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Smart Agriculture Technologies for Nitrogen Use Efficiency and Soil Salinity Monitoring

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Abstract: The agricultural sector must develop sustainable solutions to address global challenges such as population growth, climate change, and the scarcity of natural resources. In this context, digital farming technologies play a crucial role in critical areas such as nitrogen use efficiency and soil salinity monitoring and management. This study examines the potential of smart farming applications in these areas and investigates how technologies such as the Internet of Things (IoT), wireless sensor networks (WSN), remote sensing (RS), unmanned aerial vehicles (UAVs), big data analytics, machine learning (ML), deep learning (DL), and artificial intelligence (AI) can enhance agricultural productivity and sustainability. Although nitrogen is an essential nutrient for plant growth, its excessive and improper use leads to environmental pollution and resource waste. Digital farming technologies can monitor nitrogen levels in the soil in real-time, detect plant stress, and provide optimized fertilization strategies to improve nitrogen use efficiency. Similarly, soil salinity is a significant constraint on agricultural production. Technologies such as remote sensing and wireless sensor networks offer effective tools for mapping and monitoring soil salinity, contributing to the development of salinity management and remediation strategies. In conclusion, digital farming technologies have the potential to shape the future of agriculture in areas such as nitrogen use efficiency and soil salinity management, paving the way for the widespread adoption of sustainable farming practices. The adoption of these technologies can optimize resource use, reduce environmental impacts, and enhance agricultural productivity and food security.

1. Introduction

The agricultural sector has become increasingly critical, particularly in terms of productivity and sustainability, following the third and fourth industrial revolutions. This shift is directly linked to ensuring food security and meeting the demands of global population growth. While population growth has led to a significant rise in food demand, it has also increased agricultural input costs. Climate change and environmental pressures are causing water resource depletion and a decline in biodiversity. In this context, complex challenges such as nutritional issues, food security risks, and the need to restore degraded arable land have emerged. Agriculture and food production, being water-intensive sectors, exert significant pressure on water resources. Moreover, the indiscriminate use of plant nutrients, chemical pesticides, and similar agricultural inputs exacerbates water pollution, disrupting environmental balances. In particular, the increasing pollution of groundwater with nitrates, nitrogen, and phosphorus negatively impacts soil health and productivity, making the adoption of sustainable agricultural practices imperative. In this regard, the widespread implementation of technologies that optimize input use and minimize environmental impacts is crucial for enhancing productivity and conserving natural resources (Kılıç, 2020; Çakmakçı, 2019).

Future agricultural strategies focus on adapting to climate change, improving resource use efficiency, and promoting the adoption of digital technologies. Precision agriculture (PA) and artificial intelligence (AI) applications encourage the development and implementation of innovative approaches in soil management, fertilization, and crop protection (MacPherson et al., 2022). Additionally, considering the adverse effects of pesticide use and excessive nutrient accumulation on biodiversity and ecosystems, the European Union (EU) aims to reduce pesticide use by 50% and decrease fertilizer-derived nutrients by 20% under the EU Nitrate Directive by 2030. These goals are supported by low-input farming practices and the adoption of precision agriculture technologies (EC, 2020).

The European Union (EU), by embracing a bio-based economy model, aims to enhance the sustainability of agricultural and food systems. In this context, the "Farm to Fork" (F2F) strategy seeks to strengthen the resilience of food systems against climate change and promote the more efficient use of agricultural inputs. The EU emphasizes the importance of adopting digital technologies to achieve these goals and recommends the development of innovative solutions such as biofertilizers, bioenergy, and biochemicals (EC, 2020).

Sustainable agriculture stands out as an approach that aims to optimize the use of natural resources and minimize environmental impacts (Finger et al., 2019). In this regard, digital technologies contribute significantly to ensuring food security by improving traceability and quality standards in agricultural production processes (Klerkx et al., 2009). Furthermore, innovative practices such as carbon footprint reduction methods and precision fertilization systems play a crucial role in mitigating the environmental impacts of agricultural activities (Basso & Antle, 2020).

In the field of soil and water management, digital technologies help enhance agricultural productivity by enabling more efficient resource use. The implementation of these technologies has not only increased productivity in production processes but also facilitated the achievement of environmental and economic benefits. Digital agriculture and smart-precision farming applications have become strategic tools for achieving productivity and sustainability goals in agricultural production. These technologies not only address the growing global food demand but also shape the future of the agricultural sector by minimizing environmental impacts.

This study examines the effects of digital technologies on sustainable agriculture and analyzes their role and potential in agricultural production. Digital farming applications are critically important for both increasing production efficiency and ensuring environmental sustainability.

2. Smart Agriculture Technologies

The migration from rural to urban areas in Turkey and structural changes in the agricultural sector are increasingly making it difficult to meet the country's food needs. The decline in the rural population exacerbates the shortage of human resources in agricultural production, while also leading to social and economic problems in urban areas. As a result, governments have begun to prioritize addressing the challenges faced by young farmers remaining in rural areas and supporting rural development (Berk & Armağan, 2019). However, the predominance of small family-owned farms and fragmented land structures in Turkey hinders the efficient use of resources and the widespread adoption of technological innovations (Başer & Bozoğlu, 2019).

Smart agriculture is an approach that involves the integration of information and communication technologies (e.g., the Internet of Things, data transformation, and signaling tools) into agricultural production processes. These applications aim to enable agricultural activities to adapt to spatial and temporal variations, ensuring more efficient and accurate use of inputs (Gürsoy & Çolak, 2023). Within the scope of smart agriculture, practices such as yield mapping, land classification, precision irrigation, and fertilization stand out. Technologies such as autonomous vehicles, robotic systems, satellites and aerial vehicles, cloud computing systems, the Internet of Things, big data analytics, and machine vision systems are widely used.

Globally, challenges such as urbanization, population growth, a shortage of skilled labor, competitive pressures, and risks associated with unhealthy food have made the adoption of digital technologies in agriculture essential. These technologies offer effective solutions in areas such as cost and waste reduction, productivity improvement, and enhanced product quality. Additionally, AI-based systems contribute significantly to the future of agricultural production by increasing the efficiency and sustainability of farming practices (Dertli & Dertli, 2023).

Precision agriculture technologies have become a cornerstone of modern farming, offering significant advantages at every stage of agricultural production processes. These technologies enhance agricultural productivity, enabling the production of healthier and higher-quality crops. They also minimize product losses by ensuring timely and accurate execution of agricultural activities, contributing to better time management. From an economic perspective, precision agriculture technologies have the potential to increase farmers' incomes through more efficient resource use. By reducing input costs and improving crop productivity, these technologies enhance farmers' profitability. In terms of sustainability and environmental protection, precision agriculture practices promote eco-friendly production methods and minimize environmental impacts by reducing the use of chemical inputs (Kaplan et al., 2024).

Figure 1. Smart Agriculture Technologies

3. Nitrogen Use in Agriculture

Determining the nitrogen (N) requirements of plants is of great importance due to the critical role nitrogen plays in plant growth, yield, and defense mechanisms. Nitrogen is an essential macronutrient required by plants in large quantities and is often a limiting factor in soils (Delgado & Follett, 2011). Therefore, effective nitrogen management is vital for both economic productivity and environmental sustainability (Jat et al., 2012). Optimizing nitrogen use not only enhances agricultural productivity but also contributes to reducing environmental harm (Midolo et al., 2018; Chen et al., 2020). This is particularly critical in the context of sustainable agriculture goals (Zhang et al., 2023).

Recent research has provided a more comprehensive understanding of the effects of nitrogen on plant nutrition and growth. Nitrogen not only supports plant growth but also influences plants' resistance to diseases. Nitrogen supply plays a significant role in regulating plant defense mechanisms, and its effects vary depending on the form and concentration of nitrogen (Sun et al., 2020). For example, NH4-N (ammonium) nutrition increases anion uptake, free protein ratios, and acidity in the root zone, while

NO3-N (nitrate) nutrition promotes cation uptake, tissue carbohydrate content, and alkalization of the root zone. These processes directly affect plants' growth rates and dry matter accumulation (Fernandes & Rossiello, 1995).

The effects of nitrogen on plants occur through physiological, biochemical, and genetic mechanisms, significantly influencing parameters such as growth rate, protein content, and seed quality. However, excessive nitrogen use can lead to environmentally harmful consequences, necessitating careful management. Current research delves deeper into the complex interactions of nitrogen in plant nutrition and growth, contributing to the development of more effective strategies in agricultural practices.

4. Enhancing Nitrogen Use Efficiency with Smart Agriculture Technologies

Variable-rate nutrient application is a method that enables the precise determination and application of nutrients required by plants in agricultural fields. This system optimizes nutrient application rates based on the specific needs of plants, taking into account field heterogeneity, thereby improving resource use efficiency. Providing the correct amounts of essential macronutrients such as nitrogen (N), potassium (K), and phosphorus (P) plays a decisive role in plant quality, productivity, and growth. Variable-rate fertilization, particularly through the optimization of nitrogen use, also contributes to reducing environmental impacts (Kaplan et al., 2024). This method reduces greenhouse gas emissions by minimizing fertilizer use. GPS-based variable-rate nitrogen applications have been found to reduce N2O emissions by up to 34% (Sehy et al., 2003). In wheat production, this method has been reported to increase yields by 1% to 10% while saving 4% to 37% on nitrogen fertilizer use (Tekin, 2010). A study conducted in Colorado showed that variable-rate nitrogen fertilization was 6% to 46% more efficient than traditional methods and resulted in resource savings (Koch et al., 2004).

In regions where precision agriculture technologies are widely adopted, there is strong evidence of a 20% to 40% reduction in water and fertilizer use. In some cases, these practices have also contributed to yield increases (McBratney et al., 2005; Pedersen et al., 2004; Roland, 2016). These findings highlight the significant role of variable-rate nutrient applications in both enhancing agricultural productivity and supporting environmental sustainability.

5. Soil Salinity

Salts are natural components of soil ecosystems; however, an increase in their concentration in the soil profile due to environmental factors leads to significant changes in the physicochemical and biological properties of the soil (Dagar et al., 2019). Soil salinity is particularly prevalent in arid and semi-arid regions where irrigation or rainfall is insufficient to leach salts from the soil profile, drainage conditions are poor, or shallow groundwater is present. Currently, soil salinity affects more than 8.3 million square kilometers of land globally, posing a serious threat to agricultural productivity (Corwin & Scudiero, 2019).

The salinization process is characterized by the accumulation of salts in the surface or near-surface layers due to insufficient rainfall and high evaporation rates. This increases salt concentration in the root zone, negatively affecting plants' ability to absorb water and nutrients. Salt accumulation in the soil results from natural processes (rock weathering, wind erosion, seawater intrusion) and anthropogenic activities (excessive fertilizer use, improper irrigation practices, and the use of industrial saline water for irrigation) (Tanji, 2002). Saline soils are classified based on parameters such as exchangeable sodium percentage (ESP), electrical conductivity (EC), and pH. These parameters are used to determine the degree of salinity and the effects of sodium accumulation, playing a critical role in developing agricultural management strategies. Soil salinity not only reduces agricultural productivity but also has adverse effects on ecosystem health and biodiversity. Therefore, effective management of salinity is crucial for sustainable agriculture and environmental conservation.

The impacts of soil salinity are not limited to negative effects on plant growth and agricultural productivity. Salinity significantly affects nutrient cycles in the soil, particularly biochemical processes involved in the nitrogen (N) cycle. The nitrogen cycle plays a critical role in maintaining soil fertility, ecosystem health, and controlling greenhouse gas emissions.

Soil salinity inhibits the metabolic activities of microorganisms responsible for converting nitrogen into plant-available forms, reducing soil biological activity. This disrupts soil fertility functions and leads to significant inefficiencies in the delivery of ecosystem services (Pan et al., 2016). Specifically, salinity disrupts fundamental microbial processes such as nitrogen fixation, nitrification, and denitrification, limiting the effective use of nitrogen resources in the soil and negatively affecting ecosystem balance. The disruption of these processes not only impacts agricultural productivity but also influences global environmental processes such as the soil carbon cycle and greenhouse gas emissions. Therefore, the effects of soil salinity on the nitrogen cycle are of great importance for sustainable agricultural practices and ecosystem management. In this context, preventing salinity-induced degradation and preserving soil health are critical requirements for both increasing agricultural productivity and ensuring environmental sustainability.

6. Monitoring and Managing Soil Salinity Using Smart Agriculture Technologies

Soil salinization is a global issue, particularly prevalent in arid and semi-arid regions, and poses a serious threat to agricultural productivity. It is estimated that by 2050, approximately 50% of global agricultural land will be affected by salinity (Abdelaziz et al., 2019). This situation represents a significant threat to food security, ecological balance, and sustainable agriculture (Zhang et al., 2020).

Satellite-based remote sensing methods are widely used for monitoring and managing soil salinity due to their ability to cover large areas and their efficiency advantages (He et al., 2023). Optical and radar satellites provide rich data sources, such as spectral information and texture features, which effectively reflect soil properties (Mohamed et al., 2023). Texture features, which represent the spatial structure of object surfaces, are more stable compared to spectral information (Zhang et al., 2020).

Studies using Sentinel-1/2 data have shown that integrating texture features and spectral information improves the accuracy of soil salinity prediction (Taghadosi et al., 2019). However, selecting the appropriate window size for extracting texture features is critical. Windows that are too small or too large can negatively affect model accuracy (Chen et al., 2004).

In a study conducted in the Shahaoqu Irrigation Area, soil salinity distribution maps were created using Sentinel-1/2 data and measured soil salinity data, employing machine learning models such as Random Forest (RF) and Support Vector Machines (SVM) (Taghadosi et al., 2019). These models serve as important tools for understanding the spatiotemporal variations in soil salinity and developing effective management strategies.

Figure 2. Nitrogen use efficiency and soil salinity monitoring with smart agriculture Technologies

7. Challenges in the Adoption of Smart Agriculture Technologies and Factors Influencing Success

The main obstacles facing Precision Agriculture (PA) include user perceptions, lack of technical knowledge, data quality and cost, infrastructure deficiencies, privacy and security concerns, profitability issues, and agricultural challenges. Farmers' lack of knowledge about technological innovations, integration problems among different technologies, and short-term profitability-focused approaches slow down the adoption of PA. Additionally, factors such as high machinery and equipment costs, the presence of small agricultural lands, connectivity issues in rural areas, and equipment incompatibilities limit the economic feasibility of PA. Precision Agriculture (PA) technologies are recognized as an industry with the potential to enhance agricultural productivity, reduce environmental impacts, ensure food security, and contribute to sustainable production processes. However, the widespread adoption of these technologies remains limited due to high initial investment costs, the need for technical expertise, and various implementation challenges (Masi et al., 2022). Particularly, deficiencies in scalability, accessibility, and usability hinder the full adoption of PA (Megeto et al., 2020).

The integration of Internet of Things (IoT) technologies into PA also faces challenges such as high initial costs, resilience issues under adverse climate conditions, battery life limitations, and security vulnerabilities (Qazi et al., 2022). Moreover, the widespread adoption of Artificial Intelligence (AI) technologies in the agricultural sector brings socio-economic risks, including unemployment, data security, economic inequalities, and the spread of monoculture (Sparrow et al., 2021). AI-based technologies like Deep Learning (DL) play a significant role in the development of PA but face technical challenges such as overfitting, long training times, and gradient problems. To overcome these issues, techniques like data augmentation, batch normalization, and transfer learning are recommended (Saranya et al., 2023). However, the high costs of data collection and storage in the agricultural sector make the development of DL models challenging (Megeto et al., 2020).

To enhance the scalability of PA, solutions such as wireless communication, low-energy devices, interoperability, and security measures are proposed (Saranya et al., 2023). Additionally, the integration of new technologies into the agricultural industry requires addressing equipment cost reduction, data management, cybersecurity, and interdisciplinary collaboration (Javaid et al., 2022).

Despite their potential to increase agricultural productivity, reduce environmental impacts, and ensure sustainable production, Precision Agriculture (PA) technologies are not widely adopted due to high costs, technical deficiencies, and implementation challenges. Issues such as scalability, accessibility, and lack of user knowledge hinder the adoption of PA. Technologies like Deep Learning (DL) and the Internet of Things (IoT) face technical difficulties and high data costs. Moreover, the widespread adoption of AI technologies carries socio-economic risks such as unemployment and data security. Solutions like wireless communication, low-energy devices, and interdisciplinary collaboration are suggested to enhance the scalability of PA. The success of these technologies depends on government support, educational programs, and the development of low-cost solutions.

8. Conclusion

The agricultural sector faces complex challenges such as global population growth, climate change, and the limited availability of natural resources. In this context, smart agriculture technologies stand out with their potential to increase agricultural productivity, reduce environmental impacts, and contribute to sustainable production processes. Precision agriculture practices, particularly in areas like nitrogen use efficiency and soil salinity monitoring, enable more effective use of resources, offering both economic and ecological benefits. However, the widespread adoption of these technologies is limited by high costs, lack of technical knowledge, and infrastructure deficiencies. Innovative approaches such as satellite-based remote sensing and machine learning in critical areas like soil salinity and nitrogen management enhance agricultural productivity while supporting environmental sustainability. Practices like variable rate fertilization and precision irrigation optimize input use, reducing costs and greenhouse gas emissions. Nevertheless, the successful adoption of these technologies requires farmer education, government support, and the development of low-cost solutions. In conclusion, smart agriculture technologies play a key role in shaping the future of the agricultural sector. The effective implementation of these technologies will be a significant step towards ensuring food security, conserving natural resources, and combating climate change. However, overcoming the encountered challenges and widespread adoption of these technologies will be possible through interdisciplinary collaboration and comprehensive policy support.

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