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Revolutionizing Agriculture through Digital Technologies: A Review of AI, IoT, and Precision Farming

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ABSTRACT

Recent technological advances are transforming agriculture. This review discusses how AI, ML, IoT, and big data analytics might solve modern agriculture's biggest problems. These technologies are changing agricultural monitoring, disease detection, and resource management, improving productivity and sustainability. AI and ML improve predictive modelling, automate decision-making, and optimise irrigation, while IoT technologies give real-time soil and environmental data. Precision agricultural technology include smart sensors, autonomous systems, and GIS tools help conserve water, fertilisers, and pesticides, reducing waste and environmental effect. This paper synthesises existing research and examines how technology advances might sustain agricultural expansion, increase food security, and satisfy future demands.

***Keywords**: Precision Agriculture, Smart Farming, Big Data Analytics, Crop Monitoring, Sustainable Agriculture, Smart Irrigation.*

Introduction

Technology has transformed agriculture, improving food security, sustainability, and resource management. AI, IoT, big data analytics, and WSN are replacing or supplementing existing agricultural methods to revolutionise them. Recent studies show these technologies can improve precision agriculture, smart farming, and sustainable food production. AI works well in land suitability, disease detection, agricultural management, and water resource management. Deep drives and fuzzy logic reduce pesticide use and environmental impact in agriculture [1]. Smart agricultural systems use sensors and wireless connection to monitor crop conditions, manage irrigation, and make real-time decisions to conserve water and boost crop yields [4].

High-resolution satellite pictures and drones monitored crop health, soil condition, and water levels for precision agriculture [2]. These technologies increase productivity and resource conservation by providing agricultural database information. Sustainability decline and promotion [5]. The cloud and edge provide real-time data processing and better agricultural decisions[13]. Climate change, water scarcity, arable land shortages, and population growth affect agriculture. Traditional agricultural practices often ignore these challenges, causing inefficiency and environmental damage. AI, IoT, and autonomous learning solve these issues and make agriculture smarter.

Crop yield forecasting is a major technology influence. Machine learning algorithms assess past and current soil moisture, temperature, and precipitation to predict crop yields. Farmers can adjust planting and harvesting dates to maximise yields and avoid waste. Early detection of hazards using AI-based pest and disease monitoring systems reduces agricultural losses and helps farmers safeguard their harvests [7]. Sustainable agriculture requires water and soil management. IoT devices and wireless sensors monitor soil, moisture, and nutrients for data-driven irrigation. Smart water-saving solutions decrease waste and enhance resource sustainability [15]. This device is essential in water-stressed places where drops matter. AI and IoT technologies improve cattle output and welfare by monitoring animal health, tracking movements, and optimising feeding. Wearable sensors can monitor livestock behaviour and diagnose disease in real time, enhancing management and health [23].

Finally, AI, IoT, big data, and remote sensing are enhancing agriculture's efficiency, sustainability, and productivity. These technologies affect agriculture and have the ability to alleviate problems and build a more sustainable and efficient ecosystem.

Literature Review

In 2019, Jha et al. published “A Comprehensive Review on Automation in Agriculture Using Artificial Intelligence.” In this report, experts stressed the necessity for agriculture automation to meet rising global food demand. The researchers stressed the drawbacks of traditional agriculture and chemical misuse on soil quality. The review examined disease detection and diagnostic automation using AI, deep learning, and machine learning models. For crop management, researchers addressed fuzzy logic expert systems and automation technologies such smart GPS-based remote-controlled robots and smart irrigation systems. The paper also discussed using IOT systems and wireless sensors to automate drip irrigation and check water quality. Jha et al.'s extensive investigation showed the revolutionary potential of AI, machine learning, and IoT to revolutionise agricultural practises to solve industry problems and increase sustainable and effective agricultural output[1].

Precision agriculture remote sensing was thoroughly evaluated by Sishodia et al. Geospatial technology, IoT, big data analysis, and AI were used to optimise agricultural operations, increase crop yield, and reduce input losses.

The article described how high-resolution satellite images have accelerated precision agriculture's remote sensing adoption in recent decades. Remote sensing monitored crops, fertiliser use, irrigation, diseases, weeds, and yield. We assessed precision agriculture's remote sensing and vegetation indexes.

Commercial farming innovations like UAVs and variable fertiliser rate application equipment were valued. Crop production efficiency and agricultural optimisation were explored using AI, machine learning, and IoT.

Precision agriculture and remote sensing technology can improve agricultural processes and sustainability, as shown in the study[2].

Mohamed El-Sayed et al. (2021). Improve agricultural management by analysing smart farming. 5G, IoT, and AI can solve food shortages and population increase. Smart sensing, decision support systems, and the IoT can improve farming production and sustainability, according to the authors. Modern technologies may revolutionise agriculture and assist farmers solve today's issues, according to Mohamed et al. [3].

Qazi et al.'s "IoT-Equipped and AI-Enabled Next Generation Smart Agriculture: A Critical Review, Current Challenges, and Future Trends" addresses global hunger, arable land shortages, pesticide limits, and water scarcity. Smart agricultural systems monitor crop conditions and apply smart irrigation and other applications using IoT nodes with sensors. While reviewing hardware, wireless communication technologies, and software, the authors discussed smart agriculture system implementation, use-cases, and restrictions. The study's roadmap includes relevant research, smart irrigation, UAV use, smart agriculture, and field advances. The paper concluded with background on how AI and the IoT are altering global agriculture and their future[4].

Big data analysis in a geospatial cloud architecture may improve sustainable agriculture, according to Delgado et al. The research studied geospatial data and cloud computing to assess massive datasets to maintain farming. Because of its potential, Delgado et al. recommended big data analytics in sustainable agriculture.

Delgado et al. evaluated farming big data analysis issues and provided solutions. Geographically, they explored the difficulties of analysing massive agriculture data. Delgado et al. highlighted big data analysis's agricultural decision-making and resource optimisation potential.

Geospatial cloud frameworks may improve sustainable food systems, according to Delgado et al. Their research indicated that data-driven insights maintain agriculture. Big data analysis on a geospatial cloud architecture could alter sustainable agriculture, say Delgado et al[5].

S. R. Krishnan. "Smart Water Resource Management Using Artificial Intelligence—A Review" (2022) examined AI in water resource management. Technology, economics, administration, and wastewater reuse were explored. AI may be used in wastewater treatment, the authors said. The review of AI-based ensemble wastewater treatment plant modelling demonstrates that jittered data improves accuracy.

State of the art, application assessments, and research ideas for wastewater heavy metal removal models using AI were also presented. The paper also analysed artificial intelligence-based urban water system deterioration models and their pros and cons for forecasting and appraising water distribution networks. New research topics and difficulties were sought to create a dynamic AI-based water pipe deterioration agenda.

The report highlighted new water resource management approaches, challenges, and research aims, as well as AI's potential to modify practices[6].

Elbasi et al. reviewed AI and IoT's farming benefits in a comprehensive literature review. AI can track crops and animals, detect suspicious activity, find irrigation leaks, control operations remotely, and boost output, according to the review. Farmers may use AI for machine learning, expert systems, IoT, and image/video processing. Select papers were categorised by study advantages, downsides, and methodology. AI technology like expert systems and machine vision were recommended for agricultural operations. IoT was also found to be important in AI-based smart farming, particularly seed and crop protection development[7].

Elijah et al. reviewed all the research on how farmers use data analytics and IoT to boost output and efficiency. The paper covered farming's IoT ecosystem, encompassing devices, telecommunications, the web, and data processing and storage. The authors explore smart agriculture's pros, cons, and future trends to demonstrate how IoT and data analytics could change the agricultural industry and address food security[8].

Jha et al. (2019) examined AI-based agricultural automation and showed that food production requires cutting-edge technologies. To improve agricultural sustainability and efficiency, the study studied IoT, wireless communications, machine learning, and AI. The authors investigate how deep learning and other AI may affect agricultural practices to reduce soil deterioration and pesticide use. The study showed how agricultural automation could boost food production and solve major issues[9].

Asfaw et al. (2018) presented TAMSAT-ALERT v1, a cutting-edge agricultural decision support platform. The framework used geospatial modelling and data analysis to improve agricultural operations. To help farmers make informed irrigation, crop management, and other agricultural production decisions, TAMSAT-ALERT v1 combined multiple data sources and models. This research shows the promise of data-driven farming decision-making and the importance of using technology to make farming more sustainable and productive. To conclude, the paper provided useful information on developing new tools to improve farming processes and help farmers maximise their operations[10].

Shafi etc. Precision Agriculture: Concepts to Results, 2019. The study studied Precision Agriculture innovations including leveraging sensors and the IoT to improve farming. Top universities like Leeds and the National University of Science and Technology explain how high-resolution photography and data analytics may increase agricultural production and sustainability. The article examined IoT service-oriented systems with remote sensing vegetation indices for crop health monitoring and agricultural enhancement. The paper explained Precision Agriculture and its practical uses[11].

Precision Agriculture: Concepts to Practice (Shafi et al., 2019). The research examined Precision Agriculture advances using sensors and IoT to improve farming. National University of Science and Technology and University of Leeds experts have written on how data analytics and high-resolution photography might improve agricultural sustainability and output. The article studied how remote sensing vegetation indices and IoT service-oriented systems might track crop health and enhance productivity. Precision Agriculture and its numerous benefits were explained by the research[12].

Ferrández-Pastor et al. (2018) used distributed computing and IoT to study Precision Agriculture Design Method. A distributed IoT architecture using edge and fog computing could improve farming operations, the study found. The authors demonstrated how agricultural facilities might leverage Internet of Things (IoT) applications by involving farmers in the design phase and prioritising user-centred design. Edge and fog computing can automate farming processes and improve decision-making, as shown by tests and analysis of agricultural installations. The study revealed IoT could change precision agriculture[13].

Vuran et al. (2018) examined IOUT in precision agriculture, focussing on subsurface sensor and communication device integration for real-time soil monitoring. The authors examined the merits and cons of employing Internet of Things (IoT) solutions in farming, emphasising the necessity for energy-efficient communication protocols and equipment. They discussed the importance of standard interfaces in the IOUT cloud architecture and how big data analytics may help with soil data and satellite photographs to gain insights. Vuran et al. focus on subsurface communication networks to analyse the methodologies, tools, and challenges of deploying IoT systems for precision agriculture[14].

Paper by Tace Y. et al. (2023) stated smart irrigation will assist farmers save water and boost agricultural productivity. The AI-IOT smart irrigation system was proposed. The IOT device collected data using temperature, humidity, rain, and soil moisture sensors. This paper by Tace Y. et al. examine smart irrigation systems, methods, and accuracy. Many studies used random forest, SVM, KKN, decision tree, and other machine learning techniques to create AI models for optimum irrigation. Future researchers aim to enhance database data and construct 98% accurate decision-making algorithms. Smart irrigation will conserve water and boost crop yield to meet food demand, researchers say[15].

Digital farming can alter agriculture by merging IoT, AI, and real-time data, according to Aamir Raza et al. (2023). The extensive analysis showed that digital farming will boost conventional agriculture techniques. The study found that digital farming improves yields, water conservation, input reduction, and resource management. Autonomous machinery and smart irrigation improve agricultural efficiency. Digital farming might revolutionise agriculture with accuracy and sustainability, thus the research sought stakeholder adoption. A literature review explored how digital farming affects agricultural engineering. Precision agriculture reduced pesticide and fertiliser consumption, promoting eco-friendly farming. Efficiency gains from autonomous gear and smart irrigation systems could affect resource allocation and food availability. The study frequently called digital farming a game-changer in agriculture. By improving resource management, productivity, and sustainability, it increased agricultural efficiency. Digital farming's precision agriculture increased yields (10-20%) while reducing water, pesticide, and fertiliser use. The study indicated that smart irrigation and autonomous machinery boost agricultural productivity and efficiency. Real-time data analysis in digital farming may revolutionise decision-making, the study showed. Aamir Raza et al. (2023) contributed by reviewing digital farming and its potential to change agriculture. Resource management, sustainability, and efficiency research helped farmers enhance their ways for a more lucrative and technologically advanced agricultural business[16].

Durai R. V. et al. (2019) explored AI-driven land suitability evaluation in agriculture to enhance productivity. The researchers assessed land suitability using sensor networks and AI technologies, notably neural networks, indicating their dedication to agricultural growth. The territory was divided into four sections using sensor data to illustrate the system's viability. An excellent multiclass classification system for land suitability evaluation used MLP with four hidden layers. Evaluation of the agricultural environment in four choice classes was more challenging. Before explaining the approach, which combined sensor networks with AI systems for review, the literature analysis underlined the need for sensor networks for agriculture land suitability assessment. The suggested approach was confirmed by thorough land suitability data collecting and parameter selection. This AI- and sensor-driven system sought to boost agricultural production and give farmers crop-boosting advice. Automating crop condition variable analysis shows forethought. The article demonstrated that MLP with four hidden layers for multiclass classification can assess agricultural land in four decision classes. We showed the model's generalisability for land suitability classification anywhere to show its high accuracy and efficiency for sustainable agricultural growth. Interestingly, the study did not list any limits, letting readers focus on the approach's merits. Durai R. V. et al. expanded AI-driven agriculture by evaluating land suitability with sensor networks and AI. MLP's success and promise for land classification and appraisal boosted this contribution. Due to its widespread use and long-term viability, the approach revolutionised agricultural technology[17].

In 2018, M. Safdar Munir et al. proposed an IoT-integrated smart irrigation system to improve plant watering. This innovative method conserved water, energy, and surpassed manual methods. The smart irrigation system used sensors, a mobile app, and cheap, easily available technologies to maximise water consumption. To increase out-of-season food production and handle water constraints, the authors employed IoT and sensors to irrigate plants. The literature research suggests tunnel farming since sensor-based irrigation systems are inefficient and expensive. The scientists described an IoT system with sensors to track plant data and irrigation. A mobile phone app controls the irrigation system for plant watering and resource conservation. The smart irrigation system for energy consumption and tunnel farming was cost-effective, easy to replicate, and outperformed manual and sensor-based techniques. Despite limited financing, the study found the smart irrigation system useful. Tunnel farming used water and energy efficiently and outperformed humans and sensor-based systems. M. solved water scarcity and promoted tunnel farming's energy-saving methods. Smart agriculture was pushed by Safdar Munir. Smart irrigation systems were touted as innovative agricultural technologies with useful insights, sound technique, and convincing results[18].

In 2018, Wu Yong et al. studied how Embedded Intelligence (EI) might illuminate social patterns and behaviour. Researchers explored wireless communication, the Internet, and the Internet of Things for smart data processing, mining, and agriculture. The literature review established smart agriculture, IoT, embedded intelligence, and global interoperability. Methods comprised sensor behavioural analysis and latent variable assignment. The authors created ontologies and metadata using existing tools. Smart agriculture and urban dynamics may use embedded intelligence to analyse data and get new insights. Global interoperability and open, fair standards were stressed throughout the text. Data sharing was enhanced by "Web 3.0," which blends semantic web technologies with the Internet of Things. Given its complexity, standards and global interoperability present privacy concerns when deploying such advanced technology, according to the paper. Various information retrieval and publishing systems' search constraints were also examined. The researchers presented an Embedded Intelligence-based smart agriculture technology roadmap and irrigation case study. Smart agriculture, global interoperability, embedded intelligence, and the internet of things showed this dynamic technological environment's pros and cons[19].

Konstantinos G et al. (2020) studied sustainable agriculture using cutting-edge technologies and stakeholder participation. Agriculture 4.0, which combines Cloud Computing, IoT, robots, and big data, may improve agricultural management and sustainability. The literature review outlined how creative technology could promote agricultural growth. Smart technology and value chain re-engineering are necessary for agricultural sustainability, they say. A detailed Agriculture 4.0 study showed how communication and contemporary technology are part of this paradigm change. Complex agricultural technology requires integrating subsystems, synchronising, and communicating features, according to the study. Big Data assisted operational decisions, forecasted insights, and improved operations. For sustainable agriculture expansion, smart technologies that combine subsystems to improve task performance were emphasised. Agriculture 4.0 technology and its impact on farming were discussed. The research emphasises that sustainable agricultural management involves smart use of Big Data, Robotics, and Cloud Computing. Setting constraints were not mentioned in the study. It focused on Agriculture 4.0's transformational potential for ecologically responsible agricultural management. The paper emphasised smart technology for re-engineering the agricultural value chain and current technologies to improve agricultural operations to promote innovation and sustainability[20].

A detailed study of sensors, ICT, and data analytics in farming by Barun Basnet et al. (2018) provided useful findings. Assessing all facets of agricultural technology showed ongoing research across disciplines. Korean agriculture's progress is shown by comparing it to other advanced nations. The project included agronomy, horticulture, and apiculture sensor and data analytics. Sensors, ICT, and data analytics were advocated to improve agriculture. This was especially true for crop monitoring, data collection, and prediction. Big data and smart farm technology adoption were the paper's focus. Classifying sensors and data analytics into five categories explained their agricultural uses. A Korean agriculture case study compared to wealthier nations showed the basics. The authors examined and recommended remedies for agriculture's existing and future difficulties. The paper's narrow focus on in-field uses and lack of agricultural analysis should be noted. The comprehensive evaluation of sensors and data analytics in many categories and the analysis of Korean agriculture, its difficulties, and potential solutions make this work an essential contribution to agricultural technology[21].

Smart Agriculture uses sensors and actuators for informed decision-making, as Laura Garcia et al. (2018) demonstrated with crop monitoring via a Wireless Sensor Network (WSN). The network architecture uses WSN and WMN for efficient data transport. Researchers simulated the ideal network node count. A literature analysis on smart agriculture and precision agriculture, specifically wireless network design for crop and irrigation system monitoring.

After careful development, WSN and WMN nodes relayed data to one AP in simulations. IoT devices with strategically placed nodes improved crop monitoring wireless network performance in diverse situations. Implementation revealed that the wireless network design benefited manufacturers and was applicable to agricultural applications.

Inefficient networks and failed node data transmission were limits, however simulations showed node connection and data transmission efficacy. Despite these obstacles, the study recommended wireless network design for precision agricultural crop monitoring. The paper's focus on strategically placing nodes for agricultural wireless transmission revealed its innovative and practical approach[22].

Haidar M.J et al. (2017) examined WSN efficiency and precision in agriculture. The review investigates energy-efficient solutions like wireless power transmission and solar cells for agriculture management, waste reduction, and crop quality. Energy-efficient technologies, agricultural monitoring, and WSN were investigated. The study found ZigBee and LoRa good agricultural wireless protocols. Notable achievements include UAV-based mobile data connection services and solar cell sensor node power research. Three wireless power transfer (WPT) subcategories explained agricultural energy dynamics. The review's applications and limitations highlighted energy-efficient and wireless communication technologies. The work helped agricultural WSNs overcome field-base station distance issues. Wireless protocols' drawbacks, power consumption reduction, and precision agriculture monitoring solutions were discussed [23].

Research Gap & Observation

The research highlights the benefits of combining AI, ML, IoT, and big data in agriculture. These advances transform farming, improving efficiency, sustainability, and productivity. Precision agriculture uses AI and IoT to target and optimise resource use. Farmers can monitor soil, crop, and water conditions in real time using sensors, drones, and satellite imagery. This precise monitoring optimises water, fertiliser, and pesticide use, avoiding waste and ensuring crops get what they need. This method boosts yields, promotes sustainability, and reduces environmental damage.

Improved plant disease diagnosis and treatment is another major benefit. AI-controlled systems, using neural networks and in-depth learning algorithms, can analyse enormous plant picture data sets to detect early indicators of illnesses, pests, and nutritional deficits. Early detection provides timely intervention, decreases disease transmission, and may save a large harvest. Remote sensing and automated drones improve field monitoring and intervention speed and accuracy. Intelligent irrigation systems, another advancement, may solve water shortages, especially in water-scarce areas. These systems use IoT sensors to monitor soil humidity and weather to automatically determine water use and guarantee plants get enough water at the proper time. This conserves water and boosts crop yields by ensuring growth. AI in irrigation decision support systems helps farmers predict water needs based on weather and crop data, improving resource management. Megadont analysis and GIS technologies provide more data-driven decision-making. Farmers can anticipate agricultural yields, set planting schedules, and rotate crops using historical data, weather, and predictive analytics. This promotes long-term planning and global farmer management, improving economic results and promoting sustainable practices.

Additionally, agricultural process automation is enhancing labour efficiency. Autonomous tractors, robotic harvesters, and automated planting systems are changing farms by eliminating repetitive, labour-intensive operations. Farmers may focus on strategic tasks like planning, data analysis, and market coordination with this automation. Machine learning algorithms also let machines adapt to agricultural situations for more precise and personalised activities. Robotic weeders with computer vision can locate and remove weeds without hurting crops, lowering pesticide consumption and boosting crop quality. Efficiency gains are accompanied by cost savings, less human error, and the capacity to scale operations with fewer labour restrictions. Farmers in many locations face labour shortages and increased expenses, making automation crucial.

These technologies promote sustainable agriculture by minimising chemical inputs, boosting land and water usage efficiency, and strengthening agricultural systems against climate change. Integrating AI, IoT, and machine learning into agriculture makes it more adaptable, precise, and sensitive to food security and environmental sustainability problems. These technologies boost agriculture's economic viability and make it more robust and sustainable.

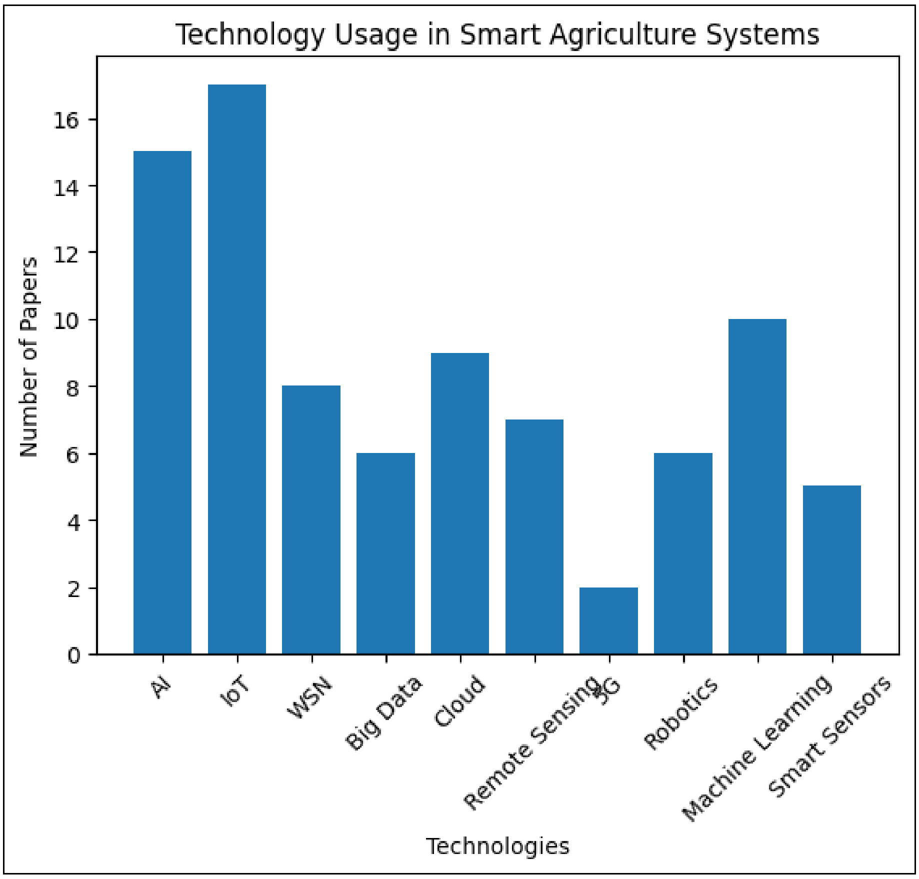

Fig. 1: Technology Usage in Smart Agriculture Systems

Result

IoT, AI, and machine learning are improving agriculture's production, precision, and sustainability. The use of this technology has improved farming methods and crop production. Farmers may get exact planting, irrigating, and harvesting advice from AI-powered predictive algorithms that assess historical data, weather, and soil conditions. This data-driven approach eliminates waste and maximises resource efficiency, helping crops grow. Precision agriculture saves on water, fertiliser, and pesticides. Farmers may reduce pesticide and water use by using IoT sensors and drones to monitor soil moisture, nutritional levels, and pests in real time. Agriculture's environmental impact reduction saves money and promotes sustainability.

AI-based disease identification improves plant health management. Early disease identification utilising image recognition and sensor data enhances crop yield. Automated livestock monitoring systems can detect animal health and behaviour and assist farmers handle issues instantly, improving livestock welfare. AI, machine learning, and IoT in agriculture have had a substantial economic impact and proven scalability across farm types. Resource efficiency and labour cost reductions have saved money with these technologies. Precision irrigation systems that use real-time data minimise water bills, while automated equipment cut labour costs. Long-term savings and productivity advantages are driving farmer interest in contemporary technologies.

These technologies serve small and large farms because they are scalable. Smart irrigation systems using low-cost sensors increase small farmers' yield and sustainability without requiring costly capital. Autonomous machinery and big data analytics can improve operations, manage immense data, and automate challenging processes on large farms. Scalable agricultural technology promotes greater adoption and various farming practises by adapting to different operating sizes and types.

AI and IoT technology' economic benefits and scalability promise to make agriculture more productive, profitable, and responsive to global demands and conditions. These innovations boost agricultural yield and system resilience. Farmers can now adapt to climate change and feed the world. Integrating modern technologies improves agriculture's efficiency, productivity, and sustainability.

Conclusion

In conclusion, the integration of AI, machine learning, and IoT in agriculture represents a significant step forward in the transformation of the sector. These technologies have not only improved productivity and efficiency, but have also contributed to more sustainable and precise farming practices. By leveraging predictive analytics, real-time data monitoring, and automated systems, modern agriculture has become more capable of meeting the growing global food demand while addressing environmental and resource challenges. The economic benefits of these technologies, including cost savings and scalability, underscore their value for both small- and large-scale farms. With precision agriculture reducing input costs and increasing yields, and automation minimizing labor requirements and optimizing resource use, these advances are reshaping the economic landscape of agriculture. Moreover, the ability to integrate these technologies into diverse agricultural contexts highlights their broad applicability and potential for widespread adoption. As the agricultural sector continues to evolve, ongoing innovations and research will likely further improve these technological solutions, leading to continued improvements in efficiency, productivity and sustainability.

Overall, the results of the implementation of AI, IoT and related technologies suggest a promising future for agriculture, characterized by increased resilience, adaptability and environmental sustainability. The transformative impact of these advances underscores the importance of continued investment and research to realize their full potential and ensure a sustainable and prosperous future for global agriculture.

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