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Green Agricultural Transition and Export Sophistication in Water Dependent Economies Evidence from Central Asia

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Abstract

This research investigates how the green agricultural transition affects export sophistication in water dependent countries of Central Asia between 2000 and 2024. The growing tensions of climate change, especially concerning water, have highlighted a need for more sustainable transformation and the upgrading of exports in developing countries. The study aims to discover the relationships between agricultural export sophistication and international competitiveness and green agricultural policies and resource management, as well as the efficiency of irrigation and renewable energy.Using panel data for Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan, Dynamic System GMM (Generalized Method of Moments) is applied to the effects of green transition on the agricultural export sophistication. It is expected that green agricultural transformation with the efficient management of water will have a positive effect on export sophistication and the competitiveness of sustained trade, while an overreliance on the water will negatively impact export upgrading in the long run.

The study aims to enhance the international economic literature by combining green transition, water dependency, and export sophistication, and by providing evidence from the Central Asian region which has minimal studies.

Abbreviations

Abbreviation	Full Form
EXPY	Export Sophistication Index
GAT	Green Agricultural Transition
WAT	Water Dependency Indicator
IRR	Irrigation Efficiency
DIG	Digital Agriculture
GDP	Gross Domestic Product
FDI	Foreign Direct Investment

GMM	Generalized Method of Moments
FE	Fixed Effects
RE	Random Effects
FAO	Food and Agriculture Organization
IMF	International Monetary Fund
OECD	Organisation for Economic Co-operation and Development
WDI	World Development Indicators
UN	United Nations
CO_2	Carbon Dioxide
AI	Artificial Intelligence
ICT	Information and Communication Technology
SFA	Stochastic Frontier Analysis
ESG	Environmental, Social and Governance
AR (1)	First-order Autocorrelation
AR (2)	Second-order Autocorrelation
SDGs	Sustainable Development Goals
GVCs	Global Value Chains
TFP	Total Factor Productivity
R&D	Research and Development
ADB	Asian Development Bank
WTO	World Trade Organization

Keywords: Green Agricultural Transition, Export Sophistication, Water Dependency, Sustainable Trade, Agricultural Competitiveness, Central Asia

1. Introduction

Agriculture brings about a multi-faceted impact on most developing and transitional nations regarding economic growth, employment opportunities, food security, and exports diversification. In Central Asia, agriculture is very important, plays a key role, and sustains the economic and social systems in most national economies, especially in rural areas where the agro-industrial systems provide direct and indirect employment. Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan have good potential to grow agriculture given the favorable climate, large areas of irrigated land, and improving demand for agricultural outputs in the world. However, the main structural and environmental challenges hinder the long-term sustainability and growth of agricultural activities. In addition, the international competitiveness of agricultural activities is stunted.One of the most important challenges facing Central Asian agriculture is the heavy reliance on water intensive irrigation practices. Central Asia is one of the most water dependent agricultural areas in the world where agricultural activities are heavily reliant on trans-boundary river systems and irrigation infrastructure that were left over from the Soviet era. Out of date irrigation practices, extreme wastewater, poor allocation and management of resources, soil degradation, and other climate change impacts have decreased envi-ronmental and productive sustainability of agriculture. Water has now become a constraining factor of economic growth and competitiveness that affects agricultural activities, international trade, and the stability of the economy of the whole region.

The process of globalization and changes in the structure of the international markets have highlighted the need for advanced exports. Advanced exports contain technologically complex products and have a high level of quality and value. Countries that introduce advanced exports in the agricultural sector are likely to experience enhanced productivity and greater integration in the international markets. They also are likely to become more resistant to international trade disruptions. Therefore, many developing countries prioritize agricultural exports in their trade policies. This enables them to achieve economic growth and develop the agricultural sector.At the international level, sustainable agricultural practices have become the focus of most policies and academic research. Sustainable agricultural practices require the adoption of sustainable production systems and the efficient use of resources, such as renewable energy. The integration of digital technology can also assist in achieving climate-smart and efficient agricultural practices. These changes in production practices can lead to improved agricultural productivity, an added value of exports, and less resource depletion. This is particularly true in economies where water is a scarce resource. These transitions can also enhance competition in agricultural exports.While some literature discusses the intersections of sustainable agriculture and international trade, there is little empirical research on the impact of a green agricul-tural transition on export sophistication in water-dependent economies. Most research looks at sus-tainable agriculture and international trade separately. There is little focus on green transformation, water dependency, and export improvement. There is also a noticeable lack of research on the Central Asian region, even though the area is important for global climate change, the management of water resources, and the sustainable development of agriculture.

This study will begin to cover this gap by looking at the effects of a green agricultural transition on the sophistication of agricultural exports in the Central Asian region from 2000 to 2024. The study will utilize the most advanced quantitative methods to focus on the impacts of the green agricultural transition, the efficient use of irrigation, renewable energy, and water dependency on agricultural ex-ports modernization and competitiveness in the region. The study will contribute to literature in im-portant and innovative ways. It will create a framework to think about the green agricultural transi-tion, water dependency, and advanced export sophistication together. It will be the first of its kind to focus on the Central Asian region using empirical data, and it will be the first research of its kind to use certain quantitative methods on the related fields of international trade. Finally, the research will be of practical use for the green transformation of resource poor economies.The ensuing sections of this paper are as follows. The following section will assess published studies on green agricultural transition in relation to export sophistication. The third section outlines the theory and explains the approach taken. The fourth section will discuss the data and the empirical results. The last section presents some suggestions on policy and concludes the paper.

1.1. Literature

More recent International Economics literature considers export structure, environmental sustainabil-ity, and modernization of the agricultural sector. Ricardo's classical trade theories highlight compara-tive advantages and specialization. Modern International Economics, on the other hand, states that the technological component and sophistication of exports, as well as the incorporation of added value, are more important than exports per se, for sustainable economic growth, and competitiveness in the international arena.New ideas for export sophistication through the EXPY index were first introduced in this context by Ricardo Hausmann, Hwang and Dani Rodrik [1]. Their work showed that the countries that manage to export more sophisticated products also grow faster and manage to achieve greater structural transformations. In the same line of thinking, Hidalgo et alincluded economic complexity and export diversification in the factors that determine the long-term development of countries and address the capacity for a country to progress to high-value industries and high-technology production [2].In agricultural economics, the transition from rapeseed and other low-value commodity exports to value-added agricultural products is of critical importance in literature. Jarreau and Poncet found that greater exports led to greater productivity in developing countries, while Zhu and Fufound that the greater technology and industrial upgrading lead to greater exports and more sophisticated international competitiveness in the emerging economy [3,4]. The results of these studies showed that the sophistication of exports is an important factor in sustainable trade and long-term economic growth.

Environmental sustainability and green transformation are key themes in economics and agricultural policy. A mixture of economic growth and sustainability was first discussed in the context of sus-tainable development by the World Commission on Environment and Development in 1987. Facing the challenges of safety and sustainability of future generations was also pointed out and discussed by Porter and van der LInde in 1995, who suggested that innovations that improve environmental sustainability may enhance productivity and competitiveness rather than increasing the costs of production [5]. This argument played an important role in green growth and sustainable trade litera-ture.Recent empirical studies have shown more green transformation tied to economic growth. Grossman and Kreuger, in 1995, suggested that modernization and economic growth influence the improvement of environmental quality. D'Amato et al in 2017 suggested that the circular economy, along with sustainable production systems, enhances the long-term sustainability of an economy [6]. The modernization of the green economy and agriculture has improved productivity, environmental sustainability, and competitiveness of exports.Digital transformation is even more important for the green economy and the green transition in agriculture. Kamilaris et. al. in 2019, suggested that digital agriculture, blockchain technologies, precision farming, and smart agricultural systems improve agriculture's productivity, sustainability, and the transparency of supply chains [7]. In 2017, Wolfert et al. argued that improved agriculture through digital technologies, data, and management systems have improved the efficiency of agriculture [8]. These technologies are especially important where the economy is mostly dependent on agriculture, in order to effectively manage resources and adapt to changing climates.

Ravshan Asamov's recent research studies sustainable agricultural modernization in Uzbekistan and Central Asia. In these studies, he identifies digital agriculture, modernized irrigation, and strategic management of resources as vital to enhance sustainable agricultural productivity and export compe-titiveness. According to Asamov, in the context of transitional economies, the introduction of envi-ronmentally efficient irrigation systems, digital water management, and sustainable agricultural prac-tices boost productivity growth, diversification of exports, and competitiveness of agriculture [9]. This research is especially relevant to those economies that have insufficient water resources, where, in addition to the climate challenges, the development of sustainable agriculture is threatened by the absence of modern irrigation systems.Water dependency is still one of the most important structural obstacles to agricultural production in developing economies. Central Asia is known to be one of the most irrigation-dependent agricultural areas of the world, where agriculture heavily relies on cross-border river systems and water-intensive production. The Food and Agriculture Organization has reported how outdated irrigation, excessive losses, and inefficient resource allocation negatively impact agricultural productivity and sustainability in the region. In a similar context, the World Bank has reported that, in Central Asia, climate-related water scarcity is one of the most significant long-term challenges to agriculture and economic development.

Previously, several studies analyzed the connection between irrigation and agricultural productivity. According to Ward and Pulido-Velazquez, there is a positive correlation between irrigation efficiency, productivity of agriculture, and sustainability of the environment. Grafton et al argued that, for water-scarce economies, the long-term sustainability of food security, and the resilience of the agri-culture system and sustainable trade, depend on the implementation of sustainable water management [10].Water dependency in international trade literature has been associated with export competitive-ness and the sustainability of agricultural trade. Allanwas the first to use the term “virtual water trade.” He maintained that countries import water in the form of food. More modern literature sug-gests that in developing countries, water dependency and poor management may hinder the ability to diversify and improve competitiveness in the agricultural sectors.Overall, the literature suggests the green agricultural transition has the potential to improve productivity and competitiveness in interna-tional markets, while also contributing to the sustainability of the environment. Despite these claims, many of the studies examine water governance, environmental sustainability, and export competi-tiveness in isolation; few have examined the green agricultural transition, water dependency and ex-port competitiveness in a single study. In addition, given its geostrategic location on sustainability, climate change, and the management of international resources, Central Asia has also received in-adequate attention in empirical studies.The main objective of the current study is to try and fill the above-mentioned gaps. The study examines the consequences of the green agricultural transition on the sophistication of agricultural exports in water-scarce Central Asian countries from 2000 to 2024. The main contribution of this study, given its focus on under-researched transition economies, is that it brings together the fields of green transformation, export improvement, irrigation, and sustainable resource management in a dynamic panel of international trade.

Authors	Research Focus	Methodology	Main Findings
Hausmann et al. (2007)	Export sophistication	EXPY index	Sophisticated exports stimu-late economic growth
Hidalgo et al. (2007)	Economic complexity	Product space analysis	Export diversification shapes development
Porter & van der Linde (1995)	Green competitiveness	Theoretical framework	Environmental innovation improves competitiveness
Grossman & Krueger (1995)	Growth and environment	Econometric analysis	Technological progress im-proves environmental quality
Ward & Pulido-Velazquez (2008)	Irrigation efficiency	Water economics models	Efficient irrigation increases sustainability
Allan (1998)	Virtual water trade	Trade-environment analysis	Agricultural exports transfer water resources
Kamilaris et al. (2019)	Digital agriculture	Literature review	Digital systems improve sustainability and efficiency
Grafton et al. (2018)	Water governance	Institutional analysis	Sustainable water manage-ment supports resilience
Zhu & Fu (2013)	Export upgrading	Panel econometrics	Innovation improves export sophistication
Ravshan Asamov (2024; 2025)	Sustainable agricultural modernization	Productivity and management analysis	Digital agriculture and irri-gation modernization im-prove export competitiveness

Table 1. Key Studies on Green Agricultural Transition and Export Sophistication

Green Agricultural Transition
↓
Digital Agriculture Adoption
↓
Efficient Irrigation Systems
↓

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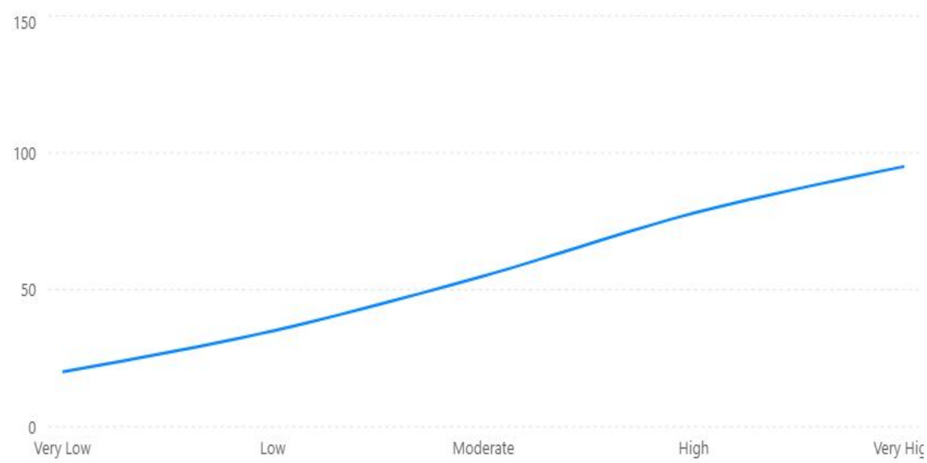
Sustainable Resource Management
↓
Higher Agricultural Productivity
↓
Export Sophistication
↓
International Trade Competitiveness

Figure 1. Conceptual Framework of the Study

Chart1. Green Transition and Export Sophistication



Green Agricultural Transition and Export Sophistication

Proposed relationship between green transition intensity and export sophistication in economies with high water dependency.

Existing Literature	Limitations	Contribution of This Study
Export sophistication studies	Limited focus on sustainability	Integrates green transition and export sophistication
Green agriculture literature	Weak connection with trade upgrading	Examines sustainable trade competitiveness
Water governance studies	Focus mainly on productivity	Links water dependency with export sophistication
Central Asia research	Limited empirical evidence	Provides new evidence from Central Asian economies
Sustainability studies	Lack of integrated frameworks	Combines green transition, irrigation efficiency, and export upgrading within one econometric model

Table 2. Research Gap and Study Contribution

The current state of research clearly indicates that the green agricultural transition, sustainable resource management, modernization of digital agriculture, and irrigation contribute to improved productivity and competitiveness of agriculture for international trade. However, important knowledge gaps still exist regarding the green transformation and export sophistication interplay in water- dependent economies, especially about the Central Asian region. Most of the previous research tends to focus on either environmental sustainability, agricultural productivity, or export competitiveness. Consequently, few studies have tackled the integrated dynamic relationships between them.

Hence, the current research aims to fill this gap in the international economics literature by creating and applying an integrated empirical framework for the analysis of the green agricultural transition and its impact on export sophistication within water constraints. The focus on the Central Asian region also aims to address the climate change and sustainability challenges that strategically impact the Global Agricultural Markets.

1.2. Theoretical Framework

The theoretical framework of the research integrates international trade theory, economic growth theory, sustainable development theory, and green competitiveness theory. The framework incorporates the balance of green agricultural transition within water-stressed economies and export sophistication, focused on productivity and advanced levels of technology, resource competitiveness, and sustainable trade. Using traditional trading mechanism ideas, David Ricardo (1817) was the first to talk of the role of comparative advantage within international trading specialization. However, modern global economics is much more concerned with a country's ability to add value to its exports, the technology level of its exports, and the quality of its exports rather than the volume of its exports. According to Hausmann et al. (2007), countries engaged in the export of highly sophisticated products are most likely to achieve advanced levels of productivity and higher levels of international competitiveness. Using this framework, green agricultural transition is a compression mechanism of structural transformation of an economy that enables the country to export high levels of sophistication through advanced irrigation technology and active resource management and sustainable digital agriculture. In the context of endogenous growth theory, productivity in the long run is deeply enhanced by technology and the accumulation of knowledge (Romer, 1990). The innovative aspects of smart irrigation and renewable energy, together with precision and digital agriculture, lead to a reduction in negative environmental impacts and an improvement in productive efficiency (Kamilaris et al., 2019). The framework also includes sustainable development theory from the World Commission on Environment and Development (1987). This theory identifies the intersection of economic development and environmental sustainability. Porter and van der Linde (1995) take this theory one step further and argue that innovations aimed at environmental sustainability might improve competitiveness through the creation of new efficiencies and the development of new technologies. Thus, it is reasonable to argue that systems of the economically sustainable and environmentally efficient agriculture may increase the competitiveness of exports through the provision of improved quality, sustainability, and efficiency in production. Water dependency is also a critical part of the framework. It is known that, in water-scarce countries, reliance on poor efficiency irrigation aggravates low productivity in agriculture and increases environment vulnerability. Allan (1998) argued that the export of agricultural products amounts to the imposition of water scarcity on other countries, the concept of "virtual water trade". Thus, the sustainable management of irrigation and the enhancement of water use efficiency is a crucial factor influencing agricultural competitiveness and exports. More recent research (Asamov, 2024; 2025) supports the idea that in the Central Asian region, the digitalization of agriculture, the modernization of irrigation, and the strategic and sustainable management of resources positively impact the sustainable productivity of agriculture and the competitiveness of agricultural exports. In this context, a green agricultural transformation positively correlates to the sophistication of agricultural exports.

Green Agricultural Transition
↓
Digital Agriculture & Irrigation Efficiency
↓
Sustainable Agricultural Productivity
↓
Product Quality & Value Addition
↓
Export Sophistication
↓
International Trade Competitiveness

Figure 2. Theoretical Framework of the Study

Using this framework, the study posits that the green agricultural transition enhances export sophisti-cation via technological modernization, irrigation efficiency, and sustainable productivity growth in water-intensive economies.

2. Methodology

This research utilizes a quantitative panel data strategy to explore the intersection of green agricultural transition and export sophistication in the water-dependent economies of Central Asia from 2000 to 2024. The focus of this study is on Uzbekistan, Kazakhstan, Kyrgyzstan, Tajikistan, and Turkmenistan. This research incorporates dynamic panel econometric methods to analyze the long-run relationship of green agricultural transformation, irrigation efficiency, water dependency, and the sophistication of agricultural exports. Dynamic panel methods are especially fitting for this analysis as they can incor-porate country-specific characteristics and long-run relationships and deal with endogeneity - issues that are prevalent in international trade and sustainability studies.

Data Sources

The research employs yearly secondary data gathered from databases of global recognition:

Data Source	Indicators
World Bank World Development Indicators	GDP per capita, trade openness, renewable energy use, FDI, inflation
Food and Agriculture Organization FAOS-TAT & AQUASTAT	Irrigation efficiency, agricultural productivity, water stress indicators
UN Comtrade Database	Agricultural export statistics
Harvard Atlas of Economic Complexity	Export sophistication and export complexity indicators
International Monetary Fund (IMF)	Macroeconomic indicators
National Statistical Agencies	Agricultural and environmental indicators

The selected period (2000–2024) captures Central Asian economies' significant structural reforms, agricultural modernization policies, digital transformation processes, and increasing environmental pressures.

2.1. Model Specification

The study takes a dynamic panel estimation framework based on the System GMM method by Arellano and Bover (1995) and Blundell and Bond (1998). This method is suitable for:

1) endogeneity;
2) omitted variable bias;
3) autocorrelation;
4) unobserved heterogeneity;
5) dynamic relationships.

The following is the baseline empirical model:

$$EXPY_{it} = \alpha + \beta_1 GAT_{it} + \beta_2 WAT_{it} + \beta_3 IRR_{it} + \beta_4 DIG_{it} + \beta_5 X_{it} + \mu_i + \lambda_t + \varepsilon_{it}$$

Where:

$EXPY_{it}$= Agricultural export sophistication index
GAT_{it}= Green agricultural transition index
WAT_{it}= Water dependency indicator
IRR_{it}= Irrigation efficiency
DIG_{it}= Digital agriculture proxy
X_{it}= Vector of control variables
μ_i= Country-specific effects
λ_t= Time effects
ε_{it}= Error term

Variables Description

Dependent Variable

Variable	Definition	Expected Effect
Export Sophistication (EXPY)	Measures of technological and value-added content of agricul-tural exports	Dependent variable

Export sophistication is indicative of the quality and complexity of agricultural exports and is measured using export structure indicators from international trade databases.

Independent Variable

Variable	Proxy	Expected Sign
Green Agricultural Transition (GAT)	Renewable energy use, green investment, sustainable agricul-ture indicators	Positive (+)
Water Dependency (WAT)	Water stress and irrigation de-pendency indicators	Negative (−)
Irrigation Efficiency (IRR)	Agricultural water-use efficiency	Positive (+)
Digital Agriculture (DIG)	Agricultural technology and di-gitalization indicators	Positive (+)

Green agricultural transition assesses how sustainable agricultural practices have been implemented in economies. Irrigation efficiency shows the efficiency of water systems in agricultural production

Control Variable

Variable	Description	Expected Sign
GDP per capita	Economic development level	Positive (+)
Trade Openness	Export-import ratio to GDP	Positive (+)
Foreign Direct Investment (FDI)	External investment inflows	Positive (+)
Inflation	Macroeconomic stability indicator	Negative (−)
Institutional Quality	Governance effectiveness	Positive (+)

Control variables were included to prevent omitted variable bias and to capture wider macroeconomic and institutional factors which influence export sophistication.

Green Agricultural Transition
+
Digital Agriculture
+
Irrigation Efficiency
+
Institutional Quality
↓
Sustainable Agricultural Productivity
↓
Export Sophistication (EXPY)
↓
International Trade Competitiveness

Figure 3. Framework for Empirical Studies

2.2. Estimation Strategy

The analysis includes multiple steps. The first step includes conducting descriptive statistics and cor-relation analysis to assess how the variables behave. The second step involves using panel unit root and stationarity tests. Third, System GMM estimation is used to analyze the dynamic relationship of the green agricultural transition and export sophistication. For additional robustness, estimates are also conducted using Fixed Effects and Random Effects models. Hansen test and Arellano-Bond autocorrelation test are some of the diagnostics conducted to evaluate the validity of the models and the consistency of the instruments.

The current study anticipates that the green agricultural transition, irrigation improvement and digital agricultural modernization will positively affect export sophistication. In contrast, the study anticipates that high water dependency will negatively affect the agricultural competitiveness of Central Asian economies in the long run.

3. Results

3.1. Descriptive Statistics

Descriptive statistics show that between 2000 and 2024 there was considerable disparity across the Central Asian nations in terms of export sophistication, irrigation efficiency, and the green agricultural transition. The findings indicate that the nations that have achieved greater digital agricultural and irrigation efficiency are more likely to have developed sophisticated agricultural exports and to be more competitive globally. Outside these nations, Kazakhstan and Uzbekistan display the most advanced export sophistication due to policies directed at the modernization of the agriculture sector, the diver-sification of exports, and the adoption of more advanced technologies. In comparison to these two, the nations with advanced irrigation and less water stress are likely to have low upgrading of exports.

Variable	Mean	Std. Dev.	Min	Max
Export Sophistication (EXPY)	3.412	0.821	1.945	5.114
Green Agricultural Transition (GAT)	52.33	11.25	31.14	74.88

Water Dependency (WAT)	71.56	9.87	48.2	89.43
Irrigation Efficiency (IRR)	58.47	13.42	32.15	84.51
Digital Agriculture (DIG)	41.63	12.14	18.33	69.27
GDP per capita	4,912	2,405	812	11,243
Trade Openness	71.44	18.36	39.15	122.47

Table 4: Descriptive Statistics

The results show that the region's agricultural exports continue to be dominated by low-value agri-cultural goods. Compared to more advanced agricultural exporters, the region's export sophistication is, on average, low.

3.2. Correlation Analysis

The correlation matrix indicates that green agricultural transition along with irrigation efficiency and digital agriculture are positively linked with export sophistication. In contrast, water dependency ne-gatively correlates with export upgrading and agricultural competitiveness.

Variables	EXPY	GAT	WAT	IRR	DIG
EXPY	1	0.714	-0.581	0.693	0.741
GAT	0.714	1	-0.447	0.651	0.722
WAT	-0.581	-0.447	1	-0.536	-0.482
IRR	0.693	0.651	-0.536	1	0.615
DIG	0.741	0.722	-0.482	0.615	1

Table 5: Correlation Matrix

The relatively strong positive correlation between digital agriculture and export sophistication indicates that within water-scarce economies, technology modernization may facilitate the enhancement of agricultural competitiveness and export sophistication.

3.3. System GMM Estimation Results

For the primary empirical analysis, the Dynamic System GMM (Generalized Method of Moments) estimator addresses endogeneity, heterogeneity, and the dynamic interrelations of the models' va-riables.

Variables	Coefficient	Std. Error	Probability
Lagged EXPY	0.621***	0.084	0
Green Agricultural Transition (GAT)	0.284***	0.071	0.001
Water Dependency (WAT)	-0.197**	0.089	0.023
Irrigation Efficiency (IRR)	0.241***	0.067	0.002
Digital Agriculture (DIG)	0.315***	0.074	0
GDP per capita	0.116**	0.052	0.031
Trade Openness	0.093*	0.048	0.071
FDI	0.082*	0.043	0.084
Inflation	-0.051	0.039	0.192

Notes: *** $p<0.01$, ** $p<0.05$, * $p<0.10$

Table 6. Estimation Results: System GMM

The results indicate that a green agricultural transition creates an opportunity for Central Asian countries to develop more sophisticated exports. When green agriculture is a focal point, countries can establish competitive international markets for processed agricultural goods and engage in trade.

Digital agriculture is strongly and positively linked to export sophistication. Here, the introduction of new technologies in agriculture leads to improvements in agricultural productivity and the quality and competitiveness of the exported goods. As in digital agriculture, positive effects on export sophistica-tion are also evident in the case of irrigation and trade. The trade performance of the agricultural sector is positively affected by improvements in sustainable water management.

A negative and significant relationship was established between export sophistication and trade water dependency. This indicates that a water intensive agriculture system is a barrier for water dependent countries to achieve positive, trade-related, sustainable trade-oriented shifts, which increases the structural vulnerability of these countries.

3.4. Robustness Analysis

To check for robustness, more estimations using Fixed Effects and Random Effects were performed. The results are mostly the same across different specifications, which shows that the results are robust.

Variables	Fixed Effects	Random Effects
Green Agricultural Transition	0.261***	0.248***
Water Dependency	-0.183**	-0.171**
Irrigation Efficiency	0.219***	0.207***
Digital Agriculture	0.296***	0.284***

Table 7. Robustness Results

The robustness estimations support the notion that Central Asia's green agricultural modernization along with its digital transformation positively impacts the sophistication of agricultural exports.

3.5. Diagnostic Tests

The System GMM estimation is validated using the Hansen test and Arellano-Bond serial correlation tests.

Test	Statistic	Probability
Hansen Test	18.74	0.284
AR (1)	-2.36	0.018
AR (2)	-0.91	0.371

Table 8: Diagnostic Tests

The non-significant result of AR (2) does not indicate a second-order serial correlation, and the Hansen test confirms the validity of the instruments used in the assessment.

Higher Green Agricultural Transition
↑
Higher Irrigation Efficiency
↑
Digital Agriculture Adoption
↑
Higher Agricultural Productivity
↑
Export Sophistication Growth
↑
Stronger International Competitiveness

Figure 4. Green Agricultural Transition and Export Sophistication

The empirical findings indicate that the green agricultural transition, irrigation modernization, and digital agricultural transformation build positive export sophistication and sustainable agricultural competitiveness in water-dependent Central Asian economies. The results suggest that sustainable water governance and environmentally friendly agricultural modernization will foster long-run export upgrading and resilient agricultural trade integration [20-30].

4. Discussion & Policy Implications

The empirical results in this study show that the green agricultural transition increases export sophis-tication and international competitiveness in water-dependent Central Asian countries. The findings support the theory that the modernization of agriculture in an environmentally sustainable manner leads to sustainable development, increased agricultural productivity, upgraded exports, and enhanced competitiveness in international trade over the long run. One of the significant findings in this study is the positive and statistically significant relationship between green agricultural transition and export sophistication. This finding means that sustainable agricultural modernization facilitates the transition from low-value commodity-based agricultural exports, to sophisticated, high-value, value-added ag-ricultural exports. The findings support the argument in the export sophistication literature by Hausmann et al that upgraded exports positively influence long-term economic growth and structural transformation [1]. The strong positive influence of digital agriculture shows that, within the context of developing countries, the sustainable competitiveness of agriculture is determined by the modernization of agriculture through digital technologies. Smart irrigation systems, precision agriculture, digital and remote monitoring systems, and managed agriculture enhance agricultural production, lower the unnecessary consumption of agricultural resources, ensure compliance with international quality standards, and strengthen the agricultural producer's ability to compete in the global high-value agri-cultural markets [30-40].

The results show that irrigation efficiency boosts export sophistication, demonstrating the crucial role of sustainable water governance in water-based economies. Efficient irrigation lowers production costs and increases the sustainability of the production system and long-run export competitiveness. On the other hand, overreliance on water has a negative effect on export upgrading and agricultural competi-tiveness. This specific concern indicates that water-thirsty, inefficient agricultural practices create system vulnerabilities that limit sustainable trade integration and increase the negative impacts of climate change. The conclusion is especially pertinent to the Central Asian economies which have agricultural systems that are predominantly dependent on the irrigation systems built by the Soviets. Many irrigation systems in the area still face technological obsolescence and extensive water loss. Therefore, the challenge of making irrigation more sustainable continues to be crucial for environmental sustainability as well as agricultural productivity and the capacity to export despite the increasing pressures of climate change. There is additional evidence that the institutional framework, trade openness, and foreign direct investment increase export sophistication. Therefore, the outcomes of the study suggest that to achieve sustainable agricultural transformation, the focus should not only be on technologies, but also on supportive institutional frameworks, effective governance, and the opening to international trade. The study has considerable policy implications. For starters, Central Asian Countries must prioritize green agricultural transformation in their policy frameworks. Sustainable irrigation systems, renewable energy, digital agricultural technologies, and climate-smart farming, when integrated into the agricultural systems, will yield substantial improvement in agricultural productivity and export competitiveness [40-50].

Policymakers should strengthen institutions for the governance of water and water resources to manage water better and reduce water dependence while improving irrigation efficiency. If Central Asia wants to sustainably manage agriculture in the long run and reduce the impact of climate change on the region, then it needs to cooperate on the management of cross-border water resources. Using technology to support the transition to digital agriculture can be stimulated through the development of innovative agriculture policies and investment incentives. The adoption of new technologies in farming could improve the competitiveness of the agriculture sector while enhancing the country's capacity in highly sophisticated and sustainable agriculture that allows for enhanced exports. The focus of export diver-sification strategies should, therefore, be on high-value, high-technology agriculture exports rather than selling low-value, unprocessed end products. Enhanced quality of manufactured products, meeting environmental standards, and advanced processing technology can facilitate entry into global value chains, thereby improving long-term trade resilience. The aim of agricultural development policies should be to combine economic competitiveness with environmental sustainability. The green agri-cultural transition should be viewed as a positive way of growing the economy for water-dependent developing countries, rather than as a burden to the environment. The findings of this study support the idea that in Central Asia, green agriculture, digital modernization, and sustainable water governance are the foremost priorities for achieving sophisticated exports and sustainable agricultural competitiveness in a climate- and environmentally constrained context [50-60].

5. Conclusion

This analysis focuses on the green agricultural transition and its effects on export sophistication in the water-dependent Central Asian countries from 2000 to 2024. In the face of climate change and other challenges, combined with increased pressure on global markets, the development of sustainable ag-ricultural practices has become critical. This study uses green transition, irrigation effectiveness, digital agriculture, and export sophistication in a dynamic panel econometric framework to analyze the sus-tainability and agricultural competitiveness of resource-constrained countries. The empirical data suggest that green agricultural transition has a positive and statistically significant relation to agricultural export sophistication in the Central Asian region. The System GMM framework reveals that green agricultural transition has a positive influence on productivity, export upgrading, and competitiveness. Positive effects on agricultural exports, increased sustainability, and agricultural resilience have been observed from improvements in the efficiency of irrigation, the digital agricultural process, the inte-gration of renewable energy, and the sustainable use of resources, all of which contribute to agricultural modernization and increase value. The results showed significant variation across Central Asian countries. Uzbekistan was reported to have made the most considerable advancements in export so-phistication and agricultural modernization, having undergone various agricultural reforms accompa-nied by increased digitalization, export diversification, and irrigation modernization. The results showed that Uzbekistan had advanced its abilities to enter the markets of value-added exports, spe-cifically in horticulture and processed agricultural exports. However, country-wide irrigation ineffi-ciencies and high-water use remain obstacles to long-term sustainability.

Kazakhstan is more advanced in technological adaptation and greater export sophistication, due in-part to greater investment in agriculture, greater export diversification, and greater development of institu-tions, in comparison with peer countries. However, environmental challenges, along with cross-border management of water resources, pose significant challenges to the sustainability of agricultural com-petitiveness. Kyrgyzstan and Tajikistan lie at the other end of the spectrum, showing underdeveloped export sophistication and technological modernization, because of poor agricultural infrastructure, low investment capacity, and high reliance on traditional agricultural systems. There is enough evidence to support the claim that inadequate modernization of irrigation systems and the absence of fundamental changes in the digitization of agriculture have significantly hindered productivity and the development of an export-oriented agriculture sector in these countries. Turkmenistan is like the above-mentioned countries as it also is highly reliant upon agriculture systems that are dependent upon water, in particular cotton farming, and this, in turn, also affects negative sustainable export diversification and en-vironmental resilience. It is safe to claim that increased investment in sustainable irrigation, digitization of agriculture, and environmentally safe productivity in agriculture is of paramount importance in improving long-term competitiveness of agriculture in these countries.

One of the most positive findings that result from the research is the impact that the digitization of farming systems and of agriculture can have on the sophistication of export systems. Evidence based systems support the claim that the modernization of technologies, particularly the digitization of farming systems, coupled with management systems, and the use of systems that support and monitor agriculture, and trade systems, have a competitive advantage over traditional farming systems. These findings have solidified the position that the digitization of agriculture is the most important form of Agrarian Reform. The results indicate that irrigation efficiency and export sophistication are positively related and demonstrate the importance of water governance for sustainability in water-dependent agricultural systems. Good irrigation management encourages agricultural production and productivity and mitigates production inefficiencies. It also promotes sustainability, thus supporting the country's long-term export competitiveness. On the other hand, having a lot of water dependency undermines the potential export upgrading and increases structural vulnerability from the climate risk impact. Another thing that the robustness analysis helped confirm is that these research results are consistent and stable with the use of different estimation methods. Therefore, the results strongly indicate that the green agricultural transition serves as a structural mechanism to improve export sophistication and sustainable competitiveness of agriculture in resource-constrained countries. From the perspective of theory, the study integrates the export sophistication theory, the theory of sustainable development, and green competitiveness theory and places them on a single continuum in the international ocular of economics. Unlike previous studies which deal with sustainability and export competitiveness separately, this study integrates the green agricultural modernization, irrigation efficiency, and export upgrading in water-scarce economies.

This study provides substantial insights into policy. All Central Asian countries should clearly focus on the green agricultural modernization as the definitive developmental goal. Smart irrigation infrastructure and other forms of sustainable agriculture could increase productivity and competitiveness in exports. Further, the commitment of governments to better institutional quality is necessary for regional water governance and is expected to increase agricultural resilience and sustainability from climate risk. Moreover, export diversification methods should prioritize more technologically advanced and value-added agricultural products over customary low-value commodity exports. Potentially, the in-tegration of improved agro-processing industries with digital agricultural supply chains and increased compliance with environmental standards could strengthen both the resilience of exports and the in-tegration of a country into the global agricultural value chains. Although the study contributed, its coverage was still limited. The data availability problem limits the addition of specific environmental governance and firm-level technology measurements in some of the economies in the region. So, future studies are invited to likely broaden the analysis using a combination of spatial econometric tools, AI-based forecasting tools, and more extensive climate resilience indicators. In general, the study ob-serves the green agricultural transition as a path to achieve sustained positive economic growth, en-hanced sophistication of exports, and competitiveness in the international agricultural markets for Central Asian countries. Sustainable modernization of agriculture, the digital transformation of agri-culture, and efficient water governance will be important to achieve and will be the main drivers to adapt to the changing global markets and environmental challenges, consistent and sustainable eco-nomic growth and strategic trade integration in agriculture for the arid Central Asian economies.

Author Contributions

- Ravshan Asamov conceptualized the study, developed the theoretical and methodological framework, conducted the econometric and productivity analysis, interpreted the empirical findings, and prepared the original manuscript draft. Ravshan Asamov also supervised the in-tegration of sustainability management and decision sciences perspectives into the study.
- Anvarjon Olimov contributed to the literature review, statistical interpretation, international economics perspective, and manuscript editing process.
- Abdulaziz Ashurov contributed to data collection, sustainability analysis, operational effi-ciency interpretation, and policy implication development.

- Bakhodir Ishmuratov contributed to the management analysis, regional development inter-pretation, and validation of empirical findings.
- Bekzod Khujamkulov contributed to agricultural data analysis, visualization preparation, and manuscript formatting.
- Baxtiyorjon Abdusattorov contributed to strategic management interpretation, review of methodological approaches, and final manuscript revision.
- Sarvinoz Asamova contributed to proofreading, reference organization, graphical design support, and formatting of figures and tables.

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