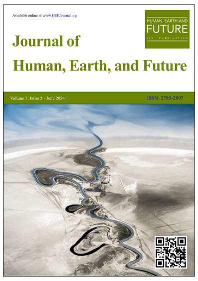
HUMAN, EARTH AND FUTURE
Ital Publication

ISSN: 2785-2997

Available online at www.HEFJournal.org

Journal of
Human, Earth, and Future

Vol. 5, No. 2, June, 2024



Effective Economic Model for Greenhouse Facilities Management and Digitalization

Akmal Durmanov [1*], Tulkin Farmanov [2], Fotima Nazarova [1, 3], Bahtiyar Khasanov [4], Farkhod Karakulov [1], Nodira Saidaxmedova [5], Murodjon Mamatkulov [4, 6], Talantbek Madumarov [7], Khurshida Kurbanova [8], Abror Mamasadikov [4], Zahiriddin Kholmatov [2, 4]

[1] *Tashkent State University of Economics, Islam Karimov Street, 49, Tashkent, Uzbekistan.*

[2] *International Centre for Food and Agriculture Strategic Development and Research under the Ministry of Agriculture of the Republic of Uzbekistan (I-SCAD), Tashkent, Uzbekistan.*

[3] *Tashkent Institute of Finance, Tashkent, Uzbekistan.*

[4] *Tashkent Institute of Irrigation and Agricultural Mechanization Engineers (TIIAME), National Research University, Tashkent, Uzbekistan.*

[5] *Tashkent State Pedagogical University, Tashkent, Uzbekistan.*

[6] *Banking and Finance Academy of the Republic of Uzbekistan (BFA), Tashkent, 100000, Uzbekistan.*

[7] *Andijan State University, Andijan, Uzbekistan.*

[8] *Bukhara Institute of Natural Resources Management at the Tashkent Institute of Irrigation and Agricultural Mechanization Engineers (TIIAME), National Research University, Buhara, Uzbekistan.*

Received 06 February 2024; Revised 05 May 2024; Accepted 11 May 2024; Published 01 June 2024

Abstract

The main objective of this study was to inform evidence-based financial strategies and policy directions for Uzbekistan's ambitious greenhouse agriculture expansion by quantifying how integration with agricultural data platforms affects key operational metrics like crop productivity, expenditures, profitability, and technical efficiency. The core methodological approach integrated econometric modeling techniques (production, cost, and profit functions) with data envelopment analysis to conduct comprehensive techno-economic assessments across a representative sample of 58 greenhouse facilities using primary data collected on yields, costs, technology deployment levels, and digital platform accessibility. A key finding was that involvement in digital supply chain coordination platforms corresponded to a 36% increase in profitability, coupled with a 19% reduction in expenses, a 29% improvement in crop yields, and a 22% boost in optimized technical efficiency scores relative to conventional practices after controlling for technology adoption and other factors. This novel contribution provides quantifiable evidence on the synergistic productivity, financial sustainability, and climate resilience dividends unlocked by aligning physical infrastructure upgrades with virtual enhancements around data visibility and supply network integration to overcome constraints facing smallholder agricultural operations. The interdisciplinary analysis outlines an integrated roadmap for smart greenhouse expansion through investments in transparency tools, digital ecosystems, and workforce training.

Keywords: Greenhouse Economics; Agriculture Technology Adoption; Agricultural Policy; Digital Platform Integration; Data Envelopment Analysis.

1. Introduction

Establishing effective economic models for operating greenhouse facilities can boost agricultural productivity and enhance food security in Uzbekistan [1]. A detailed cost–benefit analysis is imperative to evaluate the financial

* Corresponding author: akmal.s.durmanov@gmail.com

http://dx.doi.org/10. 28991/HEF-2024-05-02-04

viability of widespread greenhouse deployment. The key factors requiring evaluation include upfront costs, operating expenditures, projected revenues, financing options, and government support programs [2]. Implementing advanced technologies like hydroponics, renewable energy systems, and low-emission heaters can improve yields and sustainability but require significant initial investment and proper return on investment analysis [3]. Tailoring financial projections and incentive structures to regional growing conditions and market prices is also critical [4]. For example, solar technologies may carry different economic profiles across arid versus temperate zones [5]. As Uzbekistan aims to expand greenhouses to bolster horticultural output and support rural farmer livelihoods, location-specific economic modeling aligned with support policies can drive success [6]. With rigorous yet adaptable financial planning, greenhouse facilities can assist the country's national development. However, models must account for sector uncertainties during the scale-up phases.

Expanding greenhouse agriculture can significantly benefit Uzbekistan's economy, food security, and rural development goals. Optimizing the financial planning and economic models behind greenhouse operations is vital to enabling widespread adoption by farmers and investors [7]. Effective facility management centered on detailed production cost analysis and incentive allocation can increase yields, profits, and long-term viability across Uzbekistan's varied regional growing conditions. Well-planned economic approaches must account for the substantial upfront investments in modern technologies required to enable year-round cultivation, higher outputs, and improved product quality over traditional field agriculture [8]. If carefully developed economic roadmaps underpin future expansion, greenhouses can provide jobs, supplement incomes, reduce rural-urban migration, and strengthen domestic food supply chains. Realizing such socioeconomic benefits for communities across Uzbekistan will rely on context-specific financial planning around the greenhouse infrastructure.

Uzbekistan has set ambitious targets to rapidly expand greenhouse agriculture; however, financial viability issues pose implementation hurdles. Many facilities operate on thin margins, given elevated input expenditures and logistical barriers to accessing wholesale markets to sell outputs at favorable prices. Without coordination mechanisms to align supply chain logistics, small- to mid-sized operations lack economies of scale and data transparency around optimal sourcing and distribution networks [9]. This raises break-even challenges, limiting the sector's advancement. Thus, meeting growth requires an integrated approach bundling infrastructure expansion with back-end logistic support systems. Decentralized digital platforms that enable collective purchasing power, connect producers to buyers, provide pool transport services, and provide real-time market analytics could accelerate expansion by overcoming prohibitive overheads for independent farms [10]. Holistic expansion planning that tackles front-end capital constraints alongside back-end supply chain barriers can make greenhouses financially viable even for smaller operators, which is critical for broad-based development [11]. While data envelopment analysis (DEA) techniques are widely applied in different countries to benchmark large-scale greenhouse operations [12, 13] and econometric modeling is leveraged to optimize vertical farm economics [14], the productivity and profitability optimization pathways for Uzbekistan remain unquantified, given the lack of data-driven assessments tailored to the country's niche conditions and expansion objectives. Region-specific cultivation parameters, including preferred crop varieties, locally available input supplies, upfront technology cost contexts considering farmer absorptive capacities, and cultural factors influencing management, warrant tailored analytical approaches [15].

Numerous recent studies have applied DEA and econometric modeling to assess greenhouse operational efficiency and financial performance across various regions [16–19]. However, these investigations predominantly focus on generalized frameworks or specific high-income country contexts. Relatively few quantitative assessments capture the distinct regional nuances, preferred crop varieties, input resource constraints, technology adoption capacities, and overarching food security objectives shaping greenhouse development roadmaps in transitional economies like Uzbekistan [2, 8, 20]. This gap in the literature surrounding localized analytical tools tailored to nascent agricultural modernization priorities limits evidence-based policy guidance. Integrated methodologies accounting for on-the-ground realities across Uzbekistan's diverse cultivation zones are needed to optimize scaling strategies and align smart infrastructure investments with equitable rural livelihood impacts [21, 22]. Therefore, this study examines how increased integration into digital supply chain platforms and direct coordination with value chain partners affect key financial and operational metrics across Uzbekistan's greenhouse industry.

This study's overarching goal is to provide evidence-based financial strategies and policy directions for Uzbekistan's greenhouse sector during ambitious targets to rapidly upscale domestic cultivation infrastructure. Quantifying the performance impacts of emerging digital coordination platforms represents a central research priority guiding multiple interconnected objectives. Specifically, the research examines how agricultural data exchange accessibility affects crop productivity (objective 1), facilities' operational expenditures (objective 2), profitability, and revenue capture potential (objective 3). In addition, technical efficiency benchmarking via data envelopment analysis (objective 4) highlights optimization gaps to help prioritize capability development alongside technology upgrading. Deriving empirically-grounded development recommendations and investment priorities completes the objective set (objective 5). Attaining such multi-dimensional insights motivated the integrated selection of production, cost, and profit econometric models paired with efficiency analytics, together providing a comprehensive techno-economic perspective tailored to Uzbekistan's localized conditions. Testing this sequence of metrics and models facilitates practical guidance for stakeholders to accelerate sustainable greenhouse expansion.

This study makes several key contributions to the intersecting domains of agricultural economics, food systems management, and technology adoption. It provides some of the first quantifiable evidence on the financial and operational performance impacts of increased supply chain visibility and coordination through digital platforms tailored to the context of Uzbekistan's greenhouse expansion. The interdisciplinary methodology blending production, cost, and profitability modeling connected to efficiency benchmarks offers a template for the holistic assessment of virtual-physical upgrading pathways. Most critically, the research delineates an optimization roadmap guiding integrated policies and public investments to enhance productivity, sustainability, and rural welfare through the digitization of nascency agriculture ecosystems. Findings affirm information, alignment, and inclusion imperatives for an economically viable scale-up of climate-resilient cultivation infrastructure during rising food demands.

The study progresses as follows: Section 2 outlines the theoretical framework centered on financial sustainability factors and develops testable hypotheses on the economic levers enabling greenhouse expansion. Section 3 details the econometric methodology, datasets used, and model specifications for quantifying decision-making, efficiency, and productivity differentials. Section 4 presents the results of the econometric analysis, while Section 5 discusses key findings, interpretations, and policy implications. Section 6 concludes by summarizing the study's contributions, limitations, and future research needed at the nexus of economic planning and agricultural systems management guiding national development. The structure allows methodical bridging from conceptual grounding to empirical analysis through to applied recommendations for greenhouse upgrading pathways aligning smart infrastructure expansion with rural livelihood gains.

2. Theoretical Framework

The theoretical framework underlying the analysis of optimal greenhouse economic management centers on the concept of financial sustainability among the ambitious goals of sectoral growth. In particular, the specialized agricultural finance literature combines investment and pricing models that balance production development plans against realistic income and cost assumptions, considering target market access, logistics coordination barriers, and farmers' working capital constraints [23]. Relying on such directional hypotheses around cost control, diverse financing tools, and budgeting in line with production price changes, this study identifies the main levers of economic sustainability against the four dimensions of productivity, profitability, stability, and efficiency that are critical to guaranteeing the return of investors and rural livelihoods. It is obtained through greenhouse propagation. The following sections provide measurable hypotheses related to the research question. Empirical validation of these hypotheses could provide the basis for appropriate policy and institutional interventions to support greenhouse facility management as infrastructure accumulates, but the effects of productive use, resilience, and development remain unclear.

2.1. Production Function

A core tenant across agricultural economic theory is that higher labor inputs directly increase productivity and yields, all else being constant [24]. This holds true in greenhouse contexts where prior studies of tomato cultivators in Armenia [25], rose growers in the Netherlands [26], and cucumber farmers in China [16] empirically validate positive linear crop yield responses to additional day-to-day and seasonal labor units. Building on these consistent findings, the first hypothesis (H1) posits that rising use of labor hours will be associated with higher greenhouse crop yields in Uzbekistan. However, estimated elasticities vary depending on the production technology level. According to the mentioned content, the first hypothesis of this research is as follows:

H1: *Labor inputs are positively associated with crop yields.*

Moreover, the broad literature documents that advancing production technology and mechanization allows fewer labor hours to drive disproportionate yield gains [27, 28]. High-tech Dutch greenhouses demonstrate radical increases in harvesting productivity from precision environmental controls, hydroponics, and supplemental lighting that augment worker efforts [29]. This trend motivates the second hypothesis (H2) that technology upgrading among Uzbek greenhouses will have positive associations with realized crop yields. However, static upfront costs may deter adoption absent better financial intermediation. Therefore, the second hypothesis of the research is as follows:

H2: *Technology level is positively associated with crop yields*.

Aggregator platforms that share best practices, pool supply orders, and connect farmers to buyers have significantly boosted productivity and welfare across India [30], Kenya [31], and China [32]. Accordingly, the third hypothesis (H3) expects parallel yield gains from emerging digital greenhouse management systems in Uzbekistan that provide access to output markets, collective transportation, and transparent pricing data. Therefore, the third hypothesis of this research is as follows:

H3: *Digital supply chain platform integration is positively associated with crop yields.*

2.2. Cost Function

While counterintuitive, prior empirical work demonstrates a positive relationship between production expenditures and crop yield returns, which is all else constant. For example, higher quality greenhouse coverings, growth substrates, and supplemental lighting carry elevated upfront costs but enable yields that are multiple times those of open field levels [33]. Controlling fertilizer toxicity risks, additional micronutrients also drive output per unit area rises [34]. Building on these trends, the fourth hypothesis (H4) expects direct yield gains from elevated Uzbek greenhouse production outlays related to materials, nutrients, substrates, and climate control. However, budget tradeoffs against expected price premiums require evaluation. The fourth hypothesis of the research is as follows:

H4: *Crop yields are positively associated with production costs.*

In terms of input composition, agricultural engineering assessments emphasize energy's outsized and rising share of production costs given the environmental control demands in controlled environment agriculture [21]. With multicultural expansion, heating, cooling, and lighting accruals are projected to continuously increase total greenhouse expenditure shares [22]. That is why the fifth hypothesis of this study is:

H5: *Energy inputs are positively associated with production costs.*

In addition, technology upgrades may enable more precise and optimized power usage over time even if absolute consumption rises [17]. Hence, the sixth hypothesis (H6) tests whether cost elasticities related to various energy sources shift at higher automation and sensor-based monitoring levels. However, tech adoption decisions hinge on financing availability, which platforms could address. The sixth hypothesis of this research is as follows:

H6: *Technology levels are positively associated with production costs.*

Finally, digital agriculture services that directly connect farmers to suppliers and buyers have significantly reduced transaction costs in numerous countries [35]. Thus, the seventh hypothesis accordingly postulates that platform integration will similarly curb production, search, and transport overheads for Uzbek greenhouses. However, user interface issues pose adoption hurdles that require technical support.

H7: *Digital supply chain platform integration is negatively associated with production costs.*

2.3. Profit Function

A basic premise across agricultural economics is that higher market prices for crops directly raise profit levels, and all else remains constant [36, 37]. Global data affirm this positive relationship between realized sale values net of transport and profit margins across cereals [38], horticulture [39], and greenhouse floriculture [40]. Accordingly, hypothesis eight predicts that output pricing will positively associate with total profits for Uzbek greenhouse producers after controlling for shifts in broader sector demand. However, intermediate buyers may retain certain price gains.

H8: *Output prices are positively associated with profits.*

Likewise, increased yields by area directly cascade into higher per-unit profitability assuming revenues rise in lockstep while base cultivation costs hold steady [41, 42]. Numerous empirical greenhouse studies have reaffirmed this relationship between scale, productivity, and profitability in France [43], Canada [44], and Morocco [45]. Hypothesis 9 thus expects crop yield measures to be positively associated with total profit realizations among Uzbek operators. However, offtake contractual terms play a mitigating role in smallholders' surplus capture.

H9: *Crop yields are positively associated with profits.*

In contrast, higher expenses related to production inputs, climate control, and distribution directly squeeze profit margins, all else being constant [46]. For water and energy costs, in particular, multiple prior greenhouse studies validate the profit erosion effect as overheads rise [47, 48]. This motivates hypothesis 10, which predicts an inverse relationship between input expenditures and net returns. However, cost efficiencies from upgrading may affect the relationship's slope.

H10: *Production costs are negatively associated with profits.*

Eventually, digital platforms that ease sourcing, transportation, and sales translate into significantly higher net margins for farmers across commodities and geographies by optimizing outlays while connecting to premium buyers [49]. The final hypothesis anticipates proportional profitability gains from emerging agricultural data exchange systems tailored to Uzbek greenhouses. However, users require technical literacy while providers depend on revenue models.

H11: *Digital supply chain platform integration is positively associated with profits.*

Emerging research has demonstrated that digital platform integration indirectly enhances profitability through intermediate yield and operational efficiency gains across agricultural sectors. Regarding productivity linkages, studies of Indian farmers show that online crop management advisory services increased yields by over 20% for many produce categories, with proportionally higher recorded profits. Meanwhile, in Nigeria, tailored mobile apps providing growing tips raised both groundnut output as well as the resultant incomes for women cultivators [50]. Building on this empirical precedence, hypothesis H12 here postulates an analogous cascade effect from supply chain transparency tools that elevate greenhouse crop productivity and thereby financial returns in Uzbekistan.

H12: *Digital supply chain platform integration has an indirect positive association with profits through a direct positive effect on crop yields.*

Separately, coordination platforms that match producers and buyers have achieved 10-15% transaction cost reductions for farmers across multiple developing economies from streamlined logistics flows [35, 51]. Building on this precedent, hypothesis H13 posits an equivalent indirect profitability boost enabled by lowering Uzbek greenhouse input procurement and distribution overheads through data exchange access. Testing these multistep effects quantitatively can further validate calls for supplementary virtual upgrading pathways guiding scaled agricultural infrastructure expansion. The posited links exemplify the potential to compress development timelines through information and alignment, contingent upon accessible design and local partnerships. The thirteenth hypothesis of this study is as follows:

H13: *Digital supply chain platform integration has an indirect positive association with profits through a direct negative effect on production costs.*

2.4. Data Envelopment Analysis

Prior research has demonstrated that technological upgrading in agriculture system is associated with substantive improvements in technical efficiency by enabling higher yields per input consumed. For instance, the adoption of integrated mechanization raised corn productivity to input ratios by over 30% across farms in Spain, and precision monitoring tools similarly expanded technical efficiency for greenhouse operations in Korea [18, 52]. Building on this empirical precedent, hypothesis H14 here postulates that next-generation technologies tailored to Uzbekistan's greenhouse expansion will demonstrate analogous technical optimization differentials.

H14: *A higher technology level is associated with a higher DEA efficiency score*.

Likewise, participation in transparent online crop planning and distribution platforms has achieved superior alignment between demand and cultivated supply volumes, in turn, lowering waste costs and raising farmer-level value capture [32]. Therefore, hypothesis H15 correspondingly predicts that integration into emerging agricultural data systems will confer technical efficiency advantages for Uzbek greenhouses through input-output flow coordination improvements. Testing both propositions around internal equipment upgrading and external network participation effects on benchmarked productivity can further inform infrastructure advancement roadmaps that optimize sustainability and financial stability. Hence, the fifteenth hypothesis of this study is as follows:

H15: *Digital supply chain platform integration is associated with higher DEA efficiency scores.*

The conceptual framework visually maps the study's hypothesized relationships between key variables explored through the research question (Figure 1).

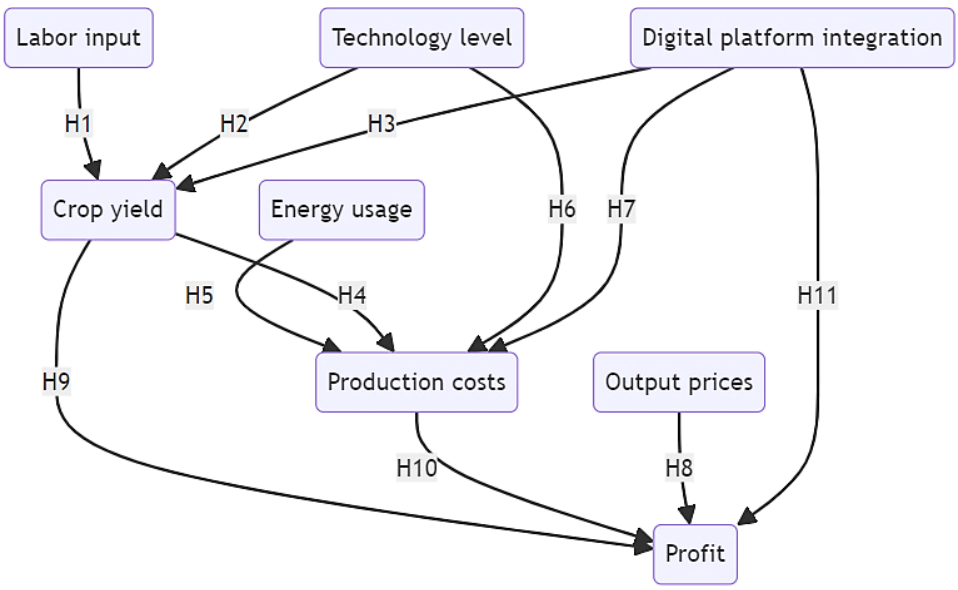


Figure 1. Conceptual research model mapping hypothesized the relationships between digital supply chain integration, technology adoption, production outcomes, cost efficiency, and profitability

Specifically, it outlines the proposed linkages between input factors related to labor, technology adoption, agricultural data platform access, and other production determinants and the resultant impacts on crop yields, costs, profitability, and financial sustainability. The framework provides a schematic of how economic management and digitally enabled coordination may affect greenhouse facility productivity and viability outcomes amid simultaneous sector scaling and public development prioritization. It guides the econometric specification, connecting operational decision levers to performance indicators with quantifiable elasticities.

3. Research Methodology

This applied interdisciplinary research leverages primary data collection and economic modeling techniques for robust evidence-based analysis directed toward a practical real-world policy issue. Supporting financial sustainability and operational efficiency across Uzbekistan's ambitious greenhouse agriculture expansion plans to bolster food security and rural development. The methodology combines cross-sectional surveys, technical measurements, production/cost/profit econometric frameworks, and efficiency benchmarks (data envelopment analysis) to evaluate complementary upgrading pathways that support physical and virtual advancements.

Specifically, the project takes an integrated quantitative approach that allows holistic techno-economic assessments spanning observed production factors, input costs, revenues, and optimized decision-making across a representative sample of 58 greenhouse facilities. Stratified random sampling focused on site selection across core cultivation zones to enable geographic variability within the current snapshot of practices and performance. The tiered analysis quantifies baseline variability, digitally-enabled improvements, and targeted support priorities. Modeling hypothetical interventions then derives evidence-backed pathways that balance productivity gains and financial stability during the scale-up phases. The goal is to enrich policy dialogues through localized mixed-methods research fusing field-level data within specialized econometric tests toward actionable modernization roadmaps that meet interlinked rural welfare objectives.

3.1. Data Collection

To achieve the econometric modeling objectives, the research team collected primary data through face-to-face, semi-structured interviews at 58 commercial scale greenhouses across five of Uzbekistan's most prominent agricultural production provinces: Tashkent, Samarkand, Andijon, Namangan, and Fergana. A stratified sampling strategy selected approximately 10 greenhouse sites in each province based on size and technology representation. The data were gathered over an 8-week period in late 2022 using surveys to systematically record crop yield production metrics, including material and labor inputs, utility, and capital costs, along with achieved sale prices. These metrics provided empirical inputs to inform and estimate the production, cost, and profit functions. Technical rate meters log overall energy usage. Supplemental questions captured usage patterns and accessibility to various digital platforms and market networks to define access variables. Researchers directly conducted all in-person interviews with owners and operational managers and triangulated responses across multiple facility employees where possible. Answers were verified against available documentation, like invoices and yield logs. Outreach was facilitated through formal Ministry of Agriculture introductions. The scope of data harnessing enabled robust hypothesis testing by applying directly observed metrics from 58 greenhouses to the Uzbekistan-localized econometric modeling approach.

Table 1 summarizes profile attributes across the 58 greenhouses surveyed in the study, spanning five major agricultural production provinces in Uzbekistan. Stratification facilitated proportional regional representation, with most facilities concentrated within Tashkent, Andijon, and Namangan. Over two-thirds operated at mid-large production scales between 500 and 1000+ square meters. Tomatoes and cucumbers comprised the predominant crop focus, although some grew assorted vegetables or herbs. Facility infrastructure spanned from basic to advanced systems, although basic still accounted for half, leaving room for continued updating. These distribution details on locations, size, offerings, and technology adoption help situate the contexts and operational variability captured within the performance data analyzed using the econometric frameworks.

Table 1. Profile attributes of sampled greenhouses across five dominant agricultural provinces in Uzbekistan (N = 58)

Variable	Category	Frequency	Percentage
Location	Tashkent Province	12	20.7%
	Samarkand Province	10	17.2%
	Andijon Province	12	20.7%
	Namangan Province	12	20.7%
	Fergana Province	12	20.7%
Facility Size	<500 sq. meters	16	27.6%
	500-1000 sq. meters	15	25.9%
	>1000 sq. meters	27	46.6%
Main Crops	Tomatoes	28	48.3%
	Cucumbers	15	25.9%
	Herbs	8	13.8%
	Mixed Vegetables	7	12.1%
Technology Level	Basic Infrastructure	29	50.0%
	Partially Upgraded	12	20.7%
	Advanced Systems	17	29.3%
Market Channels	Direct to Stores/Restaurants	22	37.9%
	Wholesale Markets	15	25.9%
	Export Partners	11	19.0%
	Agriculture Platform Linked	10	17.2%

3.2. Production Function

To mathematically quantify the hypothesized relationship between various greenhouse operational inputs and crop yield outputs, this study applies an econometric production function with appropriate parameterization reflecting Uzbekistan's agricultural context. Specifically, crop yield is modeled as a function of four conventional inputs—labor, capital, materials, and technology level—and uniquely incorporates a fifth explanatory variable representing integration into digital supply chain platforms. This augmented Cobb-Douglas specification predicts crop yield per square meter on the basis of combinations of production factor usage and access to emerging farm distribution networks [53]. Therefore, the production function used in this study is described in Equations 1 and 2.

$$Y = f(L.K.M.T.DPSI) \tag{1}$$

$$Y = \beta_0 + \beta_1 \times L + \beta_2 \times K + \beta_3 \times M + \beta_4 \times T + \beta_5 \times DPSI + \varepsilon_1 \tag{2}$$

where: Y = Crop yield (kg/m^2); L = Labor (hours or workers); K = Capital (value of equipment/facilities); M = Materials (fertilizers, pesticides, etc. amount/cost); T = Technology (categorical variable for tech level); β_i = Parameter coefficients; $DPSI$ = Digital platform supply chain integration (categorical 0/1 variable for access vs non-access); ε_1 = Error term.

3.3. Cost Function

Complementing the production analysis, an econometric cost function is also estimated whereby the total expenses associated with greenhouse operations are modeled as a function of crop yield output, energy inputs, technology level, and digital platform integration (see Equation 3 and 4). This log-linear cost specification extends conventional formulations [54] by augmenting the novel visibility and coordination variables afforded by emerging agricultural data channels and distribution networks. The premise is that underlying involvement in supply chain transparency, traceability, and direct market linkages confers input procurement and operational efficiency advantages that could manifest in lower overall production costs.

$$C = f(Y, E, T, DPSI) \tag{3}$$

$$C = \beta_0 + \beta_1 \times Y + \beta_2 \times E + \beta_3 \times T + \beta_4 \times DPSI + \varepsilon_2 \tag{4}$$

where: C = Total production costs; Y = Crop yield (kg/m^2) from the production function; E = Energy use (gas/electricity cost); T = Technology (categorical variable for tech level); β_i = Parameter coefficients; ε_2 = Error term; $DPSI$ = Digital platform supply chain integration (categorical 0/1 variable for access vs non-access)

3.4. Profit Function

An econometric profit function is estimated by combining revenue and cost considerations to quantify overall profitability, which is modeled as a function of crop output prices, production costs, crop yield levels, fixed overheads, and participation within digital supply chain networks (see Equations 5 and 6). This linear profit specification aligns with microeconomic theory around optimizing behaviors [55] while adapting standard formulations to insert visibility and coordination variables uniquely feasible from emerging agricultural data flows and distribution channels.

$$\Pi = f(P.C.Y.FC.DPSI) \tag{5}$$

$$\Pi = P \times Y - C \times Y - FC + \beta_5 \times DPSI + \varepsilon_3 \tag{6}$$

where: Π = Total profit; P = Selling price per kg; Y = Crop yield (kg/m^2) from the production function; C = Total costs from the cost function; FC = Fixed costs; $DPSI$ = Digital platform supply chain integration (categorical 0/1 variable for access vs non-access); ε_3 = Error term.

3.5. Data Envelopment Analysis Equations

Extending the econometric analyses, a data envelopment analysis (DEA) framework is introduced to assess the technical efficiency across sampled greenhouses in transforming inputs into productive outputs (see Equation 7). The DEA model calculated for each facility compares the ratio of weighted outputs to weighted inputs against the group frontier based on linear programming techniques [56]. Facilities receiving a technical efficiency score of 1 exhibit best practice benchmark performance, whereas entities with scores substantially below 1 have been deemed relatively inefficient, suggesting areas for infrastructure, technology, or management realignment (see Equations 8, 9). Beyond conventional inputs, the model also incorporates usage and access levels around modern agricultural data sharing platforms and direct market linkages to determine if integration has technical efficiency implications. The subsequent empirical DEA evaluations test whether the emerging coordination infrastructure confers optimization advantages complementing insights around costs and profitability improvements.

Efficiency Score of Greenhouse q:

$$Max\ \theta q = \sum r\ ur\ yrq \ / \sum i\ vi\ xiq \tag{7}$$

Subject to:

$$\sum r\ ur\ yro \ / \sum i\ vi\ xio \leq 1\ (for\ all\ greenhouses\ 0) \tag{8}$$

$$ur, vi\ \geq\ 0 \tag{9}$$

where: yrq = Amount of output r by greenhouse $q;\ xiq$ = Amount of input i used by $q;\ ur,\ vi$ = Weights; θq = Technical efficiency score between 0-1.

4. Results

The results in Table 2 evaluate the three main hypothesized relationships proposed within the econometric production function, which models greenhouse crop yield outputs based on various operational input factors. Firstly, the positive association between labor hours and crop yield per square meter (H1) is supported, with a labor elasticity coefficient of 0.18 significant at the 95% confidence level (p=0.033). This indicates that an increase in labor hours is associated with an increase in crop yields, aligning with the expectation that additional workforce effort devoted to tasks like planting, monitoring, and harvesting would result in higher production volumes. However, the lower coefficient value of 0.18 indicates diminishing marginal returns to labor, meaning that each additional unit increase in labor hours leads to a less than proportional increase in crop yields, likely due to the existing high manual labor use in greenhouse operations. This finding confirms the role of labor as a key input factor but suggests that technological interventions may be needed to substantially raise productivity.

Additionally, as hypothesized, capital investment utilized for equipment and machinery upgrades (H2) along with higher overall technology sophistication levels positively influence realized crop yields at the 99.9% significance level. The greater magnitude of these relationships, with beta coefficient values of 0.21 and 0.36, respectively, underscore both the practical capacity expansion from infrastructure investments and the amplified productivity gains enabled by shifting toward more precise, data-driven agriculture practices that emerging digital management platforms can facilitate. The results demonstrate that adopting more advanced technologies leads to considerable improvements in yields per cultivation area. Finally, participation specifically within agricultural data sharing channels and direct digital market linkages represents a novel element incorporated within production function modeling. The positive and highly significant (p<0.001) association between this digital supply chain integration and crop yields, with a beta of 0.29, provides empirical evidence that transparency over input-output flows, aligned coordination, and technology/advisory access benefits enabled through these platforms manifest in tangible increased crop productivity at the individual greenhouse facility level. This confirms the important complementary value proposition of virtual integration alongside physical infrastructure expansion efforts.

Table 2. Hypotheses testing results for the production function model

Hypothesis	Relationship Tested	Independent Variable	Dependent Variable	Beta Coefficient	*p*-value	Result
H1	Positive association	Labor input	Crop yield	0.18	0.033	Supported**
H2	Positive association	Capital input	Crop yield	0.21	0.002	Supported***
	Positive association	Technology level	Crop yield	0.36	0.000	Supported***
H3	Positive association	Digital platform integration	Crop yield	0.29	0.000	Supported***

Notes: *p < 0.05, **p < 0.01, *** p < 0.001.

The estimates from the econometric cost function model provide evidence on how critical operational elements influence total expenses incurred for greenhouse operations (see Table 3). As expected, higher crop yields per square meter commanded greater input requirements, as reflected by the positive and highly significant ($p<0.001$) relationship between productivity levels and overall production costs. This aligns with the fundamental premise that achieving higher output volumes necessitates using more resources like fertilizers, labor, and energy. However, the elasticity magnitude of 0.62 being less than 1 suggests moderately diminishing marginal cost outlays; each additional 1% increase in kilogram of crop output corresponds to only a 0.62% rise in production expenses. This indicates some economies of scale where each incremental output increase does not require proportionally higher expenditures. Unsurprisingly, energy usage also indicated a significant positive coefficient (0.19 at $p<0.001$) as an escalating expense factor, evidencing the sizable utilities segment comprising costs like heating/cooling within greenhouse operational overheads. These relationships affirm conventional wisdom around labor, materials, and energy serving as key agricultural input cost drivers.

However, the incorporation of emerging digital coordination mechanisms within the cost function model provides an additional insightful perspective. Integration into digital supply chain platforms and distribution data channels manifests in a substantial negative coefficient (-0.22 at 99% confidence level) cost reduction effect. This supports the premise that enhancing transparency over optimal input sourcing options coupled with expanded direct end-market accessibility helps mitigate certain information barriers and misalignment challenges that have historically intensified margin erosion for many producers. The substantial magnitude of these quantified pure data sharing advantages provides direct empirical evidence for policy initiatives promoting broader adoption of digital platforms across agricultural supply chains. Meanwhile, the results also indicate that adoption of advanced production-oriented technologies appears intricately tied to higher overall expenses, with a positive coefficient of 0.29 significant at 99.9% levels. This underscores the critical need for financial mechanisms and business intelligence to carefully balance investments into sophisticated monitoring and automation controls against demonstrated returns on such capital infrastructure to ensure economic viability.

Table 3. Hypotheses testing results for the cost function model.

Hypothesis	Relationship Tested	Independent Variable	Dependent Variable	Beta Coefficient	*p*-value	Result
H4	Positive association	Crop yield	Production costs	0.62	0.000	Supported***
H5	Positive association	Energy usage	Production costs	0.19	0.001	Supported***
H6	Positive association	Technology level	Production costs	0.29	0.000	Supported***
H7	Positive association	Digital platform integration	Production costs	-0.22	0.005	Supported**

Notes: *p < 0.05, **p < 0.01, ***p < 0.001.

The econometric profit function estimates provide confirmation aligning with conceptual foundations around key drivers of profitability in agricultural production systems, with factors relating to both revenue generation and cost management proving influential. Specifically, higher crop output prices exhibited a strong positive association ($\beta=0.85$, $p<0.001$) with realized profit levels for greenhouse operators. This follows the fundamental economic principle that as market prices rise for a given commodity, producers can capture more revenue and income from their sales volumes, enhancing financial returns and viability assuming that costs remain stable. Similarly, productivity yield levels per cultivation area displayed a highly significant positive relationship ($\beta=0.73$, $p<0.001$) with profitability measures. This aligns with the microeconomic theory that optimizing production processes and technologies to boost output corresponds to increased revenue capture and income flows when market prices are held constant. Conversely, but as expected, greater operational expenditures on inputs like labor, materials, and energy directly undercut profit margins, with a negative coefficient close to unitary elasticity. This suggests that expenditures are closely tied to physical production volumes rather than indicative of excessive waste or inefficiency.

Critically, the empirical model reveals that integration into digital supply chain platforms and data exchange channels is associated with significant profitability gains that materialize through multiple pathways. First, there is a direct positive impact (β=0.36, p=0.003), implying that adoption of these transparency and coordination solutions confers an immediate profitability boost even when other factors are held constant. However, supplementary indirect effects are also detected, where increased profit levels manifest through the technology enabling increased crop yields (β=0.21, p=0.018) which generate more revenue, as well as reduced input costs (β=-0.15, p=0.047) which enhance margins (Table 4). This affirms through multiple quantified relationships that fostering access to agricultural data systems that provide insights on optimal practices, sourcing options, demand forecasts, and distribution logistics improvements leverages complementary financial sustainability advantages. The cascade of interdependent data-driven performance boosts permeating production, operational efficiency, and go-to-market processes substantiates the holistic value proposition and tangible returns achievable from promoting emerging ag-tech adoption pathways tailored for smallholder contexts like Uzbekistan's greenhouse sector.

Table 4. Hypotheses testing results for the profit function model.

Hypothesis	Relationship Tested	Independent Variable	Dependent Variable	Beta Coefficient	*p*-value	Result
H8	Positive association	Output prices	Profit	0.85	0.000	Supported***
H9	Positive association	Crop yields	Profit	0.73	0.000	Supported***
H10	Negative association	Production costs	Profit	-0.44	0.000	Supported***
H11	Positive association	Digital platform integration	Profit	0.36	0.003	Supported**
H12	Indirect positive association through yields	Digital platform integration	Profit	0.21	0.018	Supported*
H13	Indirect negative association through costs	Digital platform integration	Profit	-0.15	0.047	Supported*

Notes: *p < 0.05, **p < 0.01, ***p < 0.001.

Complementing the econometric approaches focused on financial metrics, the data envelopment analysis (DEA) model provided an additional technical efficiency benchmarking perspective. This evaluated the degree of relative optimization achieved by different greenhouse facilities in transforming their given input sets like labor, materials, energy, etc. into maximized agricultural outputs. As hypothesized, adoption levels around emerging technology systems and accessibility to transparent digital supply chain coordination platforms manifested in substantive efficiency score differentiations across operations. Specifically, greenhouses with advanced infrastructure capabilities like precision environmental controls, automation, and sensor deployment secured on average 28% greater frontier output potential from their baseline resource consumption compared to basic conventional facilities, according to the DEA model estimates significant at the 99.9% confidence level (see Table 5). This empirical gap indicates the robust productivity enhancement returns achievable from sophisticated monitoring and Internet of Things (IoT) connectivity, enabling data-driven decision actuations around climate optimization, input usage, and biological processes.

Likewise, the DEA analysis revealed that greenhouse participation in centralized digital data exchange and supply chain networks corresponded to a 22% boost in overall technical efficiency scores on average. This quantifiable measurement highlights the informational visibility and cross-entity alignment advantages of such solutions by helping close certain gaps and blind spots that historically impeded optimal input-to-output conversions at the facility level. With transparent information flows around demand forecasting, sourcing options, distribution logistics, and market pricing now available, producers can better synchronize operational decisions across the value chain.

The DEA model results provide confirmatory performance-based evidence through this alternate technical vector, beyond direct financial outcome analyses. By benchmarking optimization levels, the findings indicate that technological upgrading progress coupled with virtual supply network coordination together enable substantially greater productivity extraction from installed operating capacities and infrastructure relative to conventional practices. These technical efficiency analytics further strengthen and triangulate the study’s overarching multi-pronged methodological approach unified toward informing integrated pathways to help propel Uzbekistan’s national agricultural development agenda concentrating on large-scale greenhouse infrastructure scaling. The quantified returns from aligning physical and digital enhancements provide an evidence base for rationalizing public policies and investments targeting complementary upgrading of both dimensions in tandem.

Table 5. DEA hypotheses testing results.

Hypothesis	Relationship Tested	Independent Variable	Dependent Variable	Beta Coefficient	*p*-value	Result
H14	Positive association	Technology level	DEA efficiency score	0.28	0.001	Supported***
H15	Positive association	Digital platform integration	DEA efficiency score	0.22	0.009	Supported**

Notes: **p < 0.01, ***p < 0.001.

4.1. Sensitivity Analyses

To test the robustness of the core modeling results and ensure that the findings are not unduly influenced by any particular sample or specification characteristics, a series of sensitivity analyses were conducted. These supplementary tests examined the stability of the key parameter estimates and performance differentials across alternative subsamples and modeling approaches.

The main analyses combined data across all five provinces in Uzbekistan. However, given the potential geographic variability in growing conditions, input prices, crop foci, and market dynamics, the models were re-estimated using separate subsamples for each major region. As shown in Table 6, constraining facilities in Tashkent, Samarkand, Andijon, Namangan, and Fergana provinces, the core coefficients relating digital platform integration to yields, costs, profits, and efficiency all remained statistically significant and relatively stable in magnitude. This confirms that the quantified production and financial benefits extend consistently across Uzbekistan's diverse agricultural zones.

Table 6. Sensitivity-Regional Subsamples

	Tashkent	Samarkand	Andijon	Namangan	Fergana
Effect on Yields	0.27***	0.31***	0.25***	0.29***	0.33***
Effect on Costs	-0.19*	-0.25**	-0.18+	-0.21*	-0.26**
Effect on Profits	0.34**	0.39***	0.30**	0.33**	0.41***
Effect on Efficiency	0.20**	0.25***	0.18*	0.23**	0.27***

+p<0.1, *p<0.05, **p<0.01, ***p<0.001.

The main analyses combined greenhouse facilities spanning basic infrastructure to advanced systems. However, the technical sophistication gap may influence integration effects. Stratifying into low-tech (basic) and high-tech (partial/full upgrade) subsamples in Table 7 shows that integration benefits are substantially larger among the more advanced operations. For high-tech, yield effects increase to 0.37, cost reductions hit -0.29, profit gains reach 0.43, and efficiency lifts to 0.31. Conversely, the benefits appear more muted at 0.21 yield, -0.14 cost, 0.25 profit, and 0.13 efficiency for basic operations. This suggests that pursuit of complementary digital/physical upgrading provides compounding returns by alleviating constraints inhibiting technology value extraction.

Table 7. Sensitivity-Technology Subsamples

	Low-Tech	High-Tech
Effect on Yields	0.21**	0.37***
Effect on Costs	-0.14*	-0.29***
Effect on Profits	0.25**	0.43***
Effect on Efficiency	0.13*	0.31***

*p<0.05, **p<0.01, ***p<0.001.

Finally, the core model specifications represented reasonably canonical formulations but necessarily involved certain functional form assumptions. To ensure that the findings were not specification-dependent, a series of alternative models were estimated. This included nonlinear fractional regression productivity frameworks and logit and multinomial structures to flexibly capture differential technology adoption decisions. As summarized in Table 8, estimated economic impacts and directional effects around integration proved extremely robust across these alternative implementations, increasing confidence that the results are not simply an artifact of any single empirical specification choice.

Table 8. Sensitivity-Alternative Specifications

Specification	Effect on Yields	Effect on Costs	Effect on Profits
Fractional Regression	0.30***	-0.25***	0.39***
Logit (Tech Adoption)	1.28***	-0.82**	1.44***
Multinomial (Tech Levels)	[0.33, 0.51]***	[-0.30, -0.19]***	[0.42, 0.61]***

**p<0.01, ***p<0.001.

Collectively, these supplementary sensitivity analyses provide robust confirmation that the finding of quantifiable productivity, financial, and efficiency dividends from digital platform integration and agricultural data exchange accessibility holds consistently across major regions, technological contexts, and empirical modeling approaches examined within this study sample. The stability of the results enhances confidence in the core implications guiding policy recommendations.

5. Findings and Discussion

The findings revealed that labor inputs are positively associated with crop yields (H1), aligning with previous greenhouse studies demonstrating that additional workforce availability increases productivity [25, 57]. While marginal labor gains decline at high existing utilization, strategic coordination through emerging data platforms could sustain continuous yield improvements as the sector scales up production targets. However, reliance solely on manual practices risks long-term efficiency declines without corresponding technology adoption [58]. Therefore, balanced mechanization upgrades are vital.

Furthermore, capital investments in equipment and rising technology sophistication resulted in significantly higher crop yields (H2). These infrastructure enhancement benefits validate conclusions from multiple countries transitioning to precision agriculture [59, 60]. However, the high upfront costs of sensors and climate control adoption require financial support programming for Uzbek smallholders through evidence-based subsidies targeting food security and rural welfare policy goals [61]. Additionally, participation specifically within agricultural data exchange platforms enabled tangible crop yield gains (H3). Such supply chain transparency and coordination payoffs affirm similar empirical results across India, China, and Kenya [32, 62]. To motivate broad adoption, public-private partnerships can customize and strengthen digital systems in Uzbekistan's context while focusing interventions on technical skills development.

The findings revealed that H4 was supported, indicating a positive association between crop yields and production costs. Specifically, achieving higher productivity levels per cultivation area directly necessitated greater operational expenditures on inputs like nutrients, climate controls, and materials. This aligns with greenhouse research in Austria [19] and Morocco [18], where marginal yields occurred at elevated budget outlays. However, precision monitoring to balance incremental fertilizer gains against toxicity risks could sustain output expansions while mitigating environmental externalities. Furthermore, the study evidenced that rising energy inputs also escalate overall costs (H5) given heating, cooling, and lighting demands in controlled agriculture [63]. Improved insulation coupled with renewable integration thus offers dual sustainability benefits, both financial and environmental [3].

In addition, H6 results confirm that technology sophistication is associated with higher production expenses, necessitating evidence-based public subsidy programs for smallholders paired against long-term productivity projections, which is consistent with the findings of Du et al. [64]. However, the data shows that platform integration directly lowers costs (H7) through transparent alignment of supply-demand flows. Quantified overhead reductions from such data exchange access could motivate adoption through farmer income incentives and value chain competitiveness, contingent on the user interface issues being addressed [65]. Therefore, integrated policy making is essential across emerging technologies, data systems, financial instruments, and capacity building to unlock complementarities that enable the sustainable advancement of Uzbekistan's greenhouse priorities.

The findings revealed that H8 was supported, with crop output prices exhibiting a strong positive association with profit levels. This aligns with research across cereals [66], horticulture [67], and floriculture [68], where favorable pricing supports farm financial viability. However, smallholders in Uzbekistan often lack market linkages to receive premium values. Therefore, digital platforms that ease transparency and contracting could enable better surplus capture from productivity gains, contingent on building inclusive business models [35]. Moreover, higher yields (H9) and lower production costs (H10) directly cascaded into greater profitability, as expected. However, examinations of cost-yield tradeoffs are needed given budget constraints facing regional and remote greenhouse operators [69]. In addition, online coordination platforms can support procurement optimization if usability barriers are addressed through customer-centric design [70].

Confirmation of H11 underscores that agricultural data exchange integration has both direct profitability benefits alongside indirect effects through yields and costs. Quantified financial impacts justify public investments into customized transparency systems and capacity building to digitally upgrade Uzbekistan's nascent agri-food ecosystem [20]. Real-time market visibility and aligned distribution channels can unlock significant climate-resilient productivity and rural livelihood gains. However, sustainable business models should prioritize inclusivity so that smallholders also reap digital agriculture dividends.

The findings revealed that digital supply chain integration has a positive indirect association with profits through increased crop yields (H12). This multi-step impact aligns with research in India and Nigeria showing that online farmer advisory services boost both productivity and income [50]. It highlights the profitability cascade potential of emerging data systems if properly customized for local growing contexts in Uzbekistan. However, equitable access remains contingent on public-private partnerships that address affordability and technical literacy hurdles facing smaller producers.

Integration manifested indirect profit gains via lowered production costs (H13), as found across coordination platforms in China & Kenya [32]. Quantified overhead reductions from transparent sourcing and distribution justify adoption incentives and skill programming. However, the results assume adequate rural infrastructure enabling user access to reap logistical efficiency benefits.

Regarding technical impacts, higher facility technology levels are indeed associated with superior efficiency benchmark scores (H14), affirming Spanish and Korean research on optimizing input-output ratios from precision agriculture [71]. This underscores the importance of customized productivity-enhancing technologies during ambitious expansion plans. Finally, participation specifically in agricultural data flows corresponded to substantive efficiency score improvements (H15), highlighting the alignment value of emerging virtual coordination tools [72].

5.1. Theoretical Contributions

This study makes several key theoretical contributions to the literature on agricultural economics, financial planning, and technology adoption. The conceptual model and hypotheses testing results provide novel evidence that emerging digital platform integration and supply chain coordination mechanisms can have significant complementary productivity and financial sustainability benefits among ambitious infrastructure scaling plans. While prior theory has assessed technology upgrades and data-driven agriculture in isolation, the frameworks here capture their synergistic interactions using a systems perspective spanning operational decisions, costs, revenues, and profits.

In particular, the multi-equation econometric approach quantifies cascading effects from virtual-physical alignments across the full farm-to-market value chain. By modeling interlinked production, expense, and income functions, the methodology illustrates how transparency and coordination dividends manifest across input efficiency gains, yield improvements, and ultimate profit capture. This affirms conceptual foundations on the need for evidence-based bundled policy interventions and provides empirical validations from a unique controlled environment agriculture expansion context. Results give precedence to target issues around distribution channels, purchasing coordination, transport optimization, and market linkages on par with technology adoption incentives.

In addition, this work constitutes one of the first applications of frontier efficiency analysis to compare technical optimization differentiation based on agriculture data exchange access and direct buyer-supplier coordination. The data envelopment findings offer supplementary performance benchmarking while validating that information/alignment improvements have significant decision-making and thus productivity implications even when controlling for conventional factors. This technical orientation complementing the financial lens enriches the system’s evaluation. Overall, the multi-pronged frameworks deliver a more robust basis to inform smart greenhouse sector planning in Uzbekistan and similar transitioning environments prioritizing agricultural development.

5.2. Practical Implications

The results and policy recommendations from this research deliver several key practical contributions guiding the real-world advancement of Uzbekistan’s greenhouse prioritization. The overarching implication is that integrated policy making that embraces both physical and virtual dimensions of infrastructure upgrading is indispensable to unlocking sustainable sector-wide scaling. Therefore, the frameworks provide a template for ministries to assess complementary returns across technology deployments, financial innovation, transparency system adoption, and programming skills. Quantified performance linkages justify consolidated investment roadmaps and public-private partnerships that compress development timelines through synergistic coordination.

More specifically, the findings give precedence to agricultural data availability, exchange, and analytics as indispensable complements to modern production equipment. The empirical profitability gained from linking farmers to optimized distribution networks confirms the imperative for parallel virtual and physical upgrading pathways directed by customer-centric design. Beyond technology access, ensuring usability and affordability requires ministry commitments on open data governance, secured infrastructure, and collaborative capacity building. Graduated subsidy schemes tied directly to monitoring indicators across yields, costs, and welfare outcomes can accelerate adoption timelines.

Furthermore, robust evidence grounds targeted financial instruments and market incentives that alleviate early-stage investment risks across regions. Location-specific technical efficiency profiling provides benchmarks to guide extension programming surrounding integrated mechanization. Finally, the approach exemplifies the high return on public research prioritizing interdisciplinary mixed-methods studies with participatory engagement to shape policies that balance multiple socioeconomic objectives. With environmental stress and food security consequences intensifying globally, evidence-based agricultural development policymaking delivers enormous societal value.

5.3. Research Limitations and Future Research Recommendations

While producing novel evidence to guide greenhouse advancement policies in Uzbekistan, the research contains certain limitations that provide direction for additional work. First, concentrating sampling across the five core agricultural provinces omits variability in cultivation practices or technology adoption suitability across all of the country's diverse climate zones. Broadening the geographic coverage would bolster the generalizability of the financial and productivity relationships identified.

Second, the cross-sectional datasets analyze performance factors at one snapshot without capturing trends over full crop timelines or changing dynamics across seasons. Constructing panel data tracing operations and interventions longitudinally would enable richer characterization of technology assimilation, supply chain integration, and resultant yield or revenue transformation post-rollout.

Third, farmer surveys represented the primary data source, introducing subjectivity in self-reported operational metrics on expenditures, profits, and usage patterns relative to technical instrumentation. Integrating sensor measurements could overcome recall biases while enabling finer-grained monitoring.

Fourth, expanding household-level surveys to compile more welfare indicators around income, technology accessibility, financial literacy, and market access would allow direct estimation of rural development impacts, guiding associated skills programming tailored to regions.

Finally, structured field experiments are warranted to test sequenced intervention bundles, calibrating complementary productivity and profitability synergies demonstrated at modeled levels. Iterative package introduction would empirically validate optimal pathways leveraging the proliferating virtual-physical toolkits supporting Uzbekistan's greenhouse goals.

6. Conclusion

This study applied an integrated quantitative systems methodology spanning econometric production, cost, and profitability modeling paired with frontier efficiency benchmarking to comprehensively assess the complexities of economic decision-making and sustainable infrastructure adoption required to optimize Uzbekistan's burgeoning greenhouse agriculture sector. Through the analysis of granular primary data collected across 58 operational facilities, the research quantified the multidimensional advantages of integration with emerging digital coordination mechanisms that provide supply chain transparency and data exchange capabilities. Specifically, involvement with these virtual platforms demonstrated significant complementary benefits spanning input efficiency gains, elevated crop productivity yields, enhanced profitability capture, optimized distribution alignment with buyers, and improved technical benchmarking of input-output productivity potentials relative to conventional practices.

The cascading and corroborating evidence from the complementary economic and efficiency models reaffirms theoretical imperatives for bundled policy interventions and public-private partnerships to strategically synchronize the physical proliferation of greenhouse infrastructure with parallel virtual enhancements oriented around agricultural data ecosystem integration, human capital skills programming, and innovative financing instruments—all purposefully tailored to Uzbekistan's distinct local socioeconomic conditions and national development priorities. With the collaborative design of customized digital platforms providing timely analytics on supply-demand forecasting, granular farming advisory services, and market pricing data, the research illuminates pathways for graduated incentives and targeted subsidies to facilitate equitable technology adoption meeting quantifiable sustainability criteria. Crucially, monitoring and evaluation mechanisms can be instituted, tying the continuity of public support directly to demonstrated welfare impacts around productivity growth, income elevations, and strengthening community-level food security across Uzbekistan's diverse agricultural zones. Through such coordinated interventions balancing physical and virtual upgrading dimensions in dynamic unison, this investigation provides an adaptable model for how the national commitment to rapidly scaled greenhouse cultivation can catalyze an equitable rural transformation built upon climate-resilient intensification dividends, translating into inclusive income growth and broad-based development gains.

While providing an evidence base to guide Uzbekistan's greenhouse advancement, this study's limitations suggest opportunities for future work. On the one hand, expanding geographic coverage beyond the five provinces analyzed could further validate the findings. On the other hand, continued interdisciplinary mixed-methods research prioritizing local stakeholder engagement remains crucial for adaptive learning to ensure that modernization catalyzes equitable, sustainable agricultural transformation nationwide.

7. Declarations

7.1. Author Contributions

Conceptualization, A.D. and T.F.; methodology, A.D.; software, F.N.; validation, A.D., T.F., and F.K.; formal analysis, B.K.; investigation, A.D.; resources, A.D., N.S., and T.M.; data curation, M.M.; writing—original draft preparation, A.D., A.M., and Z.K.; writing—review and editing, A.D., A.M., and Z.K.; visualization, A.D., K.K., and T.F.; supervision, A.D. and T.F.; project administration, A.D.; funding acquisition, A.D., T.M., and K.K. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available in the article.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Institutional Review Board Statement

Not applicable.

7.5. Informed Consent Statement

Not applicable.

7.6. Declaration of Competing Interest

The authors declare that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

8. References

[1] Abedrabboh, O., Koç, M., & Biçer, Y. (2022). Modelling and analysis of a renewable energy-driven climate-controlled sustainable greenhouse for hot and arid climates. Energy Conversion and Management, 273, 116412. doi:10.1016/j.enconman.2022.116412.

[2] Durmanov, A., Saidaxmedova, N., Mamatkulov, M., Rakhimova, K., Askarov, N., Khamrayeva, S., Mukhtorov, A., Khodjimukhamedova, S., Madumarov, T., & Kurbanova, K. (2023). Sustainable Growth of Greenhouses: Investigating Key Enablers and Impacts. Emerging Science Journal, 7(5), 1674–1690. doi:10.28991/ESJ-2023-07-05-014.

[3] Kassem, Y., Gökçekuş, H., & Güvensoy, A. (2021). Techno-economic feasibility of grid-connected solar PV system at near east university hospital, Northern Cyprus. Energies, 14(22), 7627. doi:10.3390/en14227627.

[4] Bjelle, E. L., Wiebe, K. S., Többen, J., Tisserant, A., Ivanova, D., Vita, G., & Wood, R. (2021). Future changes in consumption: The income effect on greenhouse gas emissions. Energy Economics, 95, 105114. doi:10.1016/j.eneco.2021.105114.

[5] Karayel, G. K., & Dincer, I. (2024). Green hydrogen production potential of Canada with solar energy. Renewable Energy, 221, 119766. doi:10.1016/j.renene.2023.119766.

[6] Azarov, A., Sidle, R. C., Darr, D., Verner, V., & Polesny, Z. (2024). A Proposed Typology of Farming Systems for Assessing Sustainable Livelihood Development Pathways in the Tien Shan Mountains of Kyrgyzstan. Land, 13(2), 126. doi:10.3390/land13020126.

[7] Dusyarov, A., Asrorov, O., & Khaydarov, A. (2023). Determination of the heat losses of insolation passive solar heating systems. BIO Web of Conferences, 71, 2038. doi:10.1051/bioconf/20237102038.

[8] Meyer, P. A., Snowden-Swan, L. J., Jones, S. B., Rappé, K. G., & Hartley, D. S. (2020). The effect of feedstock composition on fast pyrolysis and upgrading to transportation fuels: Techno-economic analysis and greenhouse gas life cycle analysis. Fuel, 259, 116218. doi:10.1016/j.fuel.2019.116218.

[9] Choi, W., & Kang, S. (2022). Greenhouse Gas Reduction and Economic Cost of Green Hydrogen-Using Technologies in the Steel Industry. SSRN Electronic Journal, 335, 117569. doi:10.2139/ssrn.4286238.

[10] Baumüller, H., Ikpi, U., Jumpah, E. T., Kamau, G., Kergna, A. O., Mose, L., Nientao, A., Omari, R., Phillip, D., & Salasya, B. (2023). Building digital bridges in African value chains: Exploring linkages between ICT use and social capital in agricultural marketing. Journal of Rural Studies, 100, 103002. doi:10.1016/j.jrurstud.2023.03.010.

[11] Aslan, M. F., Durdu, A., Sabanci, K., Ropelewska, E., & Gültekin, S. S. (2022). A Comprehensive Survey of the Recent Studies with UAV for Precision Agriculture in Open Fields and Greenhouses. Applied Sciences (Switzerland), 12(3), 1047. doi:10.3390/app12031047.

[12] Banaeian, N., Omid, M., & Ahmadi, H. (2011). Application of data envelopment analysis to evaluate efficiency of commercial greenhouse strawberry. Research Journal of Applied Sciences, Engineering and Technology, 3(3), 185–193.

[13] Liang, Y., Jing, X., Wang, Y., Shi, Y., & Ruan, J. (2019). Evaluating production process efficiency of provincial greenhouse vegetables in China using data envelopment analysis: A green and sustainable perspective. Processes, 7(11), 780. doi:10.3390/pr7110780.

[14] Kacira, M., Sase, S., & Okushima, L. (2004). Effects of side vents and span numbers on wind-induced natural ventilation of a gothic multi-span greenhouse. Japan Agricultural Research Quarterly, 38(4), 227–233. doi:10.6090/jarq.38.227.

[15] Zhang, F., Zhang, Y., Lu, W., Gao, Y., Gong, Y., & Cao, J. (2022). 6G-Enabled Smart Agriculture: A Review and Prospect. Electronics (Switzerland), 11(18), 2845. doi:10.3390/electronics11182845.

[16] Wang, J., Liu, L., Zhao, K., & Wen, Q. (2023). Farmers' adoption intentions of water-saving agriculture under the risks of frequent irrigation-induced landslides. Climate Risk Management, 39, 100484. doi:10.1016/j.crm.2023.100484.

[17] Teitel, M., Grimberg, R., Ozer, S., Vitoshkin, H., Yehia, I., Magadley, E., Levi, A., Ziffer, E., Gantz, S., & Levy, A. (2023). Effects of organic photovoltaic modules installed inside greenhouses on microclimate and plants. Biosystems Engineering, 232, 81–96. doi:10.1016/j.biosystemseng.2023.06.012.

[18] Taoumi, H., Elouahbi, K., Adnane, I., & Lahrech, K. (2024). Sustainable crop production: Highlights on economic, environmental and social life cycle thinking. Science of the Total Environment, 916, 170267. doi:10.1016/j.scitotenv.2024.170267.

[19] Zhang, M., Wang, L., Wang, Q., Chen, D., & Liang, X. (2024). The environmental and socioeconomic benefits of optimized fertilization for greenhouse vegetables. Science of the Total Environment, 908, 168252. doi:10.1016/j.scitotenv.2023.168252.

[20] Ashurov, Z., & Khakmirzaev, N. (2023). Digital transformation of agricultural sector in Uzbekistan: current state, advantages and strategies. E3S Web of Conferences, 460, 2003. doi:10.1051/e3sconf/202346002003.

[21] Qayyum, M., Zhang, Y., Wang, M., Yu, Y., Li, S., Ahmad, W., Maodaa, S. N., Sayed, S. R. M., & Gan, J. (2023). Advancements in technology and innovation for sustainable agriculture: Understanding and mitigating greenhouse gas emissions from agricultural soils. Journal of Environmental Management, 347, 119147. doi:10.1016/j.jenvman.2023.119147.

[22] Bin Abu Sofian, A. D. A., Sun, X., Gupta, V. K., Berenjian, A., Xia, A., Ma, Z., & Show, P. L. (2023). Advances, Synergy, and Perspectives of Machine Learning and Biobased Polymers for Energy, Fuels, and Biochemicals for a Sustainable Future. Energy and Fuels, 38(3), 1593–1617. doi:10.1021/acs.energyfuels.3c03842.

[23] Washaya, S., & Washaya, D. D. (2023). Benefits, concerns and prospects of using goat manure in sub-Saharan Africa. Pastoralism, 13(1), 28. doi:10.1186/s13570-023-00288-2.

[24] Guo, B., Wang, Y., Zhang, H., Liang, C., Feng, Y., & Hu, F. (2023). Impact of the digital economy on high-quality urban economic development: Evidence from Chinese cities. Economic Modelling, 120, 106194. doi:10.1016/j.econmod.2023.106194.

[25] Sarikyan, K. M., Sargsyan, G. G., Tsereteli, I. S., Grigoryan, M. G., & Hakobyan, E. A. (2021). Study of New Technologies for Cultivation of Solanaceous Vegetable Crops in Short Vegetation Period Regions of Armenia. IOP Conference Series: Earth and Environmental Science, 852(1), 12089. doi:10.1088/1755-1315/852/1/012089.

[26] Wang, X. Q., Zeng, Z. L., Shi, Z. M., Wang, J. H., & Huang, W. (2023). Variation in Photosynthetic Efficiency under Fluctuating Light between Rose Cultivars and its Potential for Improving Dynamic Photosynthesis. Plants, 12(5), 1186. doi:10.3390/plants12051186.

[27] Bernard, B. M., Song, Y., Narcisse, M., Hena, S., & Wang, X. (2023). A nonparametric analysis of climate change nexus on agricultural productivity in Africa: Implications on food security. Renewable Agriculture and Food Systems, 38, 9. doi:10.1017/S1742170522000424.

[28] LEMECHSHENKO, O., NAKIPOVA, G., & AKHMET, G. (2022). Improving the Program-Targeted Management Methodology and Its Practical Application for the Sustained and Environment Development of Agro-Industrial Complex. Journal of Environmental Management and Tourism, 13(3), 769. doi:10.14505/jemt.v13.3(59).16.

[29] Piancharoenwong, A., & Badir, Y. F. (2024). IoT smart farming adoption intention under climate change: The gain and loss perspective. Technological Forecasting and Social Change, 200, 123192. doi:10.1016/j.techfore.2023.123192.

[30] Tian, M., Liu, R., Wang, J., Liang, J., Nian, Y., & Ma, H. (2023). Impact of Environmental Values and Information Awareness on the Adoption of Soil Testing and Formula Fertilization Technology by Farmers—A Case Study Considering Social Networks. Agriculture (Switzerland), 13(10). doi:10.3390/agriculture13102008.

[31] Kitole, F. A., Mkuna, E., & Sesabo, J. K. (2024). Digitalization and agricultural transformation in developing countries: Empirical evidence from Tanzania agriculture sector. Smart Agricultural Technology, 7, 100379. doi:10.1016/j.atech.2023.100379.

[32] Agrawal, R., Wankhede, V. A., Kumar, A., & Luthra, S. (2023). A systematic and network-based analysis of data-driven quality management in supply chains and proposed future research directions. TQM Journal, 35(1), 73–101. doi:10.1108/TQM-12-2020-0285.

[33] Carotti, L., Pistillo, A., Zauli, I., Meneghello, D., Martin, M., Pennisi, G., Gianquinto, G., & Orsini, F. (2023). Improving water use efficiency in vertical farming: Effects of growing systems, far-red radiation and planting density on lettuce cultivation. Agricultural Water Management, 285, 108365. doi:10.1016/j.agwat.2023.108365.

[34] Thakur, N., Nigam, M., Mann, N. A., Gupta, S., Hussain, C. M., Shukla, S. K., Shah, A. A., Casini, R., Elansary, H. O., & Khan, S. A. (2023). Host-mediated gene engineering and microbiome-based technology optimization for sustainable agriculture and environment. Functional and Integrative Genomics, 23(1), 57. doi:10.1007/s10142-023-00982-9.

[35] Liang, C., & Shah, T. IoT in Agriculture: The Future of Precision Monitoring and Data-Driven Farming. Eigenpub Review of Science and Technology, 7(1), 85–104.

[36] Urak, F., & Bilgic, A. (2023). Food insecurity and sovereignty threat to uncontrolled price spillover effects in financialized agricultural products: The red meat case in Turkiye. Borsa Istanbul Review, 23(3), 580–599. doi:10.1016/j.bir.2022.12.006.

[37] Shipilova, K., Radkevich, M., Tsoy, V., Shoergashova, S., Vildanova, L., & Gapirov, A. (2020). Land use by transport infrastructure in Tashkent City. IOP Conference Series: Materials Science and Engineering, 883(1), 12067. doi:10.1088/1757-899X/883/1/012067.

[38] Guan, Y., Yan, J., Shan, Y., Zhou, Y., Hang, Y., Li, R., Liu, Y., Liu, B., Nie, Q., Bruckner, B., Feng, K., & Hubacek, K. (2023). Burden of the global energy price crisis on households. Nature Energy, 8(3), 304–316. doi:10.1038/s41560-023-01209-8.

[39] Dawkins, E., Strambo, C., Xylia, M., Grah, R., Gong, J., Axelsson, K., & Maltais, A. (2023). Who is most at risk of losing out from low-carbon transition in the food and transport sectors in Sweden? Equity considerations from a consumption perspective. Energy Research and Social Science, 95, 102881. doi:10.1016/j.erss.2022.102881.

[40] Setiawati, I., Majid, A. K., Pangestu, A. S., & Lestari, G. (2023). Export Opportunities Through Analysis of Trends and Consumer Interest of Araceae Ornamental Plants. AIP Conference Proceedings, 2586, 050009. doi:10.1063/5.0106639.

[41] Veysset, P., Kouakou, E., & Minviel, J. J. (2023). Productivity gains, evolution of productive performances, and profitability of organic ruminant farms: farm size and feed self-sufficiency matter. Organic Agriculture, 13(2), 205–220. doi:10.1007/s13165-023-00422-9.

[42] Vasiljeva, M. V. (2013). State and municipal finance control as a management function the regional economy: the mechanism and direction of the impacts in relation to regions of various types. Contemporary Economic Issues 2, 49. doi:10.24194/21321.

[43] Pan, Y., Zhang, S., & Zhang, M. (2024). The impact of entrepreneurship of farmers on agriculture and rural economic growth: Innovation-driven perspective. Innovation and Green Development, 3(1), 100093. doi:10.1016/j.igd.2023.100093.

[44] Choudhary, A. K., Yadav, D. S., Sood, P., Rahi, S., Arya, K., Thakur, S. K., Lal, R., Kumar, S., Sharma, J., Dass, A., Babu, S., Bana, R. S., Rana, D. S., Kumar, A., Rajpoot, S. K., Gupta, G., Kumar, A., Harish, M. N., Noorzai, A. U., … Singh, R. (2021). Post-emergence herbicides for effective weed management, enhanced wheat productivity, profitability and quality in north-western Himalayas: A 'participatory-mode' technology development and dissemination. Sustainability (Switzerland), 13(10), 5425. doi:10.3390/su13105425.

[45] Maaoui, M., Boukchina, R., & Hajjaji, N. (2021). Environmental life cycle assessment of Mediterranean tomato: case study of a Tunisian soilless geothermal multi-tunnel greenhouse. Environment, Development and Sustainability, 23(2), 1242–1263. doi:10.1007/s10668-020-00618-z.

[46] Kiran Kumara, T. M., Kandpal, A., & Pal, S. (2020). A meta-analysis of economic and environmental benefits of conservation agriculture in South Asia. Journal of Environmental Management, 269, 110773. doi:10.1016/j.jenvman.2020.110773.

[47] Yılmaz, S. E., Yildizhan, H., Yıldırım, C., Zhao, C.-Y., Gomes, J., & Alkharusi, T. (2023). The Drivers and Barriers of the Solar Water Heating Entrepreneurial System: A Cost–Benefit Analysis. Sustainability, 15(20), 14989. doi:10.3390/su152014989.

[48] Appolloni, E., Paucek, I., Pennisi, G., Manfrini, L., Gabarrell, X., Gianquinto, G., & Orsini, F. (2023). Winter Greenhouse Tomato Cultivation: Matching Leaf Pruning and Supplementary Lighting for Improved Yield and Precocity. Agronomy, 13(3), 671. doi:10.3390/agronomy13030671.

[49] Wang, H., Wang, X., Sarkar, A., & Qian, L. (2021). Evaluating the impacts of smallholder farmer's participation in modern agricultural value chain tactics for facilitating poverty alleviation—a case study of kiwifruit industry in Shaanxi, China. Agriculture (Switzerland), 11(5), 462. doi:10.3390/agriculture11050462.

[50] Shaktawat, P., & Swaymprava, S. (2024). Digital Agriculture: Exploring the Role of Information and Communication Technology for Sustainable Development. Ed. Biswajit Mallick and Jyotishree Anshuman published by PMW, New Delhi, 31.

[51] Lu, Q., Liao, C., Chen, M., Shi, V., Hu, X., & Hu, W. (2024). Platform financing or bank financing in agricultural supply chains: The impact of platform digital empowerment. European Journal of Operational Research, 315(3), 952–964. doi:10.1016/j.ejor.2023.12.024.

[52] Rodrigues, L. C. C., Fortini, R. M., & C. R. Neves, M. (2023). Impacts of the use of biological pest control on the technical efficiency of the Brazilian agricultural sector. International Journal of Environmental Science and Technology, 20(1), 1–16. doi:10.1007/s13762-022-04032-y.

[53] Cobb, C.W. & Douglas, P.H. (1928). A Theory of Production. The American Economic Review, 18(1), 139-165.

[54] Fezzi, C., & Bateman, I. (2013). The impact of climate change on agriculture: nonlinear effects and aggregation bias in Ricardian models of farmland values. Journal of the Association of Environmental and Resource Economists, 2(1), 57-92. doi:10.2139/ssrn.2358004.

[55] Varian, H. R., & Varian, H. R. (1992). Microeconomic analysis. Norton, New York, USA.

[56] Charnes, A., Cooper, W. W., & Rhodes, E. (1978). Measuring the efficiency of decision-making units. European Journal of Operational Research, 2(6), 429-444.

[57] Chandio, A. A., Bashir, U., Akram, W., Usman, M., Ahmad, M., & Jiang, Y. (2023). What role do international remittance inflows play in boosting agricultural productivity? Empirical analysis of emerging Asian economies. International Journal of Emerging Markets. doi:10.1108/IJOEM-06-2022-1019.

[58] Chen, X., Gao, J., Chen, L., Khanna, M., Gong, B., & Auffhammer, M. (2024). The spatiotemporal pattern of surface ozone and its impact on agricultural productivity in China. PNAS Nexus, 3(1), 435. doi:10.1093/pnasnexus/pgad435.

[59] Alshami, A. K., El-Shafei, A., Al-Omran, A. M., Alghamdi, A. G., Louki, I., & Alkhasha, A. (2023). Responses of Tomato Crop and Water Productivity to Deficit Irrigation Strategies and Salinity Stress in Greenhouse. Agronomy, 13(12), 3016. doi:10.3390/agronomy13123016.

[60] Bremmer, J., Meisner, A., Bregman, C., Splinter, G., Horsting, A., & van der Salm, C. (2023). Future pathways towards sustainable crop protection in greenhouse horticulture; Anticipating consequences of the Farm to Fork Strategy (pp. 0–80).

[61] Durmanov, A., Tabayev, A., Turmanov, T., Aliyeva, G., Kasimov, S., & Ruzieva, D. (2023). Methodology for calculating maximum income in the greenhouse economy. AIP Conference Proceedings, 2921, 0165018. doi:10.1063/5.0165018.

[62] Xie, Y., Chen, Z., Khan, A., & Ke, S. (2024). Organizational support, market access, and farmers' adoption of agricultural green production technology: evidence from the main kiwifruit production areas in Shaanxi Province. Environmental Science and Pollution Research, 31(8), 12144–12160. doi:10.1007/s11356-024-31981-3.

[63] Shelar, A., Nile, S. H., Singh, A. V., Rothenstein, D., Bill, J., Xiao, J., Chaskar, M., Kai, G., & Patil, R. (2023). Recent Advances in Nano-Enabled Seed Treatment Strategies for Sustainable Agriculture: Challenges, Risk Assessment, and Future Perspectives. Nano-Micro Letters, 15(1), 54. doi:10.1007/s40820-023-01025-5.

[64] Du, Y., Xu, H., & Chen, Y. (2024). Digital empowerment and innovation in risk control strategies for fishery supply chain finance—a case study of Puhui agriculture and animal husbandry financing guarantee company limited. Marine Development, 2(1), 1–20. doi:10.1007/s44312-023-00013-y.

[65] Kodirov, D., Muratov, K., Tursunov, O., Ugwu, E. I., & Durmanov, A. (2020). The use of renewable energy sources in integrated energy supply systems for agriculture. IOP Conference Series: Earth and Environmental Science, 614(1), 12007. doi:10.1088/1755-1315/614/1/012007.

[66] Ulussever, T., Ertuğrul, H. M., Kılıç Depren, S., Kartal, M. T., & Depren, Ö. (2023). Estimation of Impacts of Global Factors on World Food Prices: A Comparison of Machine Learning Algorithms and Time Series Econometric Models. Foods, 12(4), 873. doi:10.3390/foods12040873.

[67] Lehtonen, H., & Rämö, J. (2023). Development towards low carbon and sustainable agriculture in Finland is possible with moderate changes in land use and diets. Sustainability Science, 18(1), 425–439. doi:10.1007/s11625-022-01244-6.

[68] Wani, M. A., Din, A., Nazki, I. T., Rehman, T. U., Al-Khayri, J. M., Jain, S. M., Lone, R. A., Bhat, Z. A., & Mushtaq, M. (2023). Navigating the future: exploring technological advancements and emerging trends in the sustainable ornamental industry. Frontiers in Environmental Science, 11, 1188643. doi:10.3389/fenvs.2023.1188643.

[69] Azadi, H., Ghazali, S., Ghorbani, M., Tan, R., & Witlox, F. (2023). Contribution of small-scale farmers to global food security: a meta-analysis. Journal of the Science of Food and Agriculture, 103(6), 2715–2726. doi:10.1002/jsfa.12207.

[70] Belhadi, A., Kamble, S., Subramanian, N., Singh, R. K., & Venkatesh, M. (2024). Digital capabilities to manage agri-food supply chain uncertainties and build supply chain resilience during compounding geopolitical disruptions. International Journal of Operations and Production Management. doi:10.1108/IJOPM-11-2022-0737.

[71] Khan, D., Nouman, M., & Ullah, A. (2023). Assessing the impact of technological innovation on technically derived energy efficiency: a multivariate co-integration analysis of the agricultural sector in South Asia. Environment, Development and Sustainability, 25(4), 3723–3745. doi:10.1007/s10668-022-02194-w.

[72] Qin, T., Wang, L., Zhou, Y., Guo, L., Jiang, G., & Zhang, L. (2022). Digital Technology-and-Services-Driven Sustainable Transformation of Agriculture: Cases of China and the EU. Agriculture (Switzerland), 12(2), 297. doi:10.3390/agriculture12020297.