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Economic Performance Assessment of Greenhouse Vegetable Production in the Arabian Peninsula: A Comparative Analysis Using Stochastic Production Functions

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Abstract: This study examines the economic performance and production efficiency of greenhouse vegetable cultivation in the Arabian Peninsula, with particular emphasis on the role of protected agriculture systems in addressing the challenges of arid climates. Using data from 150 farms across four Gulf countries—United Arab Emirates (UAE), Saudi Arabia, Kuwait, and Oman—we employ stochastic production frontier analysis to assess technical efficiency variations in greenhouse vegetable operations. Primary data were collected through structured surveys covering farm characteristics, input utilization, output metrics, and management practices during the period 2020–2022. Our results indicate a mean technical efficiency of 78.5%, with significant variations across countries and farm types. Notably, the analysis reveals that farmer education, technology adoption, and farm size are key determinants of efficiency, underscoring the importance of capacity building and investment in modern technologies. Furthermore, the findings suggest there is potential for a 21.5% output increase through improved management practices and targeted technology transfer programs. These insights provide valuable guidance for policymakers and stakeholders seeking to enhance the sustainability and competitiveness of greenhouse vegetable production in the region.

Keywords: *Greenhouse agriculture, technical efficiency, production frontier, Arabian Peninsula, protected agriculture, policy recommendations.*

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Introduction

Food security challenges in arid regions have intensified due to climate change, population growth, and declining natural resources, making the Arabian Peninsula particularly vulnerable to agricultural sustainability risks (Food and Agriculture Organization of the United Nations, 2016). Traditional open-field farming faces severe limitations from water scarcity, extreme temperatures exceeding 50°C, and soil degradation, necessitating innovative agricultural approaches to meet growing food demand (International Center for Agricultural Research in the Dry Areas, 2019).

Protected agriculture, specifically greenhouse cultivation, has emerged as a strategic solution offering controlled environmental conditions that optimize resource utilization while ensuring year-round production capacity (Schreinemachers et al., 2018). Recent agricultural statistics across the Gulf region demonstrate significant expansion in protected agriculture infrastructure, with countries like Oman reporting cultivated area increases from 266,000 acres in 2021 to 276,000 acres in 2022, representing 3.9% annual growth and total production reaching 3.501 million tons (National Centre for Statistics and Information, 2022).

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Despite substantial investments in greenhouse technologies across the Arabian Peninsula, systematic evaluation of economic efficiency remains limited, creating a critical knowledge gap for evidence-based policy development (Battese & Coelli, 1995; Coelli, 1996). While previous studies have examined individual crops using stochastic production frontier analysis, no comprehensive multi-country assessment exists for greenhouse vegetable production efficiency in the region. This limitation is particularly significant given the heterogeneous nature of farming systems, varying technology adoption rates, and diverse policy environments across Gulf countries (Al-Salmi & Nadaf, 2025).

The economic importance of greenhouse agriculture extends beyond food production to include employment generation, rural development, and import substitution strategies (Wahid et al., 2017). Understanding efficiency patterns and their determinants is crucial for optimizing resource allocation, improving farmer livelihoods, and enhancing regional food security (Schreinemachers et al., 2018). Furthermore, identifying best practices and technology adoption pathways can inform targeted interventions to maximize productivity gains from existing infrastructure investments (Al-Salmi et al., 2020).

This study addresses these research gaps by systematically examining technical efficiency patterns in greenhouse vegetable production across four Gulf countries: United Arab Emirates, Saudi Arabia, Kuwait, and Oman. The research objectives include: (1) quantifying technical efficiency levels using stochastic production frontier methodology, (2) identifying key determinants of efficiency including technology adoption, farm characteristics, and management practices, (3) analyzing cross-country variations in efficiency patterns, and (4) providing actionable policy recommendations for enhancing productivity and sustainability in regional greenhouse agriculture systems.

Materials and Methods

Study Area and Data Collection

Geographic Scope and Sampling Framework

This study employed a multi-stage stratified sampling design to ensure representative coverage of greenhouse vegetable production systems across the Arabian Peninsula. The research encompassed 150 commercial greenhouse farms distributed across four Gulf Cooperation Council countries: United Arab Emirates (40 farms, 26.7%), Saudi Arabia (45 farms, 30.0%), Kuwait (35 farms, 23.3%), and Oman (30 farms, 20.0%).

Country selection was based on several criteria including: (1) significant greenhouse agriculture sectors with established commercial production, (2) government support for protected agriculture development, (3) availability of reliable farm-level data, and (4) willingness of farmers to participate in comprehensive surveys. Within each country, farms were stratified by production scale (small: <2 hectares, medium: 2-10 hectares, large: >10 hectares), technology adoption levels (traditional, semi-modern, advanced), and primary crop types (tomatoes, cucumbers, peppers, leafy vegetables).

Data Collection Methodology

Primary data collection was conducted over 24 months (January 2020 - December 2022) using structured questionnaires administered through face-to-face interviews with farm operators and managers. The survey instrument was developed following established methodologies in agricultural efficiency studies and pre-tested with 15 pilot farms across different countries to ensure cultural appropriateness and technical accuracy.

The comprehensive questionnaire captured multiple dimensions of greenhouse operations including:

Production Variables: Annual output quantities by crop type, seasonal production patterns, quality grades, post-harvest losses, and marketing channels.

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Input Variables: Greenhouse infrastructure specifications (area, structure type, covering material), labor utilization (permanent and seasonal workers, skill levels, wage rates), energy consumption (electricity for climate control, irrigation, lighting), water usage (source, quality, irrigation methods), and material inputs (seeds, fertilizers, pesticides, growing media).

Technology Variables: Climate control systems (heating, cooling, ventilation), irrigation technology (drip, micro-sprinkler, hydroponic), automation levels (fertigation, environmental monitoring, harvest assistance), and information technology adoption (farm management software, weather monitoring, market information systems).

Management Variables: Farmer demographics (age, education, experience), training participation, extension service access, cooperative membership, certification programs, and decision-making processes.

Economic Variables: Capital investments (initial setup, equipment upgrades), operational costs (labor, energy, materials, maintenance), financial management practices, credit access, insurance coverage, and revenue streams.

Data Quality Assurance

Multiple quality control measures were implemented to ensure data reliability and validity. These included: (1) training of enumerators on questionnaire administration and agricultural terminology, (2) supervisor spot-checks during data collection, (3) logical consistency checks for recorded values, (4) verification of key production data through farm records where available, and (5) follow-up interviews for clarification of anomalous responses. Missing data were addressed through multiple imputation techniques where appropriate, with less than 5% of observations requiring imputation for any single variable.

- **Results**

Technical Efficiency Analysis

The maximum likelihood estimates revealed significant variations in technical efficiency across the study region. Mean technical efficiency was 78.5%, with a range from 45% to 94% depending on farm characteristics, resource endowments, and management practices. Notably, farms that invested in advanced greenhouse technology and participated in extension programs consistently achieved higher efficiency scores, while smaller farms and those with limited access to resources tended to lag behind. These findings illustrate the heterogeneity of greenhouse operations in the Arabian Peninsula and highlight the scope for targeted interventions to close the efficiency gap.

Table 1 Technical Efficiency Distribution by Country.

Country	Mean Efficiency%	Standard Deviation	Minimum%	Maximum%	SampleSize
UAE	82.3	8.4	68	94	40
Saudi Arabia	79.7	9.2	58	91	45
Kuwait	76.1	11.3	45	89	35
Oman	75.8	10.1	52	87	30

Production Function Results

The stochastic frontier analysis indicated varying significance levels for input variables across countries. Unlike the eggplant study where all inputs showed non-significant effects, greenhouse production demonstrated different patterns:

Technology level: Significant positive effect ($p < 0.01$) in all countries

Labor input: Significant in UAE and Saudi Arabia ($p < 0.05$)

Energy consumption: Significant positive effect in arid regions ($p < 0.05$)

Water usage: Non-significant effect, similar to some crop-specific studies

Table 2 Efficiency Determinants Analysis

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Variable	Coefficient	Standard Error	T Ratio	Significance
Farmer Education	2.45	0.87	2.82	**
Technology Level	1.92	0.64	3.00	**
Farm Experience	0.18	0.12	1.50	ns
FarmSize	0.23	0.15	1.53	ns

EconomicPerformanceIndicators

Analysis revealed significant potential for output improvement through enhanced efficiency. The results indicated that a 21.5% output increase is achievable by adopting best management practices and reaching the production frontier. This potential gain translates into increased economic returns for farmers and improved regional food security. In addition, the analysis suggests that efficiency improvements can contribute to more sustainable use of scarce natural resources, such as water and energy, which are critical considerations in the arid context of the Arabian Peninsula. Implementing strategies such as farmer training, technology transfer, and the adoption of precision agriculture techniques could further accelerate progress toward optimal production outcomes.

Table 3 Efficiency Distribution Frequency

Efficiency Range%	Number of Farms	Percentage%
Lessthan60	12	8.0
6070	23	15.3
7080	45	30.0
8090	58	38.7
90100	12	8.0

Discussion

The findings demonstrate substantial variation in technical efficiency across greenhouse operations in the Arabian Peninsula. The mean efficiency of 78.5% suggests considerable scope for productivity improvements, consistent with the 20% improvement potential identified in eggplant production in Oman (Al-Salmi & Nadaf, 2025). These results emphasize the need for evidence-based policies that prioritize the dissemination of modern agricultural technologies, investment in infrastructure, and promotion of knowledge-sharing networks among producers (Food and Agriculture Organization of the United Nations, 2016). By addressing underlying constraints, stakeholders can unlock latent productivity gains and foster resilient, competitive greenhouse industries (Schreinemachers et al., 2018).

Technology Adoption Impact: Unlike open-field production where input variables often show non-significant effects (Al-Salmi & Nadaf, 2025), greenhouse systems demonstrated strong technology-efficiency relationships. This suggests that controlled environment agriculture responds more predictably to technological investments and management improvements (Coelli, 1996).

Regional Variations: The UAE showed the highest efficiency (82.3%), likely due to advanced infrastructure and technology adoption (National Centre for Statistics and Information, 2022). This pattern aligns with national agricultural development strategies emphasizing innovation and sustainability.

Education and Training Effects: The significant negative coefficient for farmer education in the efficiency model indicates that educated farmers operate more efficiently. This finding supports the conclusion that educational programs and extension services are crucial for efficiency improvements (Al-Salmi et al., 2020).

Policy Implications: The 21.5% improvement potential identified in this study exceeds the 19–20% potential found in specific crop studies (Al-Salmi & Nadaf, 2025), suggesting that greenhouse systems offer greater optimization opportunities than traditional farming methods.

Conclusion

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This comprehensive analysis of greenhouse vegetable production across four Arabian Peninsula countries reveals significant efficiency variations and considerable potential for improvement. The mean technical efficiency of 78.5% indicates substantial room for productivity gains through enhanced management practices, technology adoption, and farmer education programs. These improvements are vital for addressing the growing food security challenges and environmental constraints faced by the region. The findings reinforce the importance of strategic investments in protected agriculture and the need for coordinated efforts among governments, research institutions, and industry stakeholders to drive sustainable growth.

The study's findings support the continued expansion of protected agriculture as a viable strategy for enhancing food security in arid regions. However, realizing the identified 21.5% improvement potential requires coordinated efforts in farmer training, technology transfer, and policy support. It is essential to develop region-specific initiatives that address the unique challenges of each country, promote innovation, and facilitate access to modern agricultural inputs and knowledge. Such targeted approaches will help bridge the efficiency gap and ensure the long-term sustainability of greenhouse vegetable production in the Arabian Peninsula.

Recommendations include strengthening extension services focused on greenhouse management; promoting incentives for technology adoption; developing training programs tailored to regional needs; and establishing efficiency benchmarking systems to facilitate knowledge transfer among producers.

Future research should investigate the specific technological components driving efficiency differences and assess the economic returns from investments in efficiency improvements across various production scales.

Limitations

While this study provides valuable insights into the efficiency of greenhouse vegetable production in the Arabian Peninsula, several limitations must be acknowledged. The sample size, though representative, is constrained by the availability of reliable farm-level data. Additionally, the study period (2020–2022) may not capture longer-term trends or the impact of exceptional events such as the COVID-19 pandemic. There may also be unobserved heterogeneity among farms related to management practices or environmental factors not fully captured in the survey. Finally, while cross-sectional analysis reveals important patterns, longitudinal studies would offer a deeper understanding of changes in efficiency over time.

Future Research Directions

Future research should consider expanding the sample size and geographic coverage to include more farms and additional countries in the region. Incorporating longitudinal data would enable the analysis of trends in efficiency and the impact of policy reforms over time. Further investigation into the role of climate adaptation strategies, digital agriculture tools, and market access could yield important insights. Collaboration with local stakeholders and the use of participatory research methods may also help tailor policy interventions to the specific needs of farmers.

Policy Implications

The results of this study suggest several actionable policy recommendations. Governments should prioritize investment in extension services and capacity-building programs to enhance farmer skills and encourage the adoption of modern technologies. Facilitating access to affordable inputs, credit, and market infrastructure will further support productivity gains. Policymakers should also consider the establishment of regional knowledge-sharing platforms and research partnerships to promote innovation and the dissemination of best practices. Tailored incentives for water-saving technologies and sustainable resource

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management can help address environmental constraints while boosting output.

Key Findings Summary

- Mean technical efficiency of greenhouse vegetable farms in the region is 78.5%, with scope for 21.5% output increase through best practices.

- Technology adoption, farmer education, and farm size are primary determinants of efficiency.

- Significant efficiency variation exists among countries and farm types, indicating the need for targeted interventions.

- Improved management and technology transfer programs are essential for sustainable productivity growth.

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