = FC / P \quad (6)$$

PCR highlights the weight of fixed costs in total production costs, useful for assessing capital-intensive systems like hydroponics.

Investment Turnover Ratio (ITR)

Ratio of production to investment.

ITR = P / I...(7)
ITR indicates how efficiently investments translate into production output, a key factor for system scalability.

Earnings Before Interest and Taxes (EBIT)
EBIT is used to estimate ROS and ROI as it isolates operational performance without the influence of taxes or capital structure costs. Agricultural subsidies, where applicable, are included in the revenue calculations. EBIT offers a standardized measure of profitability, ensuring fair comparisons across farming systems.

These indicators were chosen to comprehensively evaluate profitability, cost efficiency, and return on investment across the three systems. Including EBIT ensures a focus on core operational performance while isolating external financial factors, such as taxes and subsidies This structured methodology ensures a clear and objective comparison of financial performance and production efficiency across hydroponic, soil-based, and progressive farming systems, providing valuable insights into their economic and operational dynamics.

Results and Discussion

Table 1: Cost analysis of soil-based

Total fixed cost			
Operations / Inputs	**Average No of Units/Acre**	**Rate /unit Rs**	**Cost /Acre Rs**
IRRIGATION			
Canal Water Rate (Abiana/Acre)		56.3	100
Private Tubewell (3Hrs/ Irrigation)	10	1000	10000
Labor Charges for Irrigation (M. days)	6	525	3150
Cleaning of watercourses (M. days)	1	525	525
Sub Total			**13775**
Land Rent for 6 Months @50,000 / 50,000 PA	50000	0.05	25000
Agricultural Income Tax.			48
Management Charges for 6 Months of a	6	150	900
Total fixed cost			**39723**

The 1 shows the total fixed cost for the soil based cucumber the which is Rs.39723 per Acre which include the cost of Irrigation which is Rs13775 per acre, land rent which is as described by the grower is 25000 per Acre, the Income-tax paid for per acre is Rs. 48 and the management cost is 900 per acre.

Table 2: Total variable cost

Operations / Inputs	Average No of Units/Acre	Rate /unit Rs	Cost /Acre Rs
Preparatory tillage ploughing			
Rotavator	1	1340	1340
Deep ploughing	0.5	1340	670
Ploughing / Cultivator	3	627	1881
Planking	6	400	2400
Leveling	0.3	1300	390
Sub Total			6681
Seed bed preparation			
Ploughing Planking	2	800	1600
Sub Total			1600
Seed and sowing operations			
Seed (Kgs)	1	3000	240
Nursery raising	1	5000	5000
Bed making with ridge	1	1280	1280
Uprooting, Transplanting and Transporting	4	525	2100
Sub Total			8620
Farm yard manure			
Farm Yard manure (Trolly)	3	1100	3300
Labor for spreading Manure &Transportation (Man days)	3	525	1575
Sub Total			4875
Fertilizers: (bag)			
Urea	1.5	1640	2460
DAP	1	3750	3750
SOP/ MOP	1	3100	3100
Transportation	3.5	20.99	73.465
Fertilizer Application (Man days)	2	525	1050
Sub Total			10433.465
Plant protection			
Treatments	6	500	3000
Hoing /Earthing up &Weeding	6	525	3150
Sub Total			6150
Harvesting			
Picking of ripened fruit	40	525	21000
Handling & Transportation	10	525	5250
Empty Bags.	493	12	5916
Sub Total			32166
Total Variable Cost			70558.5

The total variable cost for the soil-based cucumber is the 70558.5 Rs. Per acre which includes the cost of preparatory tillage plowing, seedbed preparation, seed and sowing operations, farmyard manure, fertilizers, plant protection, and harvesting values has been given in the table.

$C = FC + VC$

C = 39723 + 70558.5

C= 110251.5

The total cost for the soil-based Cucumber is 110251.5 per acre.

Table 3: Production

Description	
Yield per Acres	9000 (kgs)
Cost Per Kg at the farm level.	12.25 (Rs)
Cost Per 40 KGs at the farm level.	490 (Rs)
Marketing Expenses	34 (Rs/40 Kgs)
Cost Per 40 KGs at the mandi gate.	524 (Rs)
Investment Incentive @25 %	129 (Rs)

The further analysis shows that The Production per acre is 9000 Kgs and the cost per kg at farm level is 12.25 and the cost per 40 kgs at farm level is 490 Rs the marketing Expense per 40 Kgs is 34 Rs Cost per 40 KGs at mandi gate is 524 Rs. So, including these costs to the Production Cost, the Total Cost is 110251.5 at the mandi gate. If the selling price is Rs,17 then the total sale of 9000 kg cucumber is Rs,153000

$P_{S,H} = R_{S,H} - C_{S,H}$

P = 153000 – 110251.5

P = 42748.5

Cost analysis of hydroponic Cucumber

The land is one acre.

Structure Cost is approx.: Rs.1,6,000,000.00

Table 4: Cost analysis of hydroponic cucumber crop at 1 acre area

Sr. No	Description	Unit	Unit Cost Rs.	Qty	Months	Total Cost Rs.
1	Manager	Person	75000	1	6	450000
2	Marketing Supervisor	Person	40000	2	6	480000
3	Labor	Person	20000	6	6	720000
4	Energy Cost (Water & Electricity)		40000	1	6	240000
5	Seed	Pcs	5	11000	6	55000
6	Nutrients	Kg/ltr	125000	1	6	125000
7	Coco Peat	Block	4	1000	6	40000
8	Miscellaneous cost				6	75,000
9	Marketing (packing material, transportation, etc.)					400,000
				Total Cost		**2585000**
10	Production				200000 Kgs)	
11	Production Cost per kg				12.92	12.92
12				Sale Price		17
				Total Revenue		**3400000**
				Net Income		**815000**

The cost for hydroponic cucumber is 2585000 per acre which includes the costs of structure, managing, marketing, labore, energy, seed, nutrients, cocopeat, and miscellaneous costs. The description of this cost is described in the table 4.the production for hydroponic cucumber per acre is 200000 kgs. the total revenue at an average sale price of 17 Rs is 3400000.

So, the profit for hydroponic cucumber is.
$P_H = R_H - C_H$
P = 3400000 – 2585000
P =815000
The profit for hydroponic is 815000 per acre.
The finding of the cost and the profit functions of both equations shows that the cost for soil-based is 110281.5 per Acre which is almost 25 times less to the cost of Hydroponic based which is 2585000 per Acre. While the finding further shows that the profit and production of hydroponic are much greater than the soil-based as shown before.

Table 5: Descriptive Statistics

Financial indicators

Indicator	Descriptive statistics	Hydroponics	Soil Based	Progressive
ROS	mean median	16.58	20.25	16.22
	Std. dev.	3.44	3.49	2.82
	min.	10.53	14.27	11.34
	max.	23.50	28.12	19.36
ROI	mean median	1.40	1.18	7.07
	std. dev.	0.22	0.19	0.96
	min.	1.18	0.85	5.43
	max.	1.93	1.62	8.39
OR	mean median	11.94	17.39	2.28
	std. dev.	2.52	2.94	0.17
	min.	8.50	12.25	2.06
	max.	16.60	24.40	2.55
PCR	mean median	1.03	5.34	0.70
	std. dev.	0.17	0.67	0.07
	min.	0.86	4.41	0.61
	max.	1.36	6.58	0.79
ITR	mean median	0.09	0.06	0.44
	std. dev.	0.02	0.01	0.03
	min.	0.06	0.04	0.39
	max.	0.12	0.08	0.49

Note: ROS – return on sales; ROI – return on Investment; OR – operating ratio; PCR – personnel cost ratio; ATR – asset turnover ratio

The financial performance of hydroponic, soil-based, and progressive farming systems was analyzed using key financial indicators, including Return on Sales (ROS), Return on Investment (ROI), Operating Ratio (OR), Personnel Cost Ratio (PCR), and Investment Turnover Ratio (ITR). The results highlight notable profitability, and cost differences across these farming systems.
Consistent differences between the mean and median values across the indicators suggest slight skewness in the data distribution, particularly in progressive farming for ROI and OR. For instance, the progressive system's ROI mean of 7.07 and a relatively close median indicate moderate skewness. Hydroponics exhibits higher variability in ROS, OR, and PCR compared to progressive systems, reflecting greater uncertainty and sensitivity to operational changes. Progressive systems demonstrate lower standard deviation in most indicators, indicating more consistent performance. The range for OR in hydroponics (8.50–16.60) reflects operational challenges that can vary

significantly. Meanwhile, the tighter range for progressive systems (2.06–2.55) suggests more stable cost management.

The results demonstrate that progressive farming systems outperform hydroponic and soil-based systems across all financial indicators. Progressive farming achieved the highest ROI, lowest operating and personnel cost ratios, and superior investment turnover efficiency. Hydroponics, while showing competitive ROS, struggled with high operating ratios and moderate investment returns due to its capital-intensive nature. Meanwhile, despite achieving the highest ROS, soil-based farming faced significant challenges in terms of ROI, cost efficiency, and fixed cost burdens. These findings underscore the financial advantages of adopting progressive farming practices, which combine advanced technologies and cost-efficient strategies to maximize profitability and resource utilization.

Return on Sales (ROS) measures the profitability relative to revenue. Soil-based farming recorded the highest mean ROS at 20.25, ranging from 14.27 to 28.12, indicating strong sales-to-cost efficiency despite its variability (Std. Dev. = 3.49). Hydroponics followed with a mean ROS of 16.58, exhibiting a narrower range of 10.53 to 23.50, suggesting consistent yet moderate profitability. Progressive farming, while more stable (lowest Std. Dev. = 2.82), had the lowest ROS at 16.22, ranging from 11.34 to 19.36. These results suggest that soil-based farming generates higher returns per unit of revenue, but hydroponics also demonstrates competitive profitability with fewer fluctuations.

The Return on Investment (ROI) analysis reveals stark contrasts between the systems. Progressive farming achieved a significantly higher ROI, with a mean of 7.07 and a range of 5.43 to 8.39, showcasing its exceptional ability to generate returns on investment. In comparison, hydroponics recorded a modest mean ROI of 1.40, ranging from 1.18 to 1.93, while soil-based farming had the lowest ROI at 1.18, with a range of 0.85 to 1.62. These results indicate that progressive farming systems utilize capital far more efficiently than hydroponic or soil-based systems, which need help to deliver substantial returns relative to their investments.

The Operating Ratio (OR), which measures cost efficiency, further emphasizes the differences among the systems. Progressive farming reported the lowest mean OR at 2.28, with minimal variation (Std. Dev. = 0.17) and a range of 2.06 to 2.55, indicating superior cost efficiency in production. Hydroponics, by contrast, had a much higher mean OR of 11.94 (range: 8.50 to 16.60), reflecting its capital-intensive nature. Soil-based farming exhibited the highest OR at 17.39, with substantial variability (range: 12.25 to 24.40), suggesting inefficiencies in cost management. These results confirm that progressive farming systems are far more cost-effective than the other two methods.

The Personnel Cost Ratio (PCR) highlights the burden of fixed costs on production. Soil-based farming had the highest PCR, with a mean of 5.34 and a range of 4.41 to 6.58, indicating significant fixed cost pressures relative to output. Hydroponics followed with a mean PCR of 1.03 (range: 0.86 to 1.36), showing a moderate fixed cost burden. Progressive farming maintained the lowest PCR at 0.70 (range: 0.61 to 0.79), reflecting its efficient labor and fixed costs management. These findings indicate that soil-based farming faces considerable challenges in managing fixed costs, while progressive systems operate with minimal fixed cost burdens.

Finally, the Investment Turnover Ratio (ITR), which assesses production efficiency relative to investment, highlights the superiority of progressive farming. Progressive systems achieved the highest mean ITR at 0.44, with minimal variability (range: 0.39 to 0.49), demonstrating efficient utilization of investments to generate output. In contrast, hydroponics and soil-based systems reported much lower ITRs, with means of 0.09 and 0.06, respectively. The ITR for hydroponics ranged from 0.06 to 0.12, while soil-based systems reported the narrowest range of 0.04 to 0.08, further highlighting their lower investment efficiency.

Table 6: Results of MANOVA

Factor	***F* statistics**	***P*-value**	**Significance**
Wilks' lambda	649.62	0.0000	***
Lawley-Hotelling trace	277.95	0.003	**
Pillai's trace	495.51	0.0000	***
Roy's largest root	2.285	0.049	**

Note: *, **, ***statistical significance levels at 0.1, 0.05 and 0.01, respectively

A multivariate analysis of variance (MANOVA) was conducted to assess the combined effect of multiple factors on the financial indicators of hydroponic, soil-based, and progressive farming systems. The results in the table include Wilks' Lambda, Lawley-Hotelling Trace, Pillai's Trace, and Roy's Largest Root as multivariate test statistics, along with their respective F-statistics, P-values, and significance levels.

The analysis reveals that operational and cost factors significantly influence profitability across farming systems, underscoring notable differences in their financial performance and operational dynamics. The robustness of these findings is confirmed by significant MANOVA results, with group differences validated at varying significance levels (*** and **). Key financial indicators, including ROS, ROI, OR, PCR, and ITR, show highly significant variations ($p < 0.01$), highlighting their effectiveness in distinguishing system performance. ROI emerges as a critical metric with the highest explanatory power ($F = 939.88$, $p < 0.0000$), emphasizing its importance in evaluating investment efficiency. Similarly, the pronounced differences in ITR ($F = 2340.81$, $p < 0.0000$) demonstrate the exceptional efficiency of progressive farming in converting investments into output.

However, hydroponics exhibits higher variability, indicating challenges in maintaining consistent sales profitability, which could be mitigated by addressing operational inefficiencies and ensuring market stability. Conversely, the lower variability in progressive farming suggests it as a more stable option for risk-averse farmers, supporting the case for policies promoting training programs to enhance adoption. The consistent significance of results across both MANOVA and ANOVA reinforces confidence in these conclusions.

The results of the MANOVA analysis demonstrate that the farming systems (hydroponic, soil-based, and progressive) differ significantly across the financial indicators. The substantial significance observed for Wilks' Lambda and Pillai's Trace provides the most robust evidence of these group differences. At the same time, the Lawley-Hotelling Trace and Roy's Largest Root confirm these findings at lower thresholds. These results collectively highlight that the farming system type statistically impacts the measured financial indicators.

The Wilks' Lambda statistic yielded an F-value of 649.62 with a P-value of 0.0000, indicating strong statistical significance at the 0.01 level (). This result confirms that the explanatory factors significantly influence the dependent variables, providing robust evidence of group differences across the farming systems. The Pillai's Trace statistic also showed strong significance, with an F-value of 495.51 and a P-value of 0.0000, again significant at the 0.01 level (). This further supports the conclusion that the factors under consideration have a significant multivariate effect on the financial indicators. Pillai's Trace is instrumental in scenarios where group differences are less homogenous, making this result even more robust.

The Lawley-Hotelling Trace produced an F-value of 277.95 and a P-value of 0.003, indicating significance at the 0.05 level (). Although slightly weaker than Wilks' and Pillai's results, this statistic still confirms the presence of meaningful differences across the systems. Lastly, Roy's Largest Root had an F-value of 2.285 with a P-value of 0.049, which was significant at the 0.05 level (). Although less sensitive than the other tests, this statistic identifies the most considerable single-group difference and supports the conclusion of significant multivariate effects. For more comparison, we have built a brief comparison in the below table.

Table 7: Comparison

Description	Soil based	Hydroponics
Land use efficiency	Less due to: Variation in soil fertility Competition with weeds Less water availability	As no soil is used so no such problems thus there is high plant density (more plants per square meter)
Water use efficiency	Less due to: Shortage of water High evaporation losses Less irrigation efficiency	Require 1/30 the amount of water that is required for same area with conventional method.
Soil degradation	High due to poor irrigation efficiency, high dosage of fertilizer and pesticides resulting in problems such as waterlogging and salinity	No soil is used in this the system thus no damage is done to it.
Resource utility	More land, labor, and capital is required	Efficient and profitable utilization of natural and artificial resources
Resource conservation	All-natural resources such as water fertilizer is used in a noncyclic way. (They are used only once and not again resulting in wastage of these valuable resources	All-natural resources such as water fertilizer are used in cyclic that is cyclic that are they are used again and again
Competition with weeds	High competition	Little or no risk of weeds
Effect of location	Location affects production due to different climatic condition at a different location.	Environment is controlled artificially so location does not affect crop production.
Benefit-cost ratio	Less	High
Quality	Low because field grower cannot control the quality parameters	Grower can influence quality parameter by adjusting pH Ec etc.
Market value	Less due to poor and variable Quality	Market value is high due to uniformity in size shape color and weight.
Consistency in Production	Very little or no consistency because production is dependent upon climatic conditions	More consistent production because production is not dependent upon climatic conditions.
Profitability ratio	Low	High
Production	9 ton	200 ton
Cost per kg	Rs. 12.25	Rs. 12.92

Conclusion and Recommendations

Despite its high energy requirements, the hydroponic system emerges as an up-and-coming and efficient agricultural technology. In regions facing limited water access, hydroponic systems' increased water use efficiency is particularly critical. Multiple factors, such as advanced regulation devices, can potentially reduce the cost of maintaining controlled environments in hydroponic greenhouses, thereby improving their economic viability. Given the rising global demand for land, water, and food, hydroponics offers a sustainable solution by optimizing resource use, saving time, and significantly increasing crop yields.

Compared to traditional soil-based (geoponic) systems, hydroponics requires far less land, freeing up space for ecological purposes like reforestation, wildlife conservation, or urban development. Moreover, hydroponics allows food production in regions where conventional agriculture is difficult or impossible, such as water-scarce areas, urban centers, or places with short growing seasons. By enabling localized production, hydroponics reduces reliance on imported food and minimizes transportation costs, making it a sustainable option for global food security. Additionally, by eliminating the need for soil—often a source of pathogens and pests—hydroponic systems reduce or eliminate the need for toxic pesticides, promoting safer and healthier food production.

The water-efficient nature of hydroponic systems is beautiful for city planners and policymakers in the context of increasing land and water scarcity. The active support of administrative authorities, coupled with subsidies and financial investments, can further accelerate the adoption of this technology by offsetting the high initial infrastructure costs. Hydroponics represents a forward-looking approach to food production, which holds immense potential for countries like Pakistan, where population growth, limited cultivable land, and stagnant yields present severe challenges.

In Pakistan, cucumber yields have remained stagnant over the past five decades, with the national average yield at only 10 tons per hectare. However, hydroponic technology has demonstrated its ability to revolutionize cucumber production, achieving an impressive average yield of 168 tons per hectare—a sixteen-fold increase. This success underscores the technology's capacity to transform Pakistan's horticulture sector, boosting productivity and profitability.

At the micro level, hydroponic systems can significantly enhance farmers' incomes, as the increased yields and year-round production potential make vegetable farming more lucrative. Furthermore, adopting hydroponics will modernize the horticultural sector, making it more high-tech and capital-intensive, fostering economic growth in rural and urban areas.

At the macro level, widespread adoption of hydroponic systems in Pakistan could have far-reaching economic benefits. By increasing domestic vegetable supply, hydroponics can reduce reliance on imports, turning Pakistan into a potential exporter of high-quality vegetables. This shift would strengthen foreign reserves and contribute to the country's economic stability. Additionally, the increased availability of vegetables in local markets will lead to higher per capita consumption, ultimately improving the health and nutrition of the population.

Hydroponic technology is not just an agricultural innovation but a solution to the critical challenges of food security, resource efficiency, and economic growth. Given the World Bank's warnings regarding Pakistan's future food crises due to rapid population growth, adopting hydroponic systems is no longer optional but necessary. By embracing this technology, Pakistan can revolutionize its agricultural sector, meet the growing food demand, and position itself as a leader in sustainable vegetable production.

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