

Smart Agriculture: Integrating IoT, AI, and Data Analytics for Sustainable Crop Management

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Abstract—Smart agriculture is transforming conventional agricultural methods toward sustainable crop management. It is driven by developments in the Internet of Things (IoT), artificial intelligence (AI), and data analytics. An overview of the main technologies enabling smart agriculture is given in this paper, along with examples of how they are being used to optimize certain crop farming characteristics. We go over how real-time monitoring of environmental factors like temperature, moisture content in the soil, and nutrient levels is made possible by IoT sensors, which makes precision fertilization and irrigation possible. In order to deliver useful insights for crop disease diagnosis, pest management, and yield prediction, artificial intelligence (AI) algorithms evaluate the massive volume of data gathered from these sensors. Furthermore, by combining historical data, weather forecasts, and market trends, data analytics tools enable farmers to make well-informed judgments. We look at implementation issues and case studies related to the global uptake of smart agriculture technologies. To ensure future food security, we conclude by highlighting the potential advantages of smart agriculture in terms of improving production, maximizing resource efficiency, and encouraging sustainable agricultural methods.

Index Terms—agriculture, environmental, efficiency, forecasts, smart

I. INTRODUCTION

Smart agriculture, sometimes referred to as digital farming or precision agriculture, is a revolutionary method of bringing cutting-edge technologies into agricultural processes to modernize them. The pressing need to address the issues facing the agriculture industry, such as population increase, climate change, resource scarcity, and worries about food security, is what is driving this paradigm shift. Conventional agricultural practices frequently depend on broad approaches to crop management, which results in wasteful use of resources and harm to the environment. Smart agriculture, on the other hand, makes use of cutting-edge technology like data analytics, artificial intelligence (AI), and the Internet of Things (IoT) to optimize agricultural processes and facilitate data-driven decision-making. The implementation of Internet of Things (IoT) devices and sensors throughout agricultural landscapes is the basis of smart agriculture, forming networked systems that continuously monitor a range of environmental

parameters. By gathering information on soil moisture, temperature, humidity, nutrient levels, and crop health, these sensors give farmers previously unheard-of insights into the factors influencing their crops. Farmers can apply precision fertilization and

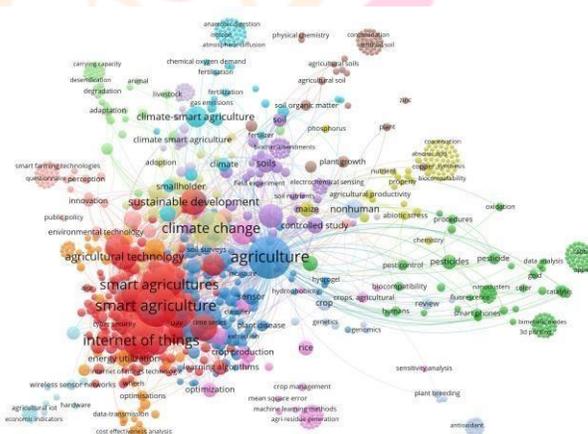


Fig. 1. Some aspects of smart agriculture

irrigation techniques by utilizing this abundance of data, adjusting resource application to the unique requirements of each crop and reducing waste. This focused strategy improves agricultural yields and quality while also conserving water and nutrients. Artificial Intelligence (AI) is a major facilitator of smart agriculture because it uses machine learning algorithms to evaluate large datasets and derive relevant insights. Early diagnosis of crop illnesses, pest infestations, and environmental stressors is made possible by AI systems' ability to identify patterns, anomalies, and correlations in agricultural data.

Farmers may prevent losses and increase overall output by proactively addressing possible dangers to their crops by utilizing AI-driven analytics. Predictive models driven by AI are also capable of predicting market demand, crop yields, and the best times to plant, giving farmers the information they need to make profitable decisions. By compiling, analyzing, and interpreting information from various agricultural data sources,

data analytics plays a critical part in smart agriculture. Through the integration of weather forecasts, market trends, agronomic knowledge, and historical data, data analytics platforms offer farmers decision support tools and actionable insights. Through the efficient management of crop rotations, planting dates, and resource allocation made possible by these platforms, farmers are able to increase farm sustainability and profitability. Additionally, data analytics improves food safety and quality assurance by facilitating traceability and transparency in the agricultural supply chain. Globally, the use of smart agriculture solutions is accelerating due to the rising demand for sustainable food production and increased awareness of the advantages of digital technologies in agriculture. Governments, academic institutions, and businesses are making significant investments in R and D projects to hasten the adoption of smart agriculture technologies. However, there are a number of obstacles that must be overcome before smart agriculture can be widely used. These include high upfront costs, restricted access to technology in rural regions, and worries about the security and privacy of data. Our goal in this study is to investigate the idea of smart agriculture in detail, looking at the applications, technology, advantages, and difficulties involved in putting it into practice. We will examine case studies and actual instances of smart agriculture initiatives from across the world, emphasizing effective tactics and takeaways. We will also talk about how smart agriculture might help with issues related to global food security and the advancement of sustainable farming methods. This study aims to give a thorough review of smart agriculture and how it will influence farming in the future.

II. LITERATURE REVIEW

Traditional farming methods have been completely transformed by the application of IoT devices and sensors in agriculture. Precision agricultural techniques are made possible by sensors installed in fields and on farm equipment that collect data in real-time on soil moisture, temperature, humidity, and crop health. IoT technology have improved crop yields, reduced environmental impact, and improved resource management, according to Liakos et al. (2018) [1]. Artificial intelligence (AI) algorithms, in particular machine learning methods, have become effective instruments for evaluating agricultural data and reaching wise conclusions. Early disease and pest identification is made possible by deep learning algorithms' ability to recognize patterns and abnormalities in agricultural photos. Mohanty et al. (2016) used image analysis techniques in their study to show how well AI-based methods detect plant illnesses [2]. Platforms for data analytics combine and examine information from many agricultural data sources to give farmers useful insights. To improve farm management techniques, these systems use historical data, weather predictions, soil data, and market trends. Qin et al. (2020) assert that the application of data analytics approaches can augment agricultural decision-making and boost farm output [3]. Several case studies demonstrate how smart agriculture technology have been successfully implemented in various parts of the world. To increase productivity and resource efficiency, Patel et al. (2019) developed the "RFID-based smart agriculture system" in India,

which makes use of IoT and RFID technology for crop monitoring and management [4]. Notwithstanding its advantages, smart agricultural implementation is hindered by issues like high upfront expenditures, intricate technology, and spotty connectivity in rural areas. Further impediments to wider adoption are worries about data security and privacy. According to Gasco et al. (2018), cooperation between interested parties and helpful policy frameworks are necessary to

Estimated market size for smart agriculture worldwide by 2025

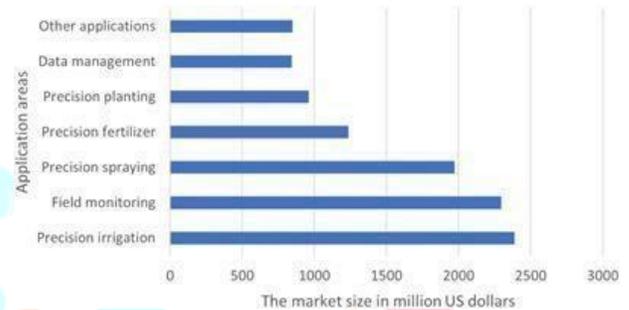


Fig. 2. Estimated market size of smart agriculture

overcome these issues [5]. Smart agriculture has the potential to greatly improve global food security by enhancing agricultural productivity and adaptability to climate change. Smart agriculture promotes sustainable farming practices such as precision irrigation and integrated pest management, which help to save the environment and manage resources responsibly. According to FAO (2019), digital technologies are critical to achieving sustainable agricultural development and maintaining food security for future generations [6]. Adoption of smart agriculture has socioeconomic effects, especially in rural areas. Through the creation and upkeep of digital infrastructure and the offering of specialized services associated with the implementation and upkeep of technology, it may result in more job opportunities. Furthermore, by giving smallholder farmers digital platform access to financial services, market data, and extension assistance, smart agriculture may empower them. Digital technologies have the ability to improve livelihoods and reduce poverty in rural areas, according to a report by Qaim (2017) [7]. Efficient farming techniques lessen the adverse effects of farming operations on natural resources, hence promoting environmental sustainability. Reduced pesticide use, soil erosion, and water pollution are achieved by precision agriculture practices including conservation tillage and variable rate input application. Reducing greenhouse gas emissions and improving carbon sequestration in agricultural soils are other benefits of optimizing resource utilization through data-driven decision making. Using smart agriculture techniques has several advantages for the environment, as a review by Pretty et al. (2018) shows [8].

Regulations and policies that encourage innovation, investment, and knowledge transfer are necessary for the effective use and expansion of smart agriculture technologies.

Governments are essential in encouraging adoption through infrastructure development, financing for research, and subsidies. Regulations pertaining to intellectual property rights, data privacy, and interoperability standards are also necessary to establish confidence and guarantee the responsible use of agricultural data. The policy considerations for advancing digitization in agriculture are covered in an OECD paper from 2020 [9]. New technologies and creative uses are emerging as smart agriculture continues to evolve. Future developments in supply chain transparency through blockchain technology, autonomous agricultural systems, and the integration of drones and satellite photos for remote sensing are some examples of emerging trends. Furthermore, improvements in data analytics, such as predictive analytics and edge computing, are anticipated to raise the efficacy and efficiency of smart agriculture techniques even further. The future directions and developing trends in smart agriculture are examined in a paper by Ahmadi et al. (2021) [10]. Resilience and sustainability can be improved by incorporating renewable energy sources like solar and wind power into smart farm systems. By lowering dependency on fossil fuels and lowering greenhouse gas emissions, renewable energy solutions can power sensors, farm machinery, and Internet of Things devices. Furthermore, off-grid agricultural options are provided by renewable energy solutions, especially in isolated places with limited access to electrical infrastructure. Bhattarai et al.'s (2020) study investigates the possible connections between smart agriculture and renewable energy [11]. The integration of smart agriculture technologies gives rise to ethical and social issues of digital divide, equity, and access. There's a chance that obstacles like exorbitant prices, a dearth of technical expertise, and poor infrastructure will cause smallholder farmers and underprivileged communities to fall behind in the digital revolution of agriculture. For agricultural data to be used fairly and responsibly, issues with data ownership, privacy, and algorithmic bias must also be resolved. An investigation on the moral and social ramifications of smart farming technology is conducted by Van Der Meulen et al. (2020) [12]. Technological breakthroughs alone won't guarantee the effective adoption of smart agriculture technology; farmers must also be open to accepting and utilizing these innovations. Perceived utility, simplicity of use, compatibility with current procedures, and availability of technical assistance and training are all factors that affect acceptance. Designing successful extension programs and removing adoption hurdles require an understanding of farmers' attitudes, beliefs, and motives about smart agriculture. The factors influencing farmers' adoption of precision agriculture technologies are the subject of a 2019 study by Abidin et al [13]. To drive innovation and scale up smart agriculture solutions, stakeholders—including farmers, academics, legislators, and technology providers—must collaborate. The sharing of best practices, lessons gained, and technical skills is facilitated by knowledge sharing platforms, farmer cooperatives, and extension agencies. Furthermore, incorporating farmers in the co-design and co-development of technology through participatory methodologies increases acceptance and guarantees that the solutions are appropriate for the given area. In a 2019 study, Birner et al. investigate cooperative strategies for advancing digital agriculture

innovation [14]. In order to ensure food security and agricultural productivity in the face of climate change, resilient farming systems must implement adaptation measures. Through real-time monitoring of crop health, soil conditions, and weather patterns, smart agricultural systems enable adaptive methods. The implementation of smart agriculture methods, such as conservation agriculture and agroforestry, along with the provision of early warning systems for extreme weather events, helps farming communities become more resilient to climate change. A 2019 study by Lobell et al. explores the use of digital technologies in agriculture to adapt to climate change [15]. Agriculture is severely impacted by water scarcity, especially in areas that are experiencing drought and water stress. Through water-use efficiency measures, soil moisture monitoring, and precision irrigation, smart agriculture technologies maximize water management techniques. Smart agriculture reduces water loss through evaporation and runoff, optimizes irrigation schedules to crop water requirements, and improves agricultural sustainability. Pereira et al.'s review from 2021 looks at how smart irrigation technologies fit into sustainable water management [16]. Modern agriculture places a high priority on ensuring the safety and quality of food, and smart agriculture technologies are essential for improving traceability along the entire food supply chain. Through the use of blockchain technology, data analytics, and IoT sensors, smart agriculture makes transparent and effective farm-to-fork traceability possible. The food system is made more trustworthy and accountable when consumers have access to comprehensive information on the provenance, manufacturing processes, and handling procedures of food products. A study conducted in 2020 by Liu et al. investigates the use of blockchain technology in food traceability [17]. By enhancing livelihoods, lowering disparities, and opening up new economic opportunities, smart agriculture has the ability to propel rural development. Through the provision of digital services including banking services, e-commerce platforms, and agricultural extension, smart agriculture strengthens the resilience of rural communities to socio-economic difficulties and empowers them. Furthermore, smart agriculture advances the general growth and welfare of rural communities by encouraging sustainable land use and natural resource management. A World Bank research from 2021 looks at how digital technologies are transforming rural areas [18]. Beyond crop management, precision livestock farming is a subset of smart agriculture that uses cutting-edge technologies to monitor and control animal output. Farmers may optimize feeding schedules, identify diseases early, and increase overall output by tracking animal health, behavior, and performance using wearable technology, IoT sensors, and automated monitoring systems. Raising livestock with precision improves animal wellbeing, lessens its negative effects on the environment, and boosts livestock producers' profits. Berckmans (2017) conducted a review that offers valuable perspectives on the utilization of smart technologies in precision livestock production [19]. In urban agricultural environments, smart agriculture technologies are being used more and more to solve the issues of urbanization, resource scarcity, and food security. IoT, AI, and automation are used by vertical farming, hydroponics, and aquaponics systems to grow high-value crops

in regulated indoor spaces. By enabling year-round growing, economical resource usage, and localized food production in metropolitan areas, these technologies lessen the carbon footprint linked to the transportation of food. The potential of smart urban agriculture for sustainable food production is examined in a research by Specht et al. (2020) [20]. The protection of biodiversity can be aided by smart agriculture practices that support agroecological concepts, landscape management techniques, and habitat restoration. Precision conservation methods, biodiversity corridors, and agroforestry systems combine wildlife habitat preservation with agriculture production, boosting ecosystem services and promoting biodiversity. Smart agriculture contributes to the ecological balance and resilience of agricultural landscapes by protecting natural ecosystems and reducing habitat fragmentation. Tschardt et al. (2012) examine how agricultural landscapes contribute to biodiversity protection in their review [21].

III. APPLICATIONS OF SMART AGRICULTURE IN CROP MANAGEMENT

Numerous applications in crop management are possible with smart agriculture, which also revolutionizes conventional farming methods and streamlines agricultural operations. Precision irrigation is one important use case where Internet of Things sensors are used to continuously monitor soil moisture levels and meteorological conditions. Smart agriculture systems can minimize water waste and lower the risk of overwatering or underwatering by precisely determining when and where irrigation is needed by evaluating this data in real-time. Precision irrigation ensures that plants receive the right quantity of moisture for growth and development, which not only conserves water resources but also improves crop yields and quality. Precision fertilization is a critical use of smart agriculture in crop management. IoT sensors give farmers information about the nutrients in the soil, enabling them to apply fertilizers specifically to the crops that need them. Smart agricultural systems enhance nutrient uptake and decrease nutrient leaching, runoff, and environmental contamination by modifying fertilizer application rates and timing based on real-time data and crop requirements. Over time, precision fertilization preserves soil health and fertility while increasing nutrient usage efficiency, lowering input costs, and supporting sustainable farming practices. Moreover, proactive pest and disease management is made possible by smart agriculture by early detection and intervention. In order to spot indications of insect infestations, crop illnesses, or environmental stressors, artificial intelligence (AI) algorithms examine data from IoT sensors, satellite photography, and other sources. Farmers can minimize losses and stop the spread of pests and diseases by implementing targeted control strategies, such as biological pest control or precision spraying, as soon as they identify these threats. With the use of smart agricultural technologies, farmers can keep an eye on the health of their crops in real time, foresee possible threats, and act quickly to safeguard them and increase harvests. Applications of smart agriculture in agricultural management also include yield prediction and crop monitoring. Throughout the growing season, IoT sensors and remote sensing

technologies monitor crop growth, development, and performance, giving farmers important information on the health and yield of their crops. AI-powered models forecast crop yields and optimize harvest time by analyzing historical data, weather forecasts, and agronomic parameters. Smart agriculture technologies help farmers plan harvesting and marketing strategies, allocate resources optimally, and maximize profitability by providing precise yield forecasts. Additionally, smart agriculture facilitates decisionmaking on land management and crop rotation. Data analytics systems create suggestions for crop rotation schedules, cover cropping tactics, and land-use planning by integrating information on soil health, crop performance, and historical yields. Smart agriculture methods lower the danger of insect and disease accumulation, increase soil fertility, and control weeds by optimizing land usage and diversifying crop rotations. Smart agriculture promotes sustainable land management techniques that minimize environmental effect while improving soil health and productivity over the long term.

IV. BENEFITS OF SMART AGRICULTURE

Numerous advantages of smart agriculture include the potential to change the agriculture industry, increase productivity, and advance sustainability. A notable benefit is a rise in resource efficiency. Smart agriculture makes it possible to precisely monitor and manage resources like water, fertilizer, and pesticides by utilizing technologies like Internet of Things sensors, artificial intelligence algorithms, and data analytics. By optimizing resource allocation based on crop requirements and real-time data, farmers may maximize efficiency while reducing waste. This lowers input prices while simultaneously protecting finite resources, lessening the impact on the environment, and advancing agriculture's long-term viability. Enhanced production and yield optimization are two more important advantages of smart agriculture. Smart agriculture solutions facilitate proactive decision-making and targeted interventions by furnishing farmers with precise and timely insights into crop health, environmental conditions, and agronomic parameters. In order to maximize agricultural yields and quality while minimizing losses from pests, diseases, and environmental stressors, precision irrigation, fertilization, pest management, and crop monitoring techniques are used. Predictive models powered by AI can also estimate crop yields, market demand, and the best times to plant, giving farmers the information they need to make the most profit. Moreover, smart agriculture enhances risk management and decision-making. Farmers can obtain important insights into crop performance, market trends, weather forecasts, and other elements influencing agricultural outcomes by utilizing data analytics and artificial intelligence. This helps farmers to plan ahead, adjust to shifting circumstances, and make wise choices to lessen possible difficulties. With the help of smart agriculture, farmers may improve results and negotiate uncertainties in a dynamic agricultural landscape by deploying pest control techniques, changing crop rotations, or tweaking planting schedules. Furthermore, environmentally conscious farming methods and environmental care are encouraged by smart

agriculture. Precision farming methods, such as targeted fertilization and irrigation, reduce chemical use, soil erosion, and water pollution, so they lessen the environmental effect of agricultural operations. Smart agriculture systems contribute to biodiversity preservation, climate change mitigation, and natural resource conservation by maximizing resource efficiency and reducing waste. A more resilient and sustainable agricultural system is achieved through the use of sustainable land management techniques supported by smart agriculture, such as conservation tillage and cover crops, which improve soil health, carbon sequestration, and ecosystem resilience. Furthermore, smart agriculture encourages economic growth and innovation in rural areas. Farmers can boost output, open up new markets, and produce goods with additional value by implementing smart agriculture techniques and digital technologies. In addition, smart agriculture opens doors for tech companies, service providers, and agri-tech startups, fostering economic growth, job creation, and entrepreneurship in rural areas. Additionally, smart agriculture increases food security, fortifies supply chains, and promotes economic resilience locally, nationally, and internationally by raising agricultural productivity and competitiveness.

V. CHALLENGES AND LIMITATIONS

Smart agriculture has many advantages, but it also has a number of drawbacks and restrictions that prevent it from being widely used. The high upfront expenses of acquiring and using smart agriculture technologies represent a significant obstacle. Automation systems, AI algorithms, data analytics platforms, and IoT sensors all demand large infrastructure, software, and hardware investments. The upfront expenditures of adopting smart agriculture may be expensive for smallholder farmers and agricultural communities with low financial resources, creating a barrier to entrance and increasing the digital gap in the agricultural industry. The lack of technological know-how and digital literacy among farmers is another issue. Even while smart agriculture technologies have a lot of promise, many farmers lack the abilities and know-how to use them to their full potential. In order to equip farmers with the technical know-how to deploy, manage, and interpret data from IoT sensors, AI algorithms, and data analytics platforms, training and capacity-building activities are crucial. Furthermore, for farmers of all backgrounds and educational levels to be able to adopt smart agriculture technologies, userfriendly interfaces and simpler tools are required. Implementing smart agriculture presents additional obstacles due to interoperability and data compatibility concerns. Agriculture uses a wide range of IoT devices, data formats, and communication protocols, which can make it more difficult to integrate and share data between many platforms and systems. To provide common protocols and data standards that allow for compatibility and interoperability across a range of smart agriculture technology, standardization initiatives are required. Concerns about data ownership, privacy, and security also need to be addressed in order to foster confidence and guarantee that stakeholders are using and sharing agricultural data responsibly. Significant obstacles arise from lack of connectivity and inadequate infrastructure,

especially in isolated and rural agricultural areas. Data from IoT sensors must be transmitted to centralized platforms for analysis and decision-making, which requires dependable internet access. However, the adoption and scalability of smart agriculture solutions are hampered by the fact that many rural areas lack access to high-speed internet infrastructure. For farmers in disadvantaged areas to have fair access to smart agriculture technology and to close the digital divide, investments in mobile network coverage and rural broadband infrastructure are essential. Moreover, not all farming situations and agroecological settings are ideal for smart agriculture technologies, which are not one-size-fits-all solutions. Variability in crop kinds, soil types, climates, and farming techniques calls for customized solutions that take the needs of farmers and the local environment into consideration. For smart agriculture technologies to be as relevant and effective as possible, they must be tailored to particular agroecosystems and socioeconomic circumstances. Furthermore, in order to tackle new issues like data governance, intellectual property rights, and ethical considerations in smart agriculture, legislative and policy frameworks must change.

VI. FUTURE TRENDS AND OPPORTUNITIES

Future developments in smart agriculture are anticipated to be substantial, fueled by the emergence of new technology and changing farming methods. Combining machine learning (ML) and artificial intelligence (AI) approaches to further improve the capabilities of smart agriculture systems is one trend for the future. Artificial intelligence (AI) algorithms will advance in their ability to analyze agricultural data, forecast crop yields, identify pests and illnesses, and improve resource management techniques. Farmers will be able to make better, data-driven decisions with the help of AI-powered decision support systems, which will increase agricultural output, efficiency, and sustainability. The use of precision agriculture techniques to larger farm management practices, beyond crop management, is another significant trend. In order to provide comprehensive farm management solutions, smart agriculture systems will incorporate data from a variety of sources, such as weather forecasts, market trends, machinery performance, and supply chain logistics. With the use of this integrated strategy, farmers will be able to maximize crop yield while also managing livestock, the health of the soil, the use of water, energy efficiency, and financial planning, creating more resilient and successful farming operations. Furthermore, new avenues for innovation and value creation in agriculture will be made possible by the confluence of smart agriculture with other cutting-edge technologies like robots, drones, blockchain, and the Internet of Things (IoT). IoT devices and sensors will keep multiplying throughout agricultural landscapes, allowing for the real-time monitoring and management of agricultural activities. Blockchain technology will improve food safety, quality assurance, and farmers' access to markets by increasing the agricultural supply chain's transparency, traceability, and trustworthiness. Laborintensive operations like field scouting, planting, spraying, and harvesting will be automated by drones and robotics, decreasing the need for human labor and boosting

operational effectiveness. Furthermore, smart agriculture will be essential in tackling global issues like sustainable development, food security, and climate change. Through the application of smart agriculture technologies, climate-smart agriculture techniques will help farmers reduce greenhouse gas emissions, improve resilience to extreme weather events, and adjust to changing climatic circumstances. Agroecology and regenerative agriculture are two examples of sustainable intensification strategies that will provide food security and livelihoods for farming communities while fostering biodiversity, soil health, and ecosystem services.

VII. CONCLUSION

In summary, smart agriculture is a revolutionary farming method that uses state-of-the-art technologies to tackle the multifaceted issues that the agricultural industry faces. Farmers may make data-driven decisions, optimize resource use, and improve productivity, sustainability, and resilience in agriculture by utilizing smart agricultural systems, which integrate automation, artificial intelligence (AI), data analytics, and the Internet of Things (IoT). Through the real-time monitoring of soil conditions, weather patterns, crop health, and farm operations, smart agriculture enables farmers to manage their crops proactively, minimize risks, and optimize yields while minimizing input costs and environmental effect. There are several advantages to smart agriculture, from higher productivity and resource efficiency to better decisionmaking and sustainability. While reducing their negative effects on the environment, precision farming techniques such as fertilization, crop monitoring, pest control, and irrigation maximize resource utilization and improve crop yields and quality. Furthermore, smart agriculture encourages social inclusion, economic growth, and innovation in rural areas, opening doors for business ventures, employment creation, and capacity building. In order to create a more resilient and just food system going forward, smart agriculture supports sustainable farming methods and tackles global issues like food security and climate change. However, there are a number of obstacles and restrictions that smart agriculture must overcome, such as expensive upfront expenses, technological difficulties, interoperability problems, connectivity constraints, and contextual variability. Governments, academic institutions, technology companies, and farmer organizations must work together to address these issues in order to remove obstacles, increase capacity, encourage innovation, and establish favorable conditions for the long-term growth of smart agriculture. For farmers of all sizes and backgrounds to have fair access to smart agriculture technology and to maximize their advantages, policy frameworks, capacity-building programs, and investments in rural infrastructure are crucial.

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