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Smart Technologies in Agriculture for Green Economy Development: Prospects for Integration and Development

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Abstract: This article analyzes the application of smart technologies in agriculture and their interrelationship with the principles of the green economy, drawing on foreign empirical research. The study is based on a mixed-method approach comprising a systematic review of the scientific literature and a comparative-descriptive analysis of official statistical data for Uzbekistan. Twenty-four foreign sources were systematically classified according to four criteria - scale of analysis, research method, technological focus, and the nature of the conclusion reached - which constitutes the scientific novelty of the article. The findings show that IoT-based and precision-agriculture technologies can reduce water consumption by 20–90% and increase resource-use efficiency by up to 92–95%; at the same time, the environmental effect of digitalization is shown not to be universal, and a critical evaluation reveals that a "rebound effect" may occur in certain cases, whereby digital infrastructure itself generates additional emissions. The article further analyzes statistical indicators on water-saving technologies in Uzbekistan and identifies the near-total absence of econometric studies establishing causal relationships between smart technologies and the green economy specific to the country and the Central Asian region, thereby outlining a clear direction for future research.

Keywords: smart technologies, precision agriculture, green economy, digital transformation, IoT, twin transition, rebound effect, Uzbekistan.

1. Introduction

Today, digital transformation processes are advancing rapidly across all sectors of the global economy. The agricultural sector is no exception: climate change, limited water resources, population growth, and the need to ensure food security are compelling the sector to adopt innovative approaches.

At the same time, the intensification of climate change and environmental problems at the global level has increased the relevance of the "green economy" concept. The green economy is an economic system based on the rational use of natural resources, waste reduction, carbon footprint reduction, and the harmonization of economic growth with environmental sustainability.

The relevance of this article lies in the fact that smart technologies not only increase agricultural productivity but also serve the goals of the green economy by saving resources and ensuring environmental cleanliness. Consequently, these two directions - digitalization and greening - should be regarded as mutually reinforcing processes.

A review of the scientific literature shows that, although numerous foreign studies exist on the interrelationship between digital and green transformation (see Section 3), a systematic analysis combining this relationship with official statistical indicators for Uzbekistan and the Central Asian region remains insufficient. This article aims to partially fill this gap.

The purpose of the study is to scientifically substantiate how the application of smart technologies in agriculture serves the principles of the green economy and what level of efficiency this provides, as well as to assess the country's potential in this regard by analyzing Uzbekistan's statistical indicators on the digital economy and innovation activity.

The following research objectives have been set:

1. To describe the main directions of smart agricultural technologies;
2. To substantiate the theoretical relationship between the green economy concept and smart technologies;
3. To systematically classify and evaluate foreign empirical studies;
4. To analyze Uzbekistan's official statistical data on water conservation, the digital economy, and innovation activity;
5. To develop conclusions and recommendations regarding existing problems and directions for development.

The integration of smart technologies, agriculture, and the green economy has been actively studied in international scientific literature in recent years. Below, studies in this field are reviewed thematically, with an exact citation provided for each source.

A number of field experiments have examined the impact of precision agriculture and IoT technologies on resource efficiency. In particular, an experimental study of IoT-based precision agriculture found that resource use efficiency can reach 92–95% [1]. A large analytical review covering 56 scientific studies showed that IoT-based drip irrigation systems can reduce water consumption by up to 70% and increase yields by up to 30% [2]. An 18-month experiment on eggplant crops found that a smart irrigation system based on cloud computing and IoT technologies reduced water consumption by up to 90% compared with conventional methods [3]. An experiment on drip-irrigated rice scientifically demonstrated that, alongside a 23.3% reduction in water consumption, methane gas emissions decreased by 78% [4]. Engineering studies have also been conducted on the development of autonomous irrigation systems based on IoT and artificial intelligence [5].

The relationship between digitalization and the reduction of carbon emissions is one of the areas most extensively studied using the example of China. An econometric study based on inter-provincial panel data found that digital agriculture also affects the reduction of carbon emissions through a spatial spillover effect [6]. Another study examined the mechanisms through which the digital economy reduces agricultural carbon emissions using a two-way fixed-effects model [7], while yet another analyzed the relationship between the digital economy, green innovation, and agricultural carbon emissions from the perspective of spillover effects, specifically noting the risk of a "rebound effect" [8].

Regarding global development trends in the smart agriculture market, several market analysis reports are available. Specifically, data on the size and growth forecasts of the global smart agriculture market [9], the development directions of the digital agriculture market through 2030 [10], and investment activity indicators in this field [11] are presented in reports by relevant market research companies.

The topic of water-saving technologies and green economy policy in Uzbekistan is covered in official sources. Data from the Ministry of Water Resources of the Republic of Uzbekistan for 2025–2026 present the scale and plans for implementing water-saving technologies [12]. The draft updated "Uzbekistan–2030" strategy sets long-term goals in the fields of water resources and agriculture [13], while the current state of drip irrigation in horticulture is examined in a separate analytical material [14]. The general theoretical foundations of the green economy concept are presented in reports of the United Nations Environment Programme (UNEP) [15], while its practical implementation in Uzbekistan is reflected in the official document "Strategy for Transition to a Green Economy" (2019–2030) [16].

One of the largest and most methodologically rigorous studies on the empirical relationship between the digital economy and economic–ecological integration at the international level was conducted using panel data for 100 countries over 2009–2022; it demonstrated a positive relationship between the level of digital economy development and the degree of economic–ecological integration using the entropy weighting method and a spatial Durbin model, and also analyzed the degree of coordination by continent (Europe — leading, Africa — lagging) [17].

The joint adoption of digital and green technologies in developing countries has been examined by the United Nations Industrial Development Organization (UNIDO) using a sample of 658 industrial enterprises in Ghana, Thailand, and Vietnam; through a bivariate probit model, it was scientifically demonstrated that the two types of technology have a complementary (mutually reinforcing) nature, with firm size, participation in global value chains, and innovation activity identified as influencing factors [18].

Regarding the complex and contradictory aspects of the "twin transition," a particularly noteworthy study examined the relationship between patent data and greenhouse gas emissions in European regions over 2007–2016, empirically demonstrating that digital technologies can, in certain cases (especially through big data and computing infrastructure), increase emissions at the local level — a phenomenon known as the "rebound effect" [19]. In addition, new patent-based methodological indicators have been developed to measure the joint development of digital and environmental innovation [20].

As an innovative solution, digital twin technology has become the subject of dedicated review studies in recent years. There is a comprehensive review of the applications and practical barriers of digital twins in agriculture [21], as well as practical studies demonstrating the implementation of this technology in agriculture [22].

Uzbekistan's national-level indicators of the digital economy and innovation activity are presented in official statistical data, reflecting the dynamics of ICT infrastructure in higher education, the structure of high-tech manufacturing, technological innovation, and R&D expenditure between 2020 and 2023/2024 [23]. Digital and environmental indicators broken down by the country's regions (provinces, the city of Tashkent, and the Republic of Karakalpakstan) have been compiled into a separate statistical dataset aimed at identifying inter-regional disparities [24].

The literature reviewed above shows that most foreign studies focus either on efficiency at the individual farm or enterprise (micro) level or on macro-level econometric relationships in large countries (mainly China). At the same time, the number of critical, balanced studies necessary for an objective assessment of the topic is limited, with only one major study serving as a clear example in this regard. Most importantly, there are virtually no primary econometric studies establishing a causal relationship between smart technologies and the green economy specifically for Uzbekistan and the Central Asian region — existing sources are mainly limited to official descriptive statistics. This gap further substantiates the scientific relevance of the article and is clearly illustrated through the classification system presented in Section 3.9.

2. Materials and Methods

Research design. This article is based on a mixed-method approach comprising: (a) a systematic narrative review of foreign scientific literature, (b) a comparative-descriptive analysis of official statistical data for Uzbekistan, and (c) a cluster analysis based on regional data.

Data sources. The study drew on the following sources:

- internationally peer-reviewed scientific journals (Sustainability, Journal of Evolutionary Economics, Environmental and Resource Economics, Frontiers, Discover Agriculture, and others — a total of 15 primary studies published between 2023 and 2026);
- reports of international organizations and market research firms (OECD, UNIDO, Grand View Research, Market.us);
- statistical data for 2025–2026 from the Ministry of Water Resources of the Republic of Uzbekistan and other official agencies;
- national statistical indicators on Uzbekistan's digital economy and innovation activity for 2020–2023/2024 (covering higher education, high-tech manufacturing, technological innovation, investment in information and communication technologies, R&D expenditure, and sources of innovation financing);
- digital and environmental indicators for 2023 across Uzbekistan's 14 regions (12 provinces, the city of Tashkent, and the Republic of Karakalpakstan), including R&D expenditure, technological innovation, the number of computers, and waste- and treatment-related indicators.

Classification criteria. Four analytical criteria were applied to systematize the foreign studies: (1) scale of analysis (micro, meso, or macro level), (2) research method used, (3) technological focus, and (4) the overall nature of the conclusion reached (positive, mixed/critical, or descriptive). This classification approach constitutes the scientific novelty of the article (see Section 3.9).

Limitations. The study is descriptive and narrative in nature and does not present its own primary causal (econometric) model at the national level; the statistical indicators presented for Uzbekistan were analyzed on the basis of ready-made data obtained from official sources. Because the regional cluster analysis is based on cross-sectional data for a single year (2023), it reflects a static snapshot of the current situation rather than dynamic (time-series) trends.

3. Results

Smart Agriculture: Essence and Main Technological Directions

Precision Agriculture

Precision agriculture is a system for managing a field not uniformly, but according to an individualized approach tailored to the characteristics of each plot (soil composition, moisture, nutrient content). Using GPS navigation, geographic information systems (GIS), and sensors, seeding rates, fertilizer and pesticide quantities, and irrigation schedules are determined through precise calculations. As a result, resource savings of 15–30% and yield increases of 10–20% are observed.

The Internet of Things (IoT) and Sensor Systems

Sensors installed in fields that measure moisture, temperature, light, and soil composition transmit data to a central system in real time. This enables farmers to automate irrigation systems, prevent the emergence of pests, and carry out agrotechnical measures adapted to climatic conditions in a timely manner.

Artificial Intelligence and Big Data

Artificial intelligence algorithms analyze years of meteorological, agronomic, and market data to forecast yields, select crop varieties, and detect risks in advance. Machine learning-based systems also make it possible to identify pests and diseases from images.

Drones and Remote Sensing

Drones used in agriculture perform tasks such as aerial photography of fields, precise application of fertilizers and treatments, and yield assessment and monitoring. This optimizes the use of chemical substances while saving labor and time.

Smart irrigation systems

When drip irrigation systems are combined with sensors, water consumption can be reduced by up to 40–50%. This is of particular importance for the water-scarce Central Asian region, including Uzbekistan.

The green economy concept and its relationship to agriculture

The concept of the green economy was put forward by the United Nations Environment Programme (UNEP) and is aimed at ensuring economic growth while reducing environmental risks and resource scarcity.

Green economy principles in agriculture are reflected in the following:

1. Resource efficiency — rational use of water, land, and energy resources;
2. Carbon footprint reduction — use of electric and solar energy in agricultural machinery, reduced use of chemical fertilizers;
3. Preservation of soil fertility — adoption of organic farming methods;
4. Waste-free production — recycling of agricultural waste (biogas, compost);
5. Preservation of biodiversity — replacing monoculture cropping with crop rotation.

Smart technologies serve precisely as the means and mechanism for implementing these principles. For example, if precision agriculture makes it possible to avoid the excessive use of fertilizers and pesticides, this directly prevents the pollution of soil and water resources and serves the goals of the green economy.

Integrated approach: the interrelationship of digital and ecological transformation.

The relationship between smart technologies and the green economy can be illustrated through the following table:

Table 1. The relationship between smart technologies and the green economy

Smart technology	Ecological–economic effect
Precision agriculture	Reducing fertilizer and pesticide use; preventing soil degradation
IoT sensors and smart irrigation	Conserving water resources; reducing the risk of salinization
AI forecasting systems	Reducing losses through early risk detection
Drones	Reducing fuel and labor costs; precise dosing
Smart Technology	Ecological–economic effect
Precision agriculture	Reducing fertilizer and pesticide use; preventing soil degradation

Source: created by the author

This integration yields a dual effect - economic (cost reduction, increased productivity) and ecological (resource conservation, reduced pollution). Below, recent scientific findings and specific quantitative indicators confirming this relationship are presented.

Empirical research findings on resource efficiency.

Experimental studies of IoT-based precision agriculture have shown that resource-use efficiency can reach 92–95%, indicating a substantial reduction in resource consumption and negative environmental impact. A major analytical review covering 56 scientific studies found that IoT-based drip irrigation systems can reduce water consumption by up to 70% and increase yields by up to 30%; similar results were achieved in an artificial-intelligence-based project implemented in the Indian state of Andhra Pradesh.

Another study found that a smart irrigation system based on IoT and cloud technologies reduced water consumption in eggplant cultivation by up to 90% compared with conventional methods; the reliability of the system was confirmed by devices installed in three different geographic regions over an 18-month observation period. A study published in 2026 found that applying an IoT-based system to manage irrigation, fertilization, and biopesticide use reduced water consumption by 47% and increased lettuce yield by 43%.

Overall, various experiments conducted worldwide show that drip irrigation can reduce water consumption by 20–80% compared with conventional (flood) irrigation, with the exact figure varying by soil type, crop type, and climatic conditions. An experiment on drip-irrigated rice found that, alongside a 23.3% reduction in water consumption, yields increased by 23.5% and methane gas emissions decreased by 78% — confirming that this technology delivers significant benefits not only for water use but also for the climate.

The relationship between digitalization and the reduction of carbon emissions.

A number of large-scale econometric studies conducted in China (based on provincial-level data covering 2013–2022) found a statistically significant negative relationship between the level of digital economy development and agricultural carbon emissions. In other words, regions with higher levels of agricultural digitalization exhibited lower carbon emissions. This effect was particularly pronounced in inland regions specializing in grain cultivation and was primarily achieved through mechanisms such as more efficient fertilizer use and the adoption of green innovations. It is worth noting that agricultural emissions account for approximately 17% of China's total greenhouse gas emissions — underscoring the enormous potential of digital technologies in this field.

Global growth rates of the smart agriculture market.

According to market analysis firms, the global smart agriculture market was worth approximately USD 22–28 billion in 2025 and is projected to grow at an average annual rate of 10–15%, reaching USD 75–84 billion by 2030–2033. The digital agriculture market is expected to grow from USD 21.4 billion in 2025 to USD 35.9 billion by 2030. In 2025 alone, more than USD 2 billion in venture capital was invested in AI-based agricultural platforms, and experts estimate that this sector could generate an additional USD 100 billion in annual economic value by 2030 through cost optimization and waste reduction.

Statistical indicators on water conservation in Uzbekistan

According to the Ministry of Water Resources of the Republic of Uzbekistan, water-saving technologies were introduced across 817,200 hectares nationwide in 2025 alone, including drip irrigation on 103,200 hectares, sprinkler irrigation on 30,700 hectares, and discrete irrigation methods on 13,700 hectares; in addition, flexible-pipe irrigation was applied on 74,000 hectares and furrow irrigation with plastic film on 49,000 hectares. For this purpose, 1.35 trillion soums were allocated in 2025, of which 1.2 trillion soums were

disbursed. According to the plans set for 2026, water-saving technologies are to be introduced on a further 503,000 hectares (including 75,400 hectares of drip irrigation, 346,000 hectares of sprinkler irrigation, and 289,000 hectares of discrete irrigation), and laser leveling work is to be carried out on 200,000 hectares, with 1.4–1.6 trillion soums expected to be allocated from the state budget for this purpose.

Under the updated "Uzbekistan–2030" strategy, the objectives are to introduce water-saving technologies on 100% of agricultural land, to expand the area under drip irrigation by an additional 500,000 hectares, and to raise the annual production capacity of domestic enterprises manufacturing such technologies to 300,000 hectares' worth of equipment. The overall goal is to improve water-use efficiency by 25% by 2030. Currently, the total irrigated area in the country amounts to 4.3 million hectares, of which the area equipped with water-saving technologies is planned to reach 2 million hectares.

At the same time, imbalances persist within the sector — for example, the share of horticultural and viticultural land equipped with drip irrigation currently stands at only 16.6%, which is a low figure. For this reason, starting January 1, 2025, the subsidy for installing drip irrigation systems in intensive orchards and vineyards was doubled to up to 16 million soums per hectare. In addition, starting in 2025, drip irrigation technology is being piloted in rice cultivation in the Republic of Karakalpakstan and the Khorezm, Bukhara, Namangan, Syrdarya, and Surkhandarya regions, with water consumption expected to decrease by 50%.

The empirical relationship between the digital economy and economic–ecological integration at the international level

A comprehensive econometric study published in 2025 in the journal *Sustainability* examined the relationship between the level of digital economy development and the degree of economic–ecological integration using panel data for 100 countries over 2009–2022. The study was conducted using the entropy weighting method and an equal-weighting method, with separate indices calculated for each country. According to the findings, a one-unit increase in the level of digital economy development leads to a statistically significant increase in the degree of economic–ecological integration (at the 1% significance level), a result confirmed through various robustness checks.

One of the study's most important conclusions is that the positive effect of the digital economy on economic–ecological integration operates through two main mechanisms: first, changes in industrial structure, and second, technological innovation. The study also identified a spatial "spillover effect" of the digital economy - that is, the development of the digital economy in one country also helps improve the economic–ecological indicators of neighboring countries. An analysis disaggregated by income level showed that this effect is particularly strong in high-income and upper-middle-income countries.

A comparison across continents shows that Europe has the highest degree of coordination between digital economy development and economic–ecological integration, followed by the Americas and Asia, with Africa ranking lowest. This finding offers an important lesson for developing countries such as Uzbekistan.

New empirical evidence on the joint adoption of digital and green technologies in developing countries

A study prepared by the United Nations Industrial Development Organization (UNIDO) based on a survey of 658 industrial enterprises in Ghana, Thailand, and Vietnam found, using a bivariate probit model, that firms' decisions to adopt digital and green technologies are not independent of one another but instead exhibit a complementary (mutually reinforcing) nature.

According to the findings, only 10.3% of the surveyed firms had adopted both digital and green technologies together, 26.4% had adopted only green technologies, 7.6% had adopted only digital technologies, and the remaining 55.6% had made no significant changes in either direction — a figure considerably lower than in developed countries (30% in the European Union and 23% in the United States).

The study identified the main factors influencing the joint adoption of the two technology types: firm size, participation in global value chains (GVCs), the level of innovation activity, and prior investments. Large firms were found to be 8.5 percentage points more likely to adopt digital technologies and 7.9 percentage points more likely to adopt green technologies; among GVC participants, these figures were 9.3% and 12.1% respectively, and among firms with active investment, 10.8% and 10.4% respectively.

The empirical evidence presented in this section can be systematically grouped according to the type of ecological-economic effect the technologies and policies under review produce. This classification cuts across the earlier technology-by-technology narrative and instead groups the findings into five effect categories: (A) water-resource effects, (B) carbon/climate effects, (C) soil, biodiversity, and input-use effects, (D) economic and market effects, and (E) institutional, cross-country, and critical/limiting effects.

Table 2. A typology of ecological-economic effects in smart agriculture: evidence by category.

Category	Effect type	Technologies / sources involved	Key quantitative evidence
A	Water-resource effects	Smart irrigation (1.5); resource-efficiency studies (3.1); Uzbekistan statistics (3.4)	Water savings of 20–90%; 817,200 ha equipped nationally; target of 2 million ha by 2030
B	Carbon / climate effects	China digital-economy studies (3.2); rice–methane experiment (3.1); rebound effect (3.7)	17% of China's GHG emissions from agriculture; 78% methane reduction; but digital infrastructure can <i>increase</i> emissions locally
C	Soil, biodiversity & input-use effects	Precision agriculture, IoT/AI, drones (1.1–1.4); green-economy principles (Section 2)	15–30% resource savings; 10–20% yield gains; reduced fertilizer/pesticide use
D	Economic & market effects	Market-growth data (3.3); firm-level adoption (3.6)	USD 22–28 bn (2025) → USD 75–84 bn (2033) market; only 10.3% of firms adopt both technologies jointly
E	Institutional, cross-country & critical effects	Cross-country integration (3.5); digital twin barriers (3.8); rebound effect (3.7)	Income-level heterogeneity; Europe leads coordination; small farms face infrastructure barriers

Critical assessment: the complex and contradictory aspects of the "twin transition".

Although the concept of the "twin transition" is widely used in the scientific literature, not all studies confirm that it produces only positive effects. A study examining the relationship between patent data and greenhouse gas emissions in European regions over 2007–2016 (Bianchini, Damioli, & Ghisetti, 2023) reached an unexpected conclusion: while the development of green technologies at the local level reduced greenhouse gas emissions, the development of digital technologies, conversely, increased them — with technologies related to big data and computing infrastructure having the most negative impact [17–19].

This finding delivers an important cautionary message: digitalization does not automatically produce environmental benefits - a phenomenon known in the scientific literature as the "rebound effect." Accordingly, when deploying IoT sensors, servers, and data centers in agriculture, the energy these devices themselves consume must also be taken into account, and, where possible, they should be powered by solar or other renewable energy sources.

In addition, a study conducted by the OECD in 2025–2026 developed new patent-based indicators to measure the extent to which digital and environmental innovations are developing jointly - this innovative methodological approach shows that digital innovation often serves as a precursor ("seed") for subsequent environmental innovation.

Digital twin technology as an innovative solution

One of the most promising innovative solutions combining the green economy and digital transformation in agriculture is digital twin technology. This technology is based on modeling an actual field, plant, or irrigation system as a complete digital replica within a virtual environment, and, by combining IoT, artificial intelligence, and remote sensing technologies, it serves to model in advance crop growth, pest pressure, and agrotechnical measures.

However, the deployment of such systems requires substantial data-collection infrastructure, which can pose a significant financial and technical barrier for small family farms - particularly the many family-based farming households in Uzbekistan. For this reason, experts recommend adopting alternative approaches such as "edge computing," meaning that data are processed on devices located near the field rather than on a central server.

In summary, the body of research reviewed above shows that the simplified assumption that "digital transformation automatically produces environmental benefits" does not fully correspond to reality. Achieving positive outcomes requires making conscious, purpose-driven technological choices and planning digital and green technologies jointly while taking local conditions into account.

A classification system for the studies reviewed above.

As the scientific novelty of this article, rather than listing the various studies presented in Section 3 individually, a systematic classification based on several analytical criteria is proposed. The studies were classified according to four criteria: (1) scale of analysis (micro - farm/field level; meso - regional/sectoral level; macro — national/global level), (2) the research method employed, (3) technological focus, and (4) the overall nature of the conclusion reached.

Table 3. Classification of integrated approaches to the interdependence of digital and ecological transformation.

No.	Source (author, year)	Scale of analysis	Research method	Technological focus	Nature of conclusion
1	BIO Web Conferences, 2024	Micro (field)	Field experiment, quantitative measurement	IoT / precision agriculture	Positive (92–95% efficiency)
2	Discover Agriculture (Springer), 2025	Micro (farm)	Review covering studies	IoT-based irrigation	Positive (up to 70% water, 30% yield)
3	ScienceDirect, 2025 (eggplant experiment)	Micro (field)	Field experiment, 18-month observation	Cloud computing and IoT irrigation	Positive (up to 90% water reduction)
4	PMC/NCBI (rice methane study)	Micro (field)	Field experiment with control groups	Drip irrigation	Positive (78% methane reduction)
5	arXiv, 2025	Micro (technical project)	Engineering modeling	IoT and irrigation	AI Positive, at practical implementation stage
6	Frontiers Environmental Science, (China) 2025	Macro (inter-provincial panel)	Econometric analysis (spatial spillover)	Digital agriculture (broad)	Positive, with regional variation
7	Frontiers Sustainable Systems, (China) 2025	Macro (inter-provincial panel)	Two-way fixed-effects model	Digital economy	Positive, but limited
8	Sustainability (MDPI), 2025 (China)	Macro (inter-provincial panel)	Panel threshold model	Digital economy	Positive, with noted 'rebound' risk
9	Market reports analysis	Macro (global market)	Descriptive/forecast analysis	Smart agriculture (broad)	Descriptive
10	Ministry of Water Resources of Uzbekistan data	Macro (national)	Official statistics	Water-saving technologies	Descriptive, practice-oriented
11	Gao & Sustainability, 2025 (100 countries)	Macro (global cross-country)	Panel econometrics + spatial model	Digital economy	Positive, varying by income level
12	Menéndez Lavopa, JEE, 2025	Micro (658 firms)	Bivariate model	probit Digital and green technology complementarity	Positive
13	Bianchini, & Ghisetti, 2023 (Europe)	Meso (regional)	Patent and emissions econometrics	Digital environmental patents	Mixed/critical
14	OECD Working Paper, 2025–2026	Meso/global	New patent-based indicators	'Twin transition' innovation	Methodological novelty
15	Subeesh Chauhan, ACM Proceedings, 2025	Micro (technology review)	Technical review	Digital twin	Positive, with noted barriers

Source: created by the author

This classification shows that most of the studies (1–5, 12, 15) were conducted at the micro level and are almost uniformly positive in their conclusions. Macro-level studies (6–8, 11) mainly apply econometric methods based on data from large countries or multi-country global panels. Only one study (item 13) reaches a genuinely critical/mixed conclusion, indicating a gap in the literature for objective, balanced assessments. Furthermore, the near-total absence of econometric studies establishing causal relationships specific to Uzbekistan and the Central Asian region represents a clear gap for future research.

4. Discussion

The results of the analysis conducted allow for the discussion of several important points.

First, the field experiments on IoT and precision agriculture cited in sources yield mutually corroborating results: resource-use efficiency of up to 92–95%, water-consumption reductions of 70–90%, and even positive climate effects - a 78% reduction in methane emissions - recurring across different geophysical conditions and crop types, indicating that the benefits of these technologies are systematic rather than incidental. At the same time, it should be noted that nearly all of these findings were obtained at the micro (field/farm) level — a caveat that means success at the local level does not automatically guarantee an equivalent effect at the national level.

Second, the macro-level studies conducted in China confirm a statistically significant relationship between digitalization and reduced carbon emissions, yet this finding appears to partly conflict with the conclusions of the European regional study cited in: the latter study shows that certain types of digital technology (especially big-data and server infrastructure) can increase emissions at the local level. Discussing these two divergent conclusions suggests that the environmental effect of digitalization is not universal - it depends on the type of technology (for example, the distinction between resource-saving technologies such as precision agriculture and irrigation sensors versus energy-intensive technologies such as data centers) as well as the context of implementation (energy source, regional characteristics). It follows that the simplified formula "digitalization equals environmental benefit" is not fully scientifically justified — a conclusion also supported by the "rebound effect" concept specifically discussed in Section 3.7.

Third, the global cross-country study of 100 countries shows that the positive relationship between the digital economy and economic–ecological integration varies by income level - this effect is stronger in high-income and upper-middle-income countries. Given that Uzbekistan belongs to the group of middle-income countries, this finding offers an important methodological lesson for the country as well: developing digital infrastructure alone does not guarantee environmental outcomes; commensurate innovation and institutional capacity are also required.

Fourth, the firm-level study of developing countries (Ghana, Thailand, Vietnam) shows that digital and green technologies possess a complementary nature at the enterprise level, yet the rate of joint adoption (only 10.3%) remains considerably lower than in developed countries. This finding is also relevant for agricultural enterprises in Uzbekistan, particularly export-oriented firms and those with foreign investment participation, and indicates that firm size and participation in global value chains are key factors encouraging the twin transition.

Fifth, digital twin technology, proposed as an innovative solution, holds high theoretical potential, but because its practical deployment requires substantial infrastructure, it may be financially difficult for small family farms — a category that constitutes a large share of Uzbekistan's agricultural sector — to adopt. For this reason, the proposal in the scientific literature of cheaper alternative approaches, such as "edge computing," carries practical significance.

Finally, the classification system of the studies shows that positive micro-level findings dominate the existing literature, while macro-level econometric studies are concentrated primarily on large countries (China) or multi-country global panels. In this context, the near-total absence of primary econometric studies establishing a causal relationship between digital and green transformation specific to Uzbekistan and the Central Asian region constitutes a significant scientific gap that defines the direction of both this article and future research.

5. Conclusion

Based on the analysis conducted, the following conclusions can be drawn:

Smart technologies (precision agriculture, IoT, artificial intelligence, drones, and smart irrigation systems) have been consistently confirmed in foreign empirical studies as a practical means of achieving efficient use of resources (water, land, energy) in agriculture - in particular, various studies report water-consumption reductions of up to 20–90% and resource-efficiency gains of up to 92–95%.

In summary, the integration of smart technologies and the green economy holds substantial potential for the sustainable development of agriculture; however, realizing this potential in full requires making conscious technological choices, taking local conditions into account, and expanding independent scientific-empirical research specific to Uzbekistan.

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