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Comparative Descriptive Economic Analysis of Greenhouse Vegetable Production, AI Adoption, and Food Safety Across Selected Countries and Regions

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Abstract

This study presents a comparative descriptive analysis of greenhouse vegetable production across seven countries and regions: Albania, Turkey (Antalya), Greece (Crete/Central Macedonia), Italy (Sicily/Puglia), Egypt, Jordan, and the Kurdish Region (Iraq). Key indicators include greenhouse area (ha), vegetable production (million tons), Agri-Tech and AI adoption, and food safety regulation. Data were compiled from national and international sources, including INSTAT, TÜİK, Eurostat, FAO, and regional reports. Results reveal substantial disparities in scale, productivity, technological integration, and regulatory compliance. Turkey (Antalya) dominates in both greenhouse area and total production, supported by advanced Agri-Tech adoption and strong food safety regulations. Italy exhibits very advanced technological integration, achieving high production efficiency with comparatively smaller area, while Greece demonstrates effective productivity and regulatory compliance despite limited greenhouse infrastructure. Egypt achieves high total production with moderate technological adoption, highlighting efficient use of available resources. Smaller and emerging regions—Albania, Jordan, and the Kurdish Region—maintain limited scale, low-to-moderate technology adoption, and moderate or developing food safety standards, indicating high growth potential through targeted investment and modernization. Integrated analysis underscores the positive correlation between technology adoption, production efficiency, and regulatory strength, while highlighting that large-scale infrastructure alone does not guarantee optimal productivity. These findings provide insights into regional strengths, technological gaps, and regulatory challenges in greenhouse vegetable production, offering guidance for policy makers, investors, and agricultural stakeholders seeking to enhance productivity, food quality, and global market competitiveness.

Keywords: Greenhouse vegetable production, AI adoption, Agri-Tech, food safety regulation, cross-country comparison, emerging regions, Kurdish Region

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Introduction

Greenhouse vegetable production has become a critical component of modern agriculture, addressing increasing global demand for high-quality, year-round vegetables while enhancing resource-use efficiency (FAO, 2021). The integration of Agri-Tech and artificial intelligence (AI) technologies in greenhouse systems is transforming cultivation practices, enabling precision irrigation, climate control, automated monitoring, and predictive yield optimization (Li et al., 2022; Zhang et al., 2020). Concurrently, robust food safety regulation ensures the quality and safety of produce for domestic consumption and international trade, which is increasingly important in a globalized market (European Commission, 2021).

This study presents a comparative descriptive analysis of greenhouse vegetable production across seven countries and regions: Albania, Turkey (Antalya), Greece (Crete/Central Macedonia), Italy (Sicily/Puglia), Egypt, Jordan, and the Kurdish Region (Iraq). The analysis focuses on four key indicators: greenhouse area (ha), total vegetable production (million tons), Agri-Tech and AI adoption, and food safety regulation. These indicators collectively reflect the scale, productivity, technological sophistication, and regulatory environment of each region, providing insight into current performance and future growth potential.

To achieve this, secondary data sources were extensively utilized, including national statistics agencies (INSTAT, TÜİK, Eurostat), international organizations (FAO), and regional reports. The descriptive comparative methodology allows for standardization and normalization of data, facilitating meaningful cross-country comparisons. For example, greenhouse area and vegetable production were expressed as percentages relative to the highest observed value, while AI adoption and food safety levels were standardized using a 0–1 scale (Emerging = 0.25, Moderate = 0.5, Advanced = 1, Very Advanced = 1.2 for AI; Developing = 0.3, Moderate = 0.5, Strong = 0.8, Very Strong = 1 for regulation). This approach ensures that both scale and efficiency are considered when comparing regions of different sizes and development stages.

The rationale for using secondary data is twofold: (1) it provides a reliable, cost-effective, and comprehensive basis for cross-regional comparison; and (2) it allows analysis of trends over time and identification of best practices without the need for primary data collection, which may be logistically challenging across multiple countries (Creswell & Creswell, 2018). By applying descriptive statistical techniques to these secondary datasets, this study identifies patterns of technological adoption, regulatory compliance, and production efficiency, highlighting disparities and opportunities for modernization in emerging and smaller-scale greenhouse sectors.

Methodology

This study employs a comparative descriptive methodology to analyze greenhouse vegetable production, AI adoption, and food safety regulation across seven selected countries and regions: Albania, Turkey (Antalya), Greece (Crete/Central Macedonia), Italy (Sicily/Puglia), Egypt, Jordan, and the Kurdish Region (Iraq).

The methodological framework combines secondary data compilation, standardization, normalization, and descriptive statistical analysis to facilitate cross-regional comparisons.

- **Data Collection**

Secondary data were collected from reputable national and international sources, including:

- INSTAT (Albania) – greenhouse area and agricultural statistics (INSTAT, 2021)
- TÜİK (Turkey) – regional vegetable production and Agri-Tech adoption (TÜİK, 2021)
- Eurostat (Greece, Italy, EU context) – greenhouse infrastructure, production, and regulation standards (Eurostat, 2021)
- FAO (Food and Agriculture Organization) – crop production, resource utilization, and technology adoption (FAO, 2021)
- National Reports and Regional Studies – including limited datasets for the Kurdish Region and Jordan.
- The selection of secondary sources was guided by data reliability, completeness, and comparability, ensuring consistency across regions (Creswell & Creswell, 2018).

- **Indicators and Standardization**

Four key indicators were analyzed:

1. Greenhouse Area (ha) – total area under protected vegetable cultivation.
2. Vegetable Production (million tons) – annual production per region.
3. Agri-Tech / AI Adoption – integration of digital technologies, precision agriculture, and automated systems.
4. Food Safety Regulation – strength and enforcement of food quality and safety standards (European Commission, 2021).

To enable cross-country comparison**,** indicators were standardized as follows:

- Greenhouse area and vegetable production were expressed as percentages relative to the maximum observed value (Turkey, Antalya = 100%) (FAO, 2021).
- AI/Agri-Tech adoption was converted to a 0–1 scale: Emerging = 0.25, Moderate = 0.5, Advanced = 1, Very Advanced = 1.2 (Li et al., 2022; Zhang et al., 2020).
- Food safety regulation was converted to a 0–1 scale: Developing = 0.3, Moderate = 0.5, Strong = 0.8, Very Strong = 1 (European Commission, 2021).

This standardization ensures that both absolute scale and relative efficiency are captured in comparisons. The numerical values assigned to AI adoption and food safety regulation are based on a combination of expert assessment and benchmarking against existing literature. For AI adoption, ‘Emerging’ (0.25) reflects basic digital practices, ‘Moderate’ (0.5) represents partial automation and adoption of some precision agriculture tools, ‘Advanced’ (1) corresponds to widespread AI integration in greenhouse management, while ‘Very Advanced’ (1.2) indicates a level of adoption exceeding the standard benchmark, including full automation, predictive AI systems, and integration with IoT-based crop monitoring. Similarly, for food safety regulation, ‘Developing’ (0.3) reflects minimal compliance mechanisms, ‘Moderate’ (0.5) denotes partial regulatory enforcement, ‘Strong’ (0.8) aligns with national standards meeting most international guidelines, and ‘Very Strong’ (1) corresponds to full alignment with EU or global regulatory frameworks (European Commission, 2021).

Transparent conversion of qualitative to quantitative.

Qualitative labels (e.g., Emerging, Very Strong) were assigned based on the presence of specific technologies, investment levels, policy frameworks, and regulatory enforcement reported in secondary sources. For example, Turkey's adoption of AI-enabled climate control and Italy's full digital integration justified 'Advanced' and 'Very Advanced' ratings, respectively. A similar approach was applied for food safety regulation, cross-referencing EU standards, national inspections, and compliance reports.

- **Descriptive Comparative Analysis**

Descriptive statistics, including percentages, ratios, and relative indices, were applied to evaluate:

- Scale vs. productivity – by comparing greenhouse area with total vegetable output (FAO, 2021).
- Technological adoption – assessing AI and precision agriculture integration relative to regional output (Li et al., 2022; Zhang et al., 2020).
- Regulatory environment – evaluating compliance strength in relation to production and technology adoption (European Commission, 2021).

The analysis highlights patterns, disparities, and potential correlations among indicators, without inferring causality. Integrated comparison tables were created to synthesize findings, showing relative performance across regions, and identifying emerging areas with high growth potential.

- **Data Interpretation and Limitations**

Interpretation of results accounts for differences in data granularity, regional reporting standards, and estimation uncertainty, particularly in regions with limited statistical coverage (e.g., Kurdish Region) (Creswell & Creswell, 2018). Descriptive methods allow for visualization of gaps, benchmarking, and prioritization of policy and investment needs**.**

By leveraging secondary data and descriptive statistics, this study provides a robust comparative overview of greenhouse vegetable production, AI adoption, and food safety regulation, informing stakeholders about technological, regulatory, and infrastructural disparities and opportunities.

- **Aim of the Study**

The aim of this study is to conduct a comparative descriptive analysis of greenhouse vegetable production, Agri-Tech and AI adoption, and food safety regulation across seven selected countries and regions**:** Albania, Turkey (Antalya), Greece (Crete/Central Macedonia), Italy (Sicily/Puglia), Egypt, Jordan, and the Kurdish Region (Iraq). The study seeks to identify patterns, disparities, and correlations among these key indicators to understand regional strengths, technological gaps, and regulatory challenges. Ultimately, it aims to provide insights for policymakers, investors, and agricultural stakeholders to enhance production efficiency, technological modernization, food quality, and competitiveness in global vegetable markets.

Theoretical Framework

1. Greenhouse Vegetable Production and Productivity

Greenhouse vegetable production represents a controlled agricultural system designed to optimize crop yield, quality, and year-round supply. Protected cultivation allows for the regulation of temperature, humidity, light, and nutrient supply, reducing dependency on external climatic conditions and improving resource-use efficiency (FAO, 2021). According to Li et al. (2022), greenhouse systems can significantly increase output per hectare compared to open-field cultivation due to optimized growth conditions and protection from pests and diseases. Furthermore, differences in greenhouse area and production across countries highlight the importance of both scale and management practices in determining overall productivity (Zhang et al., 2020).

Descriptive comparative analyses suggest that while large-scale greenhouse infrastructure provides potential for higher total production, it does not automatically translate into higher productivity per unit area. Efficiency gains often depend on the integration of technological innovations, including precision agriculture tools and climate control systems (Li et al., 2022; FAO, 2021). Thus, theoretical models of greenhouse production emphasize the combined effect of scale, technological adoption, and agronomic practices on total output.

2. Agri-Tech and Artificial Intelligence (AI) Adoption in Greenhouse Systems

The adoption of Agri-Tech and AI technologies in greenhouse vegetable production is grounded in the theory of precision agriculture, which posits that data-driven interventions can optimize inputs, improve yield quality, and reduce environmental impact (Zhang et al., 2020). AI

applications in greenhouses include predictive modeling for crop growth, automated irrigation, climate control systems, and machine vision for disease and pest detection (Li et al., 2022).

The Diffusion of Innovations theory (Rogers, 2003) provides a lens for understanding disparities in technology adoption across regions. Early adopters, typically technologically advanced countries or regions (e.g., Italy and Turkey), benefit from higher productivity and market competitiveness. Conversely, emerging regions (e.g., Albania, Jordan, Kurdish Region) often demonstrate slower adoption due to limited capital, technical expertise, or infrastructure, resulting in lower productivity and efficiency (FAO, 2021).

Empirical studies suggest a positive correlation between technological adoption and both efficiency and quality of greenhouse production (Zhang et al., 2020). Hence, the theoretical assumption underpinning this study is that AI-assisted management and precision agriculture serve as key drivers for enhancing output per hectare and achieving sustainable production.

3. Food Safety Regulation and Market Competitiveness

Food safety regulation is a critical component of agricultural production, ensuring consumer health, product quality, and market access. Regulatory theory posits that compliance with established standards fosters trust in both domestic and international markets, while weak or inconsistent regulations can constrain trade opportunities (European Commission, 2021). Greenhouse vegetable production is particularly sensitive to food safety protocols due to intensive cultivation, high nutrient inputs, and potential for contamination.

Countries with robust regulatory frameworks (e.g., Italy and Greece) often complement advanced technological adoption to maximize efficiency and compliance simultaneously. Conversely, regions with developing regulations (e.g., Kurdish Region) may face barriers to export despite increases in production or technology adoption (FAO, 2021). The intersection of technology and regulation highlights a systemic approach, where productivity gains must be balanced with adherence to quality and safety standards to ensure market integration.

4. Integrated Framework: Technology, Productivity, and Regulation

The integrated theoretical framework for this study is grounded in the interrelationship among greenhouse scale, technological adoption, and regulatory environment. Drawing on systems theory (Checkland, 1999), greenhouse vegetable production can be conceptualized as a system where inputs (land, technology, capital) interact with environmental conditions and regulatory constraints to produce outputs (yield, quality, safety).

This framework hypothesizes:

1. Scale-Productivity Relationship**:** Larger greenhouse areas provide potential for higher total production, but efficiency depends on the effective integration of technology (Li et al., 2022; FAO, 2021).
2. Technology-Output Link**:** Advanced AI and precision agriculture adoption positively influence productivity per hectare, reducing the limitations of smaller greenhouse areas (Zhang et al., 2020).
3. Regulation-Quality Link**:** Strong food safety frameworks enhance product quality, export potential, and market competitiveness, acting synergistically with technological adoption (European Commission, 2021).
4. Emerging Regions Potential**:** Smaller or less developed regions can achieve productivity gains and market integration through targeted investments in Agri-Tech adoption and regulatory strengthening (FAO, 2021; Li et al., 2022).

In sum, the theoretical framework positions greenhouse vegetable production as a multidimensional system where scale, technology, and regulation collectively determine output, efficiency, and competitiveness. This approach allows for a comparative analysis of countries and regions, highlighting gaps, opportunities, and policy priorities.

5. Analysis of the Results

The comparative descriptive analysis reveals clear structural differences among the selected countries and regions in terms of production scale, technological sophistication, and regulatory strength. When the four standardized indicators—greenhouse area, vegetable production, AI

adoption, and food safety regulation—are examined jointly, distinct development patterns emerge.

This analysis compares greenhouse vegetable production across seven countries/regions: Albania, Turkey (Antalya), Greece (Crete/Central Macedonia), Italy (Sicily/Puglia), Egypt, Jordan, and the Kurdish Region (Iraq). Key indicators include greenhouse area (ha), vegetable production (million tons), Agri-Tech / AI adoption, and food safety regulation levels. The aim is to identify patterns, technological adoption levels, and regulatory differences that may impact production efficiency and food security.

Table 1: Comparative Descriptive Analysis of Greenhouse Vegetable Production in Selected Countries/Regions.

Country / Region	**Greenhouse Area (ha)**	**Vegetable Production (M tons)**	**Agri-Tech / AI Adoption**	**Food Safety Regulation**
Albania	~2,000	~1.4	Emerging	Moderate
Turkey (Antalya)	~80,000	~30	Advanced	Strong
Greece	~5,500	~6.5	Moderate–High	Very Strong
Italy	~25,000	~16	Very Advanced	Very Strong
Egypt	~40,000	~20	Moderate	Moderate
Jordan	~4,500	~2.5	Emerging–Moderate	Moderate
Kurdish Region	~2,500 (est.)	Limited (~0.5?)	Low–Emerging	Developing

Sources: INSTAT / FAO, TÜİK / FAO, Eurostat / FAO, FAO / National Reports, Limited Regional Reports.

Note. Data compiled from national and international secondary sources, including the Albanian Institute of Statistics (INSTAT, 2024), Turkish Statistical Institute (TÜİK, 2024), Eurostat (2024), FAOSTAT (FAO, 2024), Jordan Department of Statistics (2024), OECD (2023), World

Bank (2023), WHO (2023), and regional agricultural reports from the Kurdistan Regional Government (2024). Estimates are based on the most recent available reports.

Overall Comparative Overview – Scale, Technology, and Regulation:

Scale and Production

1. Leading in Scale: Turkey (Antalya) and Egypt dominate greenhouse vegetable production, with extensive greenhouse areas (80,000 ha and 40,000 ha, respectively) and high total output (30 M tons and 20 M tons).

Low-Performing Market: The Kurdish Region exhibits minimal scale (~2,500 ha) and very low production (~0.5 M tons), highlighting limited infrastructure and early-stage development.

2. Agri-Tech / AI Adoption

Leaders**:** Italy and Turkey combine advanced AI and Agri-Tech systems to maximize yield and operational efficiency (Italy at 120%, Turkey at 100%).

Lagging Market: The Kurdish Region shows low-to-emerging adoption (15%), reflecting limited digital integration and mechanization.

3. Food Safety Regulation

Strong Regulatory Frameworks: Italy and Greece maintain very strong food safety standards (100%), enabling compliance with EU regulations and supporting export potential.

Developing Market: The Kurdish Region operates under developing regulatory frameworks (30%), which constrains market access and quality assurance.

Integrated Insight:

High-output regions combine scale, technological adoption, and strong regulatory systems to achieve competitive advantage.

Emerging or low-performing regions face significant growth potential through investments in greenhouse infrastructure, AI-driven cultivation, and regulatory strengthening.

Table 2: Greenhouse Infrastructure Across Regions.

Country / Region	**Area (ha)**	**% of Maximum**
Albania	~2,000	2.5%
Turkey (Antalya)	~80,000	100%
Greece	~5,500	6.9%
Italy	~25,000	31.3%
Egypt	~40,000	50%
Jordan	~4,500	5.6%
Kurdish Region	~2,500	3.1%

Source: Authors' compilation based on data from INSTAT, TÜİK, Eurostat, FAO, and other regional reports

Scale of Greenhouse Infrastructure Across Regions

Leaders in Scale:

Turkey (Antalya) dominates the greenhouse sector with 80,000 ha, representing the largest share among all regions. This scale reflects strategic investment in infrastructure and underpins its leadership in global vegetable production. Egypt (40,000 ha) and Italy (25,000 ha) form the second tier, indicating significant capacity for intensive production. While large area provides potential for high output, efficiency will depend on technology adoption and agronomic practices.

Emerging Markets

Greece (5,500 ha), Jordan (4,500 ha), Albania (2,000 ha), and the Kurdish Region (2,500 ha) operate on a smaller scale, each representing less than 7% of Turkey's greenhouse area. Despite the limited size, Greece demonstrates effective use of its greenhouse space, achieving high production efficiency. In contrast, Albania and the Kurdish Region show the smallest shares, reflecting emerging markets where expansion is constrained by infrastructure, investment capacity, and possibly climatic or economic limitations.

Comparative Insights:

There is a positive correlation between greenhouse area and production potential, though efficiency can be enhanced through technology and effective agronomic management (e.g., Egypt's high output with moderate technology).

Smaller regions exhibit high potential for growth if investments in Agri-Tech and regulatory support are implemented.

Understanding greenhouse area is essential for assessing production capacity and identifying opportunities for modernization in protected vegetable agriculture.

Table 3. Vegetable Output and Production Efficiency.

Country / Region	**Production (M tons)**	**% of Maximum**
Albania	~1.4	4.7%
Turkey (Antalya)	~30	100%
Greece	~6.5	21.7%
Italy	~16	53.3%
Egypt	~20	66.7%
Jordan	~2.5	8.3%
Kurdish Region	~0.5 (est.)	1.7%

Source: Authors' compilation based on data from INSTAT, TÜİK, Eurostat, FAO, and other regional reports.

Leaders in Scale:

Turkey (Antalya) dominates vegetable production with ~30 M tons, leveraging both extensive greenhouse area and advanced technology. Egypt (~20 M tons) and Italy (~16 M tons) form the second tier. Egypt achieves high output per hectare despite only moderate Agri-Tech adoption, reflecting efficient cultivation practices. Italy combines substantial area with very advanced technology, highlighting how automation and AI enhance productivity.

Leaders in Efficiency:

Greece produces 6.5 M tons from a relatively small greenhouse area (~5,500 ha), corresponding to 21.7% of Turkey’s output. This demonstrates high productivity per hectare, achieved through

effective agronomic management and moderate-to-high technology adoption. Greece exemplifies efficiency in constrained production systems.

Emerging Markerts:

Albania (~1.4 M tons), Jordan (~2.5 M tons), and the Kurdish Region (~0.5 M tons) contribute minimally (<9% of Turkey's output each). These regions face constraints from limited greenhouse area, lower technology adoption, and less optimized agronomic practices. However, they hold significant potential for growth through targeted investments in technology, expansion of infrastructure, and training in modern cultivation techniques.

Comparative Insights:

- Production generally correlates with greenhouse area, but output per hectare can shift efficiency rankings significantly.
- High-output regions combine scale and technological integration (Turkey, Italy), while smaller areas can achieve competitive productivity with efficient management and targeted Agri-Tech adoption (Greece).
- Emerging regions represent high-potential targets for investment and modernization, aligning with global trends in intensive and sustainable vegetable production.

Table 4. Technological Adoption Agri-Tech / AI Adoption in Greenhouse Production.

Country / Region	**Adoption Level**	**% of Maximum**
Albania	Emerging	25%
Turkey (Antalya)	Advanced	100%
Greece	Moderate–High	70%
Italy	Very Advanced	120%
Egypt	Moderate	50%
Jordan	Emerging–Moderate	35%
Kurdish Region	Low–Emerging	15%

Source: Authors' compilation based on data from INSTAT, TÜİK, Eurostat, FAO, and other regional reports.

Leaders in Technology:

Italy exhibits the highest level of Agri-Tech and AI adoption (120%), reflecting advanced automation, AI-assisted climate control, and precision irrigation. Turkey (Antalya) follows closely (100%), combining large-scale infrastructure with integrated AI for irrigation, crop monitoring, and yield optimization. These regions exemplify how technological sophistication amplifies productivity and efficiency in greenhouse systems.

Moderate Adopters:

Greece (70%) and Egypt (50%) show moderate-to-high and moderate adoption, respectively. Greece leverages precision agriculture tools and partial automation to achieve efficient production despite smaller greenhouse areas. Egypt maintains high output using conventional methods supplemented with selective technology integration, indicating room for further efficiency gains through expanded AI and automation.

Emerging Markets:

Albania (25%), Jordan (35%), and the Kurdish Region (15%) remain at early stages of Agri-Tech adoption. Low mechanization, limited digital tools, and underdeveloped data-driven management constrain production efficiency. These regions present substantial growth potential, as targeted investments in AI and precision agriculture could significantly enhance productivity, resource utilization, and competitiveness.

Comparative Insights:

- A clear correlation exists between technological adoption and production efficiency, especially in high-output regions.
- Moderate adopters can improve efficiency without expanding area, while low-adoption regions risk underutilizing existing infrastructure.
- Investment in AI and precision technologies is crucial for emerging markets seeking integration into global vegetable supply chains.

Table 5. Food Safety Regulation Levels by Country/Region.

Country / Region	Regulation Level	% of Maximum
Albania	Moderate	50%
Turkey (Antalya)	Strong	80%
Greece	Very Strong	100%
Italy	Very Strong	100%
Egypt	Moderate	50%
Jordan	Moderate	50%
Kurdish Region	Developing	30%

Source: Authors' compilation based on data from INSTAT, TÜİK, Eurostat, FAO, and other regional reports.

Regulatory Frameworks and Food Safety Compliance:

Benchmark Leaders: Italy and Greece maintain very strong food safety standards (100%), ensuring that greenhouse produce complies with stringent EU regulations. This facilitates high-quality exports, consumer trust, and international competitiveness. Their regulatory frameworks complement advanced Agri-Tech adoption, maximizing both efficiency and product quality.

Strong Compliance: Turkey (Antalya) demonstrates strong regulation (80%), slightly below Italy and Greece. This supports Turkey’s major export role and ensures consistent production quality, though further alignment with EU standards could enhance market integration.

Moderate Compliance:

Albania, Egypt, and Jordan operate under moderate food safety regulation (50%). While some standards are in place, these regions face limitations in achieving full compliance with global export requirements. Improvements in inspection systems, certification, and traceability would strengthen domestic quality assurance and expand access to international markets.

Developing Copliance :

The Kurdish Region (30%) exhibits early-stage food safety frameworks. Limited enforcement, monitoring, and standardization may restrict both domestic quality assurance and trade potential.

Comparative Insights:

- Strong food safety regulation reinforces the benefits of advanced technological adoption in high-output regions (Italy, Greece, Turkey).
- Emerging markets with moderate or developing regulation (Albania, Jordan, Kurdish Region) face significant constraints in trade potential and quality control.
- Policy interventions, capacity building, and regulatory modernization are critical to improve competitiveness and facilitate integration into global vegetable supply chains.

Table 6. A comparative table summarizes all indicators in % relative to the maximum value:
Summary of All Indicators (% of Maximum):

Country / Region	**Greenhouse Area**	**Vegetable Production**	**Agri-Tech AI**	**Food Safety**
Albania	2.5%	4.7%	25%	50%
Turkey (Antalya)	100%	100%	100%	80%
Greece	6.9%	21.7%	70%	100%
Italy	31.3%	53.3%	120%	100%
Egypt	50%	66.7%	50%	50%
Jordan	5.6%	8.3%	35%	50%
Kurdish Region	3.1%	1.7%	15%	30%

Source: Authors' compilation based on data from INSTAT, TÜİK, Eurostat, FAO, and other regional reports.

Integrated Comparison of Scale, Productivity, Technology, and Regulation

1. Scale vs. Productivity

- Leaders in Scale: Turkey (Antalya) dominates both greenhouse area (100%) and total vegetable production (100%), illustrating the advantages of large-scale infrastructure combined with advanced production practices.

- High-Efficiency Regions: Egypt (66.7% production from 50% of the maximum area) and Italy (53.3% production from 31.3% of maximum area) demonstrate that yield optimization and effective agronomic management can generate high output even with smaller or moderate-scale greenhouses.
- Emerging Markets: Albania, Jordan, and the Kurdish Region exhibit limited scale (<6% of maximum area) and low production (<9% of maximum), highlighting opportunities for expansion, technological upgrading, and improved cultivation practices.

2. Technological Adoption

- Leaders in Technology: Italy (120%) and Turkey (100%) showcase advanced AI and automation systems that amplify production efficiency beyond mere scale, including precision irrigation, climate control, and crop monitoring.
- Moderate Integration: Greece (70%) demonstrates that moderate-to-high Agri-Tech adoption enables efficient production in smaller greenhouses.
- Emerging Regions: Albania (25%), Jordan (35%), and the Kurdish Region (15%) lag in technology adoption, reflecting early-stage digital integration, low mechanization, and high potential for modernization to improve productivity.

3. Food Safety Regulation

- Benchmark Leaders: Greece and Italy (100%) enforce very strong food safety frameworks, ensuring compliance with EU standards, high-quality outputs, and export readiness.
- Strong Compliance: Turkey (80%) aligns with international standards, supporting both domestic quality and export capacity.
- Moderate and Developing Markets: Albania, Egypt, and Jordan (50%) maintain moderate regulatory levels, while the Kurdish Region (30%) shows developing frameworks. These regions could significantly enhance market access and product quality through strengthened regulation and inspection systems.

4. Integrated Insights

- High production efficiency results from a combination of scale, technological adoption, and regulatory compliance; large greenhouse area alone does not guarantee superior output.
- Technology adoption is a key driver of productivity, enabling smaller regions to achieve competitive yields with limited space.
- Emerging and small-scale regions represent prime targets for investment in infrastructure, AI-assisted cultivation, and regulatory capacity building.
- The integrated comparison emphasizes the technological and regulatory divide: leading regions (Turkey, Italy, Greece) maximize efficiency and competitiveness, while smaller regions (Albania, Jordan, Kurdish Region) have significant potential for growth through targeted interventions.

Discussion of the Results

The findings of this comparative descriptive analysis reveal multidimensional disparities among the selected countries and regions, confirming that greenhouse vegetable production performance is not determined solely by physical scale but by the interaction between infrastructure, technological sophistication, and regulatory strength. Previous research has emphasized that protected agriculture systems are increasingly shaped by digital transformation and regulatory harmonization (FAO, 2024; OECD, 2023). When interpreted through this framework, the results demonstrate that scale, AI adoption, and food safety regulation operate as mutually reinforcing determinants of productivity and competitiveness.

Scale versus Efficiency: Beyond Infrastructure Expansion.

Applying Rogers' Diffusion of Innovations framework helps explain observed disparities. Italy and Turkey act as early adopters, benefiting from advanced AI and precision agriculture, which provides competitive advantage through higher productivity and market access.

Greece and Egypt represent early/late majority adopters, showing moderate to high integration that supports efficiency despite smaller or moderately-sized infrastructure.

Emerging regions, including Albania, Jordan, and the Kurdish Region, fall into the late majority or laggard categories, with limited AI adoption and developing food safety standards. This categorization illustrates how the technological gap and regulatory maturity directly affect productivity, efficiency, and market competitiveness.

Data for the Kurdish Region were estimated using regional reports and partial datasets, reflecting a greenhouse area of ~2,500 ha and production of ~0.5 M tons. Given limited statistical coverage, these values should be interpreted as indicative rather than precise, highlighting the need for improved data collection in emerging regions.

The dominance of Turkey (Antalya) in both greenhouse area and vegetable production confirms the importance of large-scale infrastructure in achieving high aggregate output (TÜİK, 2024; FAO, 2024). However, comparative evidence indicates that scale alone does not guarantee proportional productivity. For instance, Egypt achieves high production levels relative to greenhouse expansion, suggesting efficient land utilization despite moderate AI adoption (FAO, 2024).

Similarly, Italy achieves substantial output with comparatively lower greenhouse area, reflecting high productivity per hectare (Eurostat, 2024).

To illustrate these differences, Table 1 shows vegetable production per greenhouse hectare (tons/ha) across all regions**,** highlighting the efficiency gains achieved through technological integration and agronomic practices.

Table*. Vegetable Production per Greenhouse Hectare (tons/ha) by Country/Region.

Country / Region	**Greenhouse Area (ha)**	**Vegetable Production (M tons)**	**Productivity (tons/ha)**
Albania	2,000	1.4	700
Turkey (Antalya)	80,000	30	375
Greece	5,500	6.5	1,182
Italy	25,000	16	640
Egypt	40,000	20	500
Jordan	4,500	2.5	556
Kurdish Region	2,500	0.5	200

From Table 1, it is evident that Greece demonstrates the highest per-hectare productivity, despite its smaller greenhouse area. Italy also achieves substantial productivity (640 tons/ha), surpassing Turkey (375 tons/ha) in efficiency despite lower total area. These figures provide concrete evidence that technological adoption, management practices, and agronomic expertise can enhance output more than sheer scale.

The Role of AI and Agri-Tech in Productivity Enhancement.

The analysis reveals a strong association between AI adoption levels and production efficiency. Italy demonstrates high output relative to greenhouse size, reflecting advanced automation, climate-control systems, and data-driven crop management (Eurostat, 2024; OECD, 2023). Turkey similarly combines technological integration with large-scale infrastructure to sustain production leadership (TÜİK, 2024). Greece presents an intermediate model: despite moderate greenhouse area, it achieves relatively high production and maintains strong regulatory alignment within the EU framework (Eurostat, 2024).

Conversely, regions with emerging or low AI adoption—such as Albania, Jordan, and the Kurdish Region—display proportionally lower production levels (INSTAT, 2024; Jordan Department of Statistics, 2024; KRG, 2024). This pattern supports the hypothesis that AI and digital agriculture function as productivity multipliers. Egypt’s relatively strong production with

moderate technological integration further suggests that management practices, labor intensity, and climate conditions also play a significant role in efficiency (FAO, 2024).

Food Safety Regulation as a Competitiveness Factor.

Food safety regulation emerges as a critical determinant of market competitiveness. Italy and Greece operate under stringent EU food safety standards, ensuring traceability, compliance, and export quality assurance (European Commission, 2023; WHO, 2023). Turkey maintains strong regulatory mechanisms aligned with international trade standards (TÜİK, 2024).

In contrast, moderate regulatory environments in Albania, Egypt, and Jordan may limit access to high-value export markets despite production potential (World Bank, 2023; WHO, 2023). The Kurdish Region faces additional institutional development challenges in strengthening regulatory enforcement and quality certification (KRG, 2024).

Integrated Development Patterns.

When all four indicators are analyzed collectively, three development patterns emerge:

1. Integrated Advanced Model (Italy, Greece) – Strong regulatory systems, high AI adoption, and efficient production relative to scale (Eurostat, 2024; European Commission, 2023).
2. Scale-Driven Advanced Model (Turkey – Antalya) – Large-scale infrastructure combined with advanced technological systems (TÜİK, 2024; FAO, 2024).
3. Emerging Development Model (Albania, Jordan, Kurdish Region) – Limited scale, developing AI adoption, and moderate regulatory capacity (INSTAT, 2024; Jordan Department of Statistics, 2024; KRG, 2024).

This visual representation synthesizes technology, regulation, and production efficiency across regions, highlighting potential investment priorities and modernization strategies.

Egypt represents an intermediate case, demonstrating strong production potential with opportunities for enhanced digital transformation (FAO, 2024; World Bank, 2023).

The results indicate that infrastructure investment must be accompanied by AI integration and regulatory strengthening to achieve sustainable competitiveness (OECD, 2023; FAO, 2024). Digital transformation in agriculture increases resource efficiency and productivity, particularly in controlled greenhouse systems. Additionally, compliance with international food safety standards enhances export capacity and market access (European Commission, 2023; WHO, 2023). Emerging regions represent high-return investment opportunities due to low baseline technological penetration and expanding domestic demand (World Bank, 2023).

6. Conclusions and Recommendations

6.1. Conclusions

This comparative descriptive analysis demonstrates that greenhouse vegetable production performance across the selected countries and regions is determined by the interaction between infrastructure scale, AI and Agri-Tech adoption, and food safety regulatory strength**,** rather than by greenhouse area alone.

First, the findings confirm that scale provides production potential but does not guarantee efficiency. Turkey (Antalya) dominates in both greenhouse area and total production, reflecting the advantages of extensive infrastructure combined with advanced technological systems (TÜİK, 2024; FAO, 2024). However, Italy achieves high productivity relative to its greenhouse area due to very advanced AI integration and automation, while Greece demonstrates efficient output with comparatively limited infrastructure under strong EU regulatory alignment (Eurostat, 2024; European Commission, 2023). These results support the theoretical assumption that productivity in protected agriculture depends on the effective integration of technology within controlled environments (Li et al., 2022; Zhang et al., 2020).

Second, the analysis highlights a strong positive association between AI adoption and production efficiency. Regions with advanced or very advanced digital systems—such as Italy and Turkey—achieve higher relative productivity and market competitiveness (OECD, 2023). Conversely, emerging regions (Albania, Jordan, and the Kurdish Region) show lower productivity levels that correspond with limited technological penetration (INSTAT, 2024; Jordan Department of

Statistics, 2024; Kurdistan Regional Government [KRG], 2024). This pattern aligns with innovation diffusion theory, which suggests that early adopters benefit from structural advantages in efficiency and competitiveness (Rogers, 2003).

Third, food safety regulation emerges as a decisive competitiveness factor. Italy and Greece, operating under stringent EU food safety frameworks, maintain strong export positioning and quality assurance (European Commission, 2023; WHO, 2023). Turkey follows closely with strong regulatory alignment, while moderate or developing regulatory systems in Albania, Egypt, Jordan, and the Kurdish Region may limit international market integration despite production potential (World Bank, 2023).

Fourth, the results reveal three development models:

1. Integrated Advanced Model (Italy, Greece): High AI adoption, strong regulatory systems, and efficient productivity.
2. Scale-Driven Advanced Model (Turkey – Antalya): Large infrastructure combined with advanced technology.
3. Emerging Development Model (Albania, Jordan, Kurdish Region): Limited scale, moderate-to-low AI integration, and developing regulatory systems.

Egypt represents an intermediate case, with strong production capacity but moderate digital and regulatory integration (FAO, 2024).

Overall, the study confirms that technology and regulation act as productivity multipliers, while greenhouse area functions primarily as a structural foundation. Sustainable competitiveness in greenhouse vegetable production therefore requires integrated modernization rather than infrastructure expansion alone.

6.2. Recommendations

Based on the findings, several strategic recommendations are proposed for policymakers, investors, and agricultural stakeholders:

1. Accelerate AI and Precision Agriculture Integration

Emerging and intermediate regions should prioritize investments in:

- AI-driven climate control systems
- Precision irrigation and nutrient management
- Digital monitoring and yield prediction tools
- Smart sensors and automated disease detection

Digital transformation enhances productivity per hectare and improves resource-use efficiency, particularly in water-scarce regions (OECD, 2023; FAO, 2024). Public–private partnerships and targeted subsidies can help overcome adoption barriers in emerging markets, ensuring equitable access to advanced technologies.

2. Strengthen Food Safety and Regulatory Harmonization

Countries with moderate or developing regulatory frameworks should:

- Align national standards with EU and internationally recognized frameworks
- Enhance traceability systems and certification procedures
- Strengthen inspection capacity and enforcement mechanisms
- Promote farmer training in compliance and quality assurance

Improved regulatory governance enhances export competitiveness and consumer confidence (European Commission, 2023; WHO, 2023). Harmonization with global standards is particularly crucial for emerging regions such as Albania, Jordan, Egypt, and the Kurdish Region.

A recommended first step for these regions is to adopt a widely recognized baseline certification standard, such as GlobalG.A.P.**,** to establish credibility in international markets.

3. Promote Integrated Infrastructure and Technology Investment

Expansion of greenhouse infrastructure should be coupled with technological modernization. Investment strategies should avoid focusing solely on increasing area, and instead integrate:

- Automation and control systems
- Renewable energy solutions
- Climate-resilient greenhouse designs
- Data-driven management platforms

This integrated approach ensures that scale expansion translates into measurable productivity and efficiency gains (World Bank, 2023).

4. Enhance Capacity Building and Knowledge Transfer
Emerging regions would benefit from:

- Technical training programs in AI-based greenhouse management
- International cooperation with advanced EU producers
- Research and innovation partnerships
- Development of digital agricultural extension services

Knowledge diffusion accelerates technology adoption and reduces structural productivity gaps, supporting long-term competitiveness (Rogers, 2003).

5. Encourage Sustainable and Climate-Smart Greenhouse Systems
Future greenhouse development should incorporate sustainability principles, including:

- Efficient water recycling systems
- Energy-efficient heating and cooling technologies
- Reduced chemical input through AI-based monitoring
- Carbon footprint assessment and reporting

Sustainability strengthens long-term sectoral resilience and aligns with global climate policy objectives (FAO, 2024; OECD, 2023).

6. Another policy would be strengthening agriculture–tourism linkages to create new markets for greenhouse vegetables and support rural economic development (Sejdiu et al., 2023).
7. Another policy would be improving labor market participation through targeted employment policies and skills development (Deda et al., 2020).
8. In addition an important policy would be linking tourism demand with local greenhouse production to strengthen regional food systems (Gjeloshi & Deda, 2026).
9. Improving education quality and implementing effective government policies enhances workforce skills, productivity, and long-term economic growth in Albania (Deda, Pacukaj, & Vardari, 2021).

Final Implications

This study contributes to the literature by demonstrating that greenhouse vegetable production competitiveness is multidimensional and system-based**.** The evidence suggests that AI adoption and food safety governance are decisive levers for transforming greenhouse agriculture into a high-efficiency, export-oriented, and sustainable sector.

Emerging regions—particularly Albania, Jordan, and the Kurdish Region—represent high-growth opportunities if modernization strategies are implemented strategically. In contrast, advanced regions must continue investing in digital innovation, regulatory excellence, and sustainable practices to maintain their competitive advantage in global vegetable markets.

Future research could extend this analysis by employing econometric modeling to quantify causal relationships among scale, technology adoption, regulatory strength, and productivity performance, thereby informing evidence-based policy and investment decisions.

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