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IMPLEMENTATION OF DIGITAL TECHNOLOGIES AND "SMART AGRICULTURE" SYSTEMS IN VITICULTURE

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Abstract
This article examines the issues of digitalization of viticulture, the introduction of innovative "Smart Agriculture" systems and artificial intelligence technologies in the Republic of Uzbekistan. Within the framework of the Presidential decrees and resolutions adopted in recent years, the possibilities of using unmanned aerial vehicles (drones), sensors and IoT devices for monitoring land and water resources are analyzed. Strategies for increasing yields and creating disease forecasting models through the introduction of a single registry of vineyards are studied. As a result of the research, scientific and practical proposals for the implementation of digital technologies in viticulture clusters and farms have been developed.

Keywords: Viticulture, digitalization, smart agriculture, drone, sensor, IoT, artificial intelligence, registry, productivity.

Introduction

Today, under the conditions of global climate change, scarcity of water resources, and land degradation, increasing the efficiency of agricultural production has become directly dependent on the level of implementation of innovative and digital technologies. The viticulture and winemaking sector, which is considered one of the strategic branches of the economy of Uzbekistan, is also undergoing profound reforms and a process of digital transformation.

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Strategic tasks aimed at the digitalization of agriculture have been defined by Shavkat Mirziyoyev, the President of the Republic of Uzbekistan. In particular, Presidential Decree No. PF-130 dated August 12, 2025, "On Measures to Increase Efficiency through the Further Acceleration of the Introduction of Modern Technologies into the Agricultural Sector," as well as the tasks outlined during the February 2026 presentation on advancing science to a new stage, initiated a new era in the sector. As emphasized by the Head of State, the development of biotechnology, "smart" agriculture, space and drone technologies, and digital agriculture constitutes the main criterion for the sustainability of the agrarian sector.

The application of Smart Viticulture systems in grape cultivation not only enables the conservation of resources but also increases the production volume of high-quality, export-oriented products. This article analyzes the scientific and practical aspects of applying digital platforms, sensors, and unmanned aerial vehicles in viticulture plantations.

Literature Review

The concept of "smart agriculture" and the application of digital technologies in viticulture have been widely studied by both international and local scholars. Among Western researchers, Smith et al. (2021) developed models for determining leaf area index and assessing crop quality through remote sensing technologies within the framework of Precision Agriculture. Garcia-Mari (2023), in his research, demonstrated the economic efficiency of IoT (Internet of Things) sensors in monitoring vineyard microclimates and optimizing irrigation regimes. Among the scholars of the CIS countries, Ivanov and Petrov (2022) highlighted the role of digital registries and Geographic Information Systems (GIS) in the management of viticulture production clusters.

Local scholars such as A. Khusanov and R. Hakimov (2024) investigated the economic problems of digitalizing the agro-industrial complex; however, the issues related specifically to the integration of digital sensors and Artificial Intelligence (AI) models in viticulture have not yet been comprehensively and systematically studied. The decrees and analytical materials of the President of the Republic of Uzbekistan in the agrarian sector, as well as the scientific directions of the newly established Academy of Agricultural Sciences, serve as the theoretical and legal basis of this research.

Research Methodology

During the research process, systematic approaches, comparative analysis, statistical grouping, induction and deduction methods, as well as econometric modeling techniques were applied. Official data from the Ministry of Agriculture of the Republic of Uzbekistan, the Ministry of Digital Technologies, and viticulture and winemaking clusters for the years 2024–2026 were analyzed.

To evaluate the effectiveness of applying digital technologies in vineyards, sensor data and drone monitoring results obtained from experimental fields in the Tashkent Region and Samarkand Region were comparatively analyzed. Cost indicators and productivity levels before and after the introduction of digital technologies were compared using analytical and empirical methods.

Analysis and Main Findings

The structural components and economic essence of smart agriculture technologies differ from traditional farming primarily in the speed of data collection, processing, and decision-making. The foundation of the system is real-time monitoring. From an economic perspective, these technologies optimize the production function by ensuring maximum yield with given resources or minimizing costs for a predetermined output level.

Artificial Intelligence (AI) serves as the "brain" of smart agriculture. By analyzing satellite imagery, drone-generated data, and sensor indicators, AI predicts productivity, identifies pest risks, and develops irrigation schedules. With the help of AI, the process of developing new crop varieties in seed production is being reduced from years to months, significantly lowering research and development (R&D) costs.

IoT (Internet of Things) devices continuously measure soil moisture, temperature, salinity, and air humidity in the fields. These data are transmitted to cloud-based platforms, enabling farmers to manage agricultural processes remotely through smartphones without physically visiting the fields. The economic impact is reflected in the reduction of human error and the allocation of resources according to actual demand. For instance, precision irrigation systems have been proven to reduce water consumption by 25–30 percent.

Spectral images obtained through drones make it possible to calculate the Normalized Difference Vegetation Index (NDVI). This helps detect diseases or water deficiency in plants before visual symptoms become apparent.

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Experimental studies conducted in the Samarkand Region revealed that the use of drones reduced the time required for manual field inspections by 60 percent and increased the efficiency of chemical treatment processes by 15 percent.

The “Digital Uzbekistan – 2030” Strategy, approved by the decree of the President of the Republic of Uzbekistan, serves as the legal framework for the transformation of agriculture. Within the framework of this strategy, specific tasks have been established regarding the creation of digital infrastructure in agriculture, the introduction of artificial intelligence, and the improvement of personnel qualifications. Digital technologies reduce operational expenditures (OpEx) by an average of 22 percent. These savings are primarily generated through the following factors:

Water conservation: Smart sensors and automated irrigation reduce water consumption by 30–35 percent.

Fertilizers and chemicals: Precision spraying and zone-based fertilization decrease the use of agrochemicals by 15–30 percent.

Labor force optimization: Automated systems reduce labor costs and help address labor shortages.

Pilot projects conducted in the Fergana Valley demonstrated that sensor-based irrigation systems reduced water consumption by 35 percent while increasing crop productivity by 28 percent. Such results are critically important for regions where water scarcity continues to intensify.

Regional Case Studies: Samarkand, Fergana, and Khorezm

The experiences of different agro-regions of Uzbekistan are highly significant for evaluating the economic impact of digital transformation.

In the Samarkand Region, projects involving drone-based monitoring of plant conditions were implemented in farming enterprises. These technologies reduced the time spent on visual field inspections by 60 percent. Economic efficiency was achieved through the early detection of pest outbreaks and the application of pesticides only to affected areas rather than across entire fields, resulting in a 15 percent reduction in pesticide use. This not only saves financial resources but also improves the environmental cleanliness of products, thereby increasing export prices.

Within the framework of the ICARDA project in the Fergana Valley, soil moisture sensors and drip irrigation systems were tested in tomato and pepper cultivation

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areas. The results showed a 35 percent reduction in water consumption and a 28 percent increase in productivity. Under conditions of limited water resources, such indicators enable farmers to cultivate additional land areas or reduce water-related expenses.

The Khorezm Region, located in the lower reaches of the Amu Darya River, faces severe challenges in water distribution. Research findings indicate that farmers situated farther from the river-particularly those at the "end of irrigation canals"-experience significantly lower incomes due to water shortages. The efficiency of the irrigation network currently does not exceed 60 percent. Digital monitoring systems help prevent theft and wastage by controlling water usage in real time, thereby ensuring social equity and economic stability.

Despite the evident economic benefits of digitalization, several systemic challenges hinder its widespread implementation:

High initial costs: For small and medium-sized farms, the costs of sensors, drones, and software remain excessively high. The experience of Telangana (India) demonstrates that 72 percent of farmers, who are small landowners, perceive these technologies as suitable only for large-scale farms.

Low digital literacy: Although many farmers use smartphones for social networking, they often lack the skills required to analyze agrotechnical data and operate sensor systems.

Infrastructure limitations: Poor internet connectivity in remote rural areas prevents the uninterrupted functioning of IoT systems. Furthermore, unstable electricity supply restricts the operation of automated pumping systems.

Psychological resistance and risks: Many farmers remain skeptical about the reliability of new technologies. Concerns related to cybersecurity and data privacy also serve as barriers.

Digital transformation in agriculture is not merely a trend but rather the only effective response to the economic and environmental challenges of the 21st century. The implementation of smart agriculture technologies enables agricultural production to reach a qualitatively new stage of efficiency.

The research findings indicate that digital solutions can increase productivity by 20–35 percent, reduce water consumption by more than 30 percent, and decrease operational costs by over 22 percent. Under the conditions of Uzbekistan, water-

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saving technologies and AI-based monitoring systems demonstrate the highest economic multiplier effect.

However, accelerating this process requires more than technology alone. The following strategic measures are necessary:

Expanding targeted state subsidies and preferential leasing programs for small farms to purchase digital technologies;

Improving 5G and high-speed internet infrastructure in rural areas;

Training "Agro-IT" specialists and organizing free educational courses for farmers;

Developing agro-technical platforms and mobile applications adapted to local conditions and the Uzbek language.

Digital transformation converts agriculture from a resource-consuming sector into a high-tech business model focused on efficient resource management. This process not only increases farmers' incomes but also strengthens the country's export potential and preserves natural resources for future generations.

The integration of agriculture with technologies such as IoT, big data, system integration, cloud computing, autonomous robotic systems, artificial intelligence, and wireless sensor networks has enabled the transition toward next-generation agriculture, namely Agriculture 4.0.[5] Smart agriculture, also referred to as smart farming or digital farming, represents a system that offers various solutions aimed at improving farm productivity, environmental sustainability, food security, and crop efficiency while addressing existing production-related challenges.

The use of smart agriculture includes processes such as data collection, diagnostics, decision-making, and action implementation. During data collection, sensors installed at critical points of the farm gather information related to soil, weather, and other environmental conditions and transmit these data to the system. The collected data are analyzed to evaluate the condition of the monitored processes and identify problems. The decision-making stage is then carried out through software platforms based on the previously identified issues.

Smart agriculture relies on technologies such as IoT, sensors, positioning systems, robots, and artificial intelligence, with the ultimate goal of optimizing human labor while increasing both the quality and quantity of crop yields. The technologies applied in smart agriculture include software platforms, GPS and satellite-based positioning systems, LoRaWAN and mobile communication

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systems, robots, sensors for monitoring soil, water, light, humidity, and temperature, as well as analytical and optimization platforms (Figure 1).

Through automated smart agriculture technologies, continuous 24/7 monitoring, accurate data collection, and observation significantly reduce the use of key resources such as water, fertilizers, and time. Studies indicate that smart agriculture can reduce water consumption by up to 85 percent, lower energy usage by up to 50 percent, increase productivity by up to 40 percent, and decrease losses caused by human error by as much as 60 percent.[6]

Figure 1. The Concept of "Smart Agriculture".

In remote areas experiencing severe water scarcity, irrigation largely depends on groundwater resources. Depending on the water level inside wells, pumps must be switched on and off accordingly. Pumps powered by diesel engines are generally water-cooled; therefore, low water levels may also cause damage to the pumping system. Consequently, alongside irrigation planning, proper monitoring of groundwater levels in wells should also be considered.

In regions facing both water shortages and energy deficiencies, IoT-based solar-powered systems can be developed for smart irrigation. In such systems, batteries can be charged using solar energy when exposed to sunlight, ensuring uninterrupted irrigation management while reducing dependence on conventional energy sources. Figure 2 illustrates the global market value of smart agriculture in 2021 and presents forecasts for the period from 2022 to 2027. According to the projections, the global smart agriculture market is expected to grow from approximately USD 15 billion in 2022 to nearly USD 33 billion by 2027.

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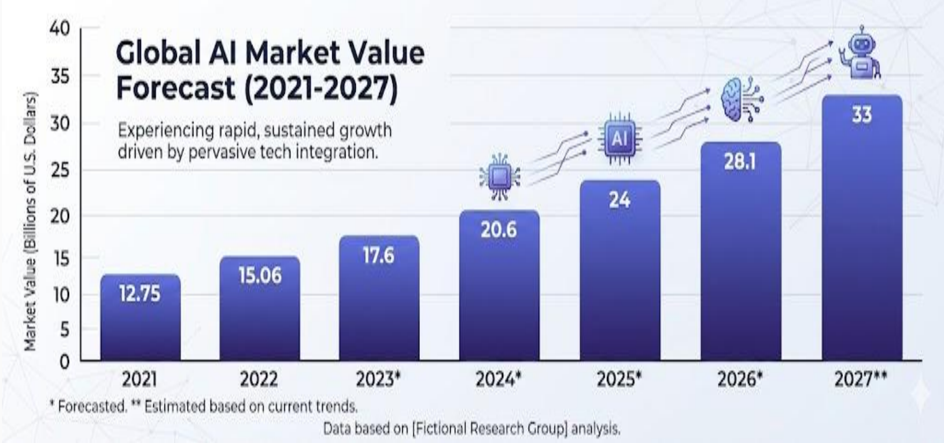

Figure 2. Forecast of the Global Smart Agriculture Market Value from 2021 to 2027, in Billion U.S. Dollars.

Financing agricultural technologies is crucial for addressing numerous challenges faced by farmers, including pests, diseases, and adverse weather conditions. Agritech also enables the cultivation of crops under non-traditional climatic conditions that are generally unsuitable for conventional agriculture.

Between 2017 and 2021, global investment in agricultural technologies exceeded USD 53 billion. In 2022, however, funding declined to approximately USD 30 billion. Among European countries, the United Kingdom ranked as the leading investor in agri-food technologies, followed by France and Germany.

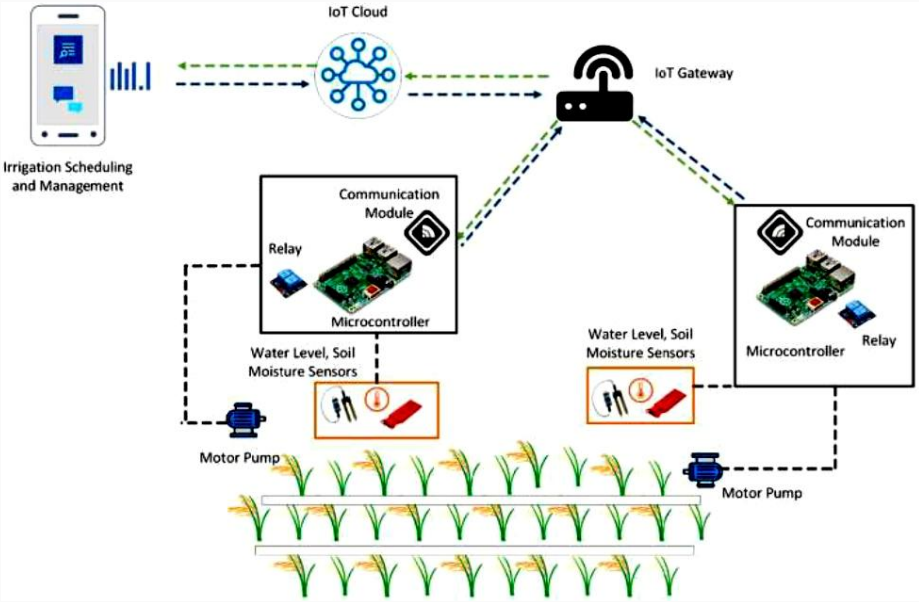

Figure 3. IoT-Based Automated Irrigation System.

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As in other irrigation systems, these systems are also equipped with sensors for measuring soil moisture, humidity, and temperature. In addition, water flow can be monitored through flow-rate sensors. Such systems are designed with a focus on energy-saving criteria. Control algorithms operating with turbid water further enhance the efficiency of irrigation methods (Figure 3). By using different combinations of input values, conditions can be created for the operation of water pumps under appropriate circumstances. Remote monitoring through mobile or web applications enables access to these systems from any location.[7]

Each country in the world has its own experience in the digitalization of agriculture. Although agriculture accounts for only about 1 percent of GDP in Japan, the country is considered one of the leading agricultural innovators. Approximately 3 percent of the labor force is employed in agriculture; however, the majority of farmers are elderly people. Japan has actively integrated advanced technologies into agriculture with the aim of improving productivity, sustainability, and production efficiency. Technologies and methods currently used in Japanese agriculture include precision farming, robotics and automation, smart greenhouses, vertical farming, and AgriTech startups. Robotics plays a major role in Japanese agriculture, particularly in planting, harvesting, and sorting processes. Smart greenhouse technologies regulate variables such as temperature, lighting, and humidity, thereby increasing productivity while conserving resources.

Since only about 12 percent of available land in Japan is used for agriculture, vertical farming methods are widely applied. This method supports controlled crop cultivation in indoor environments using hydroponic systems and LED lighting technologies. Furthermore, the government provides subsidies for agricultural technologies and supports innovative ideas specifically developed for the agricultural sector. Significant state-level attention is currently being devoted to the development of viticulture in Uzbekistan. As noted during meetings chaired by Shavkat Mirziyoyev, 155 thousand hectares of orchards and vineyards have been established across the country over the past three years. By the end of 2025 alone, approximately 2 million tons of grapes were produced, and the share of grape products within food exports increased substantially.

However, under traditional grape cultivation methods, water losses account for 30–40 percent, while the late detection of diseases and pests can result in up to 25 percent crop loss. To address these challenges, the government assigned the

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Ministry of Digital Technologies and the Ministry of Agriculture the task of implementing the "Unified Vineyard Registry Information System."

The establishment of digital viticulture includes the following key stages and smart systems:

Smart Irrigation: IoT sensors are installed to measure soil moisture around grape root systems. These sensors transmit data to a central computer, and water is automatically supplied through drip irrigation systems according to the actual needs of plants. This approach saves up to 40 percent of water resources.

Drone-Based Monitoring: Modern unmanned aerial vehicles equipped with multispectral cameras fly over vineyards and calculate the Normalized Difference Vegetation Index (NDVI). This enables the detection of nutrient deficiencies or the early onset of diseases in grape plantations without human intervention.

Artificial Intelligence-Based Forecasting: In 2026, the government planned to introduce AI technologies into more than 50 public and agricultural services. AI systems analyze weather data and sensor signals to predict the risks of oidium (powdery mildew) and mildew diseases, which commonly occur during spring, 7–10 days in advance. The obtained economic results demonstrate that, in experimental fields where digital technologies and smart agriculture systems were introduced, mineral fertilizer costs decreased by 25 percent, fuel and lubricant expenses by 15 percent, while productivity increased on average by 35–42 percent.

At present, practical monitoring activities are being carried out to ensure the timely and high-quality preparation of 3,389 grain harvest combines planned to participate in the harvesting season on 1 million 38 thousand hectares of grain fields this year. These activities clearly indicate that such operations require implementation in accordance with established standards and responsibilities. Unfortunately, violations are also being observed. For example, during January–March 2026, inspections conducted by sector inspectors identified 3,617 cases of legal violations out of 6,464 inspection activities. Among them, more than 10 cases were related to the quality of repair and service activities, 3,427 cases concerned the technical condition of agricultural, melioration, and road-construction machinery, while 179 violations were associated with other sectors. Most violations were committed by individuals. Additionally, administrative measures were applied in 3,150 cases, 69 official submissions were issued, 379

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written instructions were provided, and documents related to 76 cases were forwarded to law-enforcement authorities for legal action. These processes are also being incorporated into electronic databases.

In conclusion, the broad application of information technologies in inspection activities-including electronic information exchange with relevant organizations, digital documentation, and the use of digital technologies in agriculture—serves to save time and financial resources for citizens and legal entities while significantly increasing employee efficiency.

Conclusion and Recommendations

The widespread introduction of smart agriculture systems into the viticulture sector of Uzbekistan is the only effective way to sharply increase the international competitiveness of the industry. Based on the conducted research and analysis of the latest reforms being implemented in the country, the following practical recommendations are proposed:

First, establishing a “Digital Viticulture and Smart Technologies” scientific-practical laboratory under the newly established Academy of Agricultural Sciences. Within this laboratory, special digital monitoring models should be developed for national grape varieties such as Husayni, Rizamat, and Kishmish.

Second, strengthening subsidy mechanisms or customs duty exemptions for imported IoT sensors, multispectral drones, and smart drip irrigation equipment intended for viticulture clusters, based on the mechanisms outlined in Presidential Decree PF-130. Third, increasing educational hours by at least 30 percent in the fields of “Agro-Informatics and Smart Farming” at Tashkent State Agrarian University and specialized technical colleges, while organizing practical training directly within digitized agricultural clusters in order to train specialists with digital competencies for the agrarian sector. The implementation of these measures will facilitate the adaptation of the national viticulture sector to the requirements of the digital economy and significantly strengthen the country’s export potential.

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