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Review Article

Recent Advancements and Future Prospects in Agronomy

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ABSTRACT

Agronomy, the science of crop production and soil management, has experienced rapid transformations driven by technological innovations and the urgent need for sustainable food systems. This comprehensive review examines recent advancements in agronomy, encompassing precision agriculture, artificial intelligence (AI) and machine learning applications, drone and UAV technology, CRISPR-based genome editing, nanotechnology in crop production, Internet of Things (IoT) integration, and climate-smart agriculture practices. The global precision agriculture market, valued at USD 11.67 billion in 2024, is projected to reach USD 24.09 billion by 2030, reflecting the accelerating adoption of these technologies. Furthermore, this review explores future prospects including autonomous robotics, digital twins, vertical farming, and synthetic biology. By synthesizing current research findings, this paper provides a holistic overview of how modern agronomic innovations are reshaping crop management, enhancing resource-use efficiency, and building climate resilience for global food security.

Keywords: *Precision Agriculture; Artificial Intelligence; Climate-Smart Agriculture; CRISPR Genome Editing; Sustainable Crop Production.*

INTRODUCTION

The global agricultural sector faces unprecedented challenges in the 21st century, including the need to feed a rapidly growing world population projected to reach 9.7 billion by 2050, while simultaneously addressing the impacts of climate change, soil degradation, water scarcity, and diminishing arable land (FAO, 2023).

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Agronomy, as the foundational science of crop production and soil management, is at the forefront of addressing these challenges through the integration of advanced technologies and innovative practices (Anbarasan & Ramesh, 2022). In recent years, the convergence of digital technologies, biotechnology, and data-driven decision-making has initiated a paradigm shift in agronomic practices. Precision agriculture, powered by artificial intelligence (AI), the Internet of Things (IoT), and remote sensing technologies, has transformed traditional farming into a data-centric enterprise capable of optimizing resource use and maximizing crop yields (Le et al., 2023). Concurrently, breakthroughs in genome editing, particularly CRISPR/Cas9 technology, have opened new avenues for developing crop varieties with enhanced stress tolerance, improved nutritional content, and higher yield potential (Muha-Ud-Din et al., 2024).

Climate-smart agriculture (CSA) has emerged as a holistic framework that simultaneously addresses productivity enhancement, climate adaptation, and greenhouse gas mitigation (World Bank, 2024). Additionally, nanotechnology applications in crop production, including nanofertilizers and nanopesticides, are offering promising solutions for improving nutrient use efficiency while minimizing environmental pollution (Usman et al., 2021). The integration of drone technology for aerial surveillance, precision spraying, and crop health monitoring has further revolutionized field management practices (Guebsi et al., 2024).

This review aims to provide a comprehensive synthesis of recent advancements across key areas of modern agronomy and to explore the future prospects that will shape agricultural practices in the coming decades. By examining the current state of research and technological development, this paper offers valuable insights for researchers, policymakers, and agricultural practitioners seeking to enhance food production systems sustainably.

2. Precision Agriculture and IoT Integration

Precision agriculture represents one of the most significant technological revolutions in modern farming, combining IoT sensors, GPS technology, geographic information systems (GIS), and advanced data analytics to enable site-specific crop management (Soussi et al., 2024). The global precision agriculture market was valued at USD 11.67 billion in 2024 and is projected to grow at a compound annual growth rate (CAGR) of 13.1% to reach USD 24.09 billion by 2030 (Grand View Research, 2025). This growth is driven by increasing adoption of smart farming technologies, favourable government initiatives, and the pressing need for sustainable agricultural intensification.

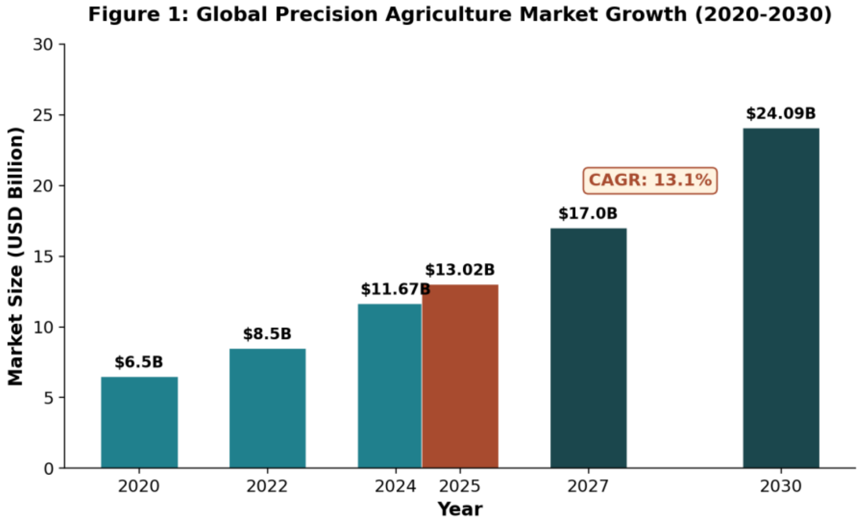

Figure 1: Global Precision Agriculture Market Growth (2020–2030). Source: Grand View Research (2025)

IoT-based smart sensors deployed across agricultural fields measure critical parameters including soil moisture, temperature, humidity, and nutrient levels in real time (Dhanasekar, 2025). These sensors, connected through low-power wide-area networks (LPWANs) such as LoRaWAN, transmit data to cloud-based platforms where AI algorithms generate actionable insights for irrigation scheduling, fertilizer application, and pest management (Daviteq, 2025). Studies have demonstrated that IoT-based soil moisture sensor systems can save up to 18% of irrigation water while increasing water use efficiency in soybean and potato fields by 49% and 16%, respectively (Boltana et al., 2023; & Dong et al., 2023).

Variable rate technology (VRT) enables farmers to apply inputs such as seeds, fertilizers, and pesticides at varying rates across a field based on spatial variability data, ensuring optimal resource allocation and minimizing waste (Erickson & Lowenberg-DeBoer, 2025). GPS-guided autoguidance systems are now employed on approximately 85% of custom farming operations in the United States, reflecting the maturity of this technology segment (Global Ag Tech Initiative, 2025).

3. Artificial Intelligence and Machine Learning in Agronomy

Artificial intelligence has emerged as a transformative force in agronomic science, offering unprecedented capabilities in crop monitoring, disease detection, yield prediction, and decision support systems (Daraojimba et al., 2024). Machine learning algorithms, including convolutional neural networks (CNNs) and deep learning models, are being extensively applied across the agricultural value chain to enhance precision and efficiency.

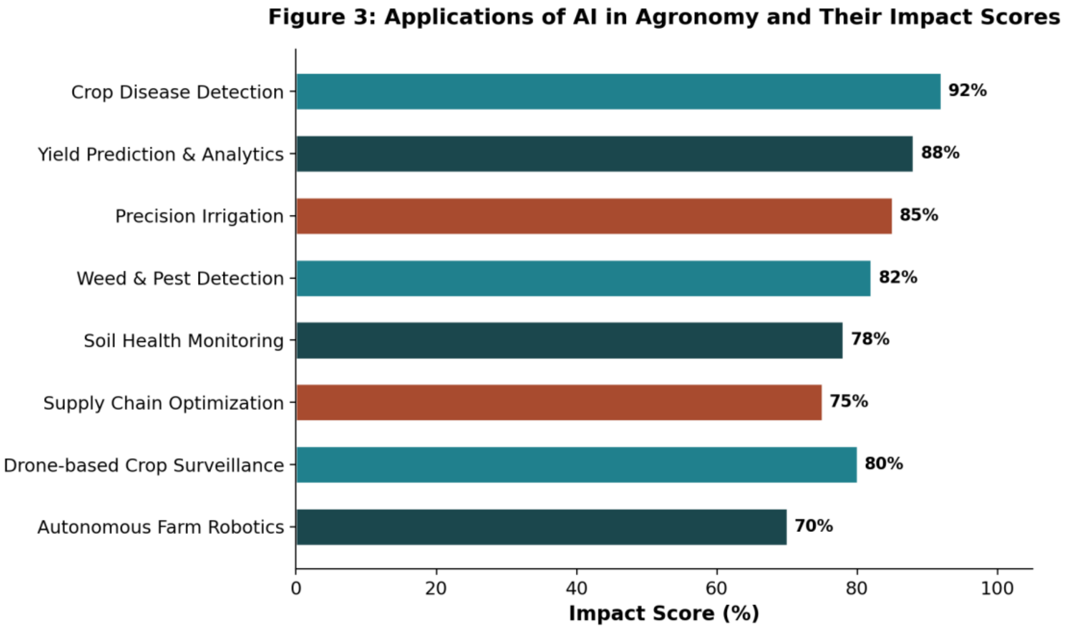

Figure 3: Applications of AI in Agronomy and Their Estimated Impact Scores

3.1 Crop Disease Detection and Monitoring

AI-powered image recognition systems have demonstrated remarkable accuracy in detecting crop diseases at early stages. Neural network-based systems have achieved up to 95% accuracy in identifying diseases such as apple scab and wheat yellow rust through analysis of leaf and field images (BasicAI, 2024). The University of California, Davis, has developed the Leaf Monitor, an AI-backed mobile tool that uses handheld spectrometry and cloud-based machine learning to predict leaf nutrient content and health status in real time, achieving approximately 65% accuracy across all traits with higher performance for nitrogen and phosphorus predictions (Pourreza, 2025).

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3.2 Automated Weed Control and Precision Spraying

AI-driven weed detection systems represent a major advancement in precision crop management. Blue River Technology, now a subsidiary of John Deere, developed the See & Spray technology, which uses high-resolution cameras and machine learning algorithms to distinguish between crops and weeds in real time. This technology enables targeted herbicide application, reducing chemical usage by up to 90% compared to conventional broadcast spraying methods (Basic AI, 2024). Machine vision for weed control is rapidly gaining adoption, with agricultural dealers projecting significant expansion in this technology segment over the next three years (Erickson & Lowenberg-DeBoer, 2025).

3.3 Yield Prediction and Decision Support

Machine learning models integrated with satellite imagery, weather data, and historical yield information enable accurate crop yield prediction, facilitating better market planning and resource allocation (Daraojimba et al., 2024). AI-driven decision support systems empower farmers to make data-informed decisions regarding planting schedules, irrigation timing, and harvest optimization, leading to crop yield improvements of 15–20% in many implementations (Earth.Org, 2025).

4. Drone and UAV Technology in Agriculture

The application of unmanned aerial vehicles (UAVs) in agriculture has expanded dramatically in recent years. In the United States alone, the number of agricultural drones registered with the Federal Aviation Administration increased from approximately 1,000 in January 2024 to around 5,500 by mid-2025, with industry reports suggesting actual usage is substantially higher (MSU, 2025). Drones equipped with RGB, multispectral, hyperspectral, and thermal sensors provide high-resolution spatiotemporal data for comprehensive field monitoring (Ybañez & Ybañez, 2025).

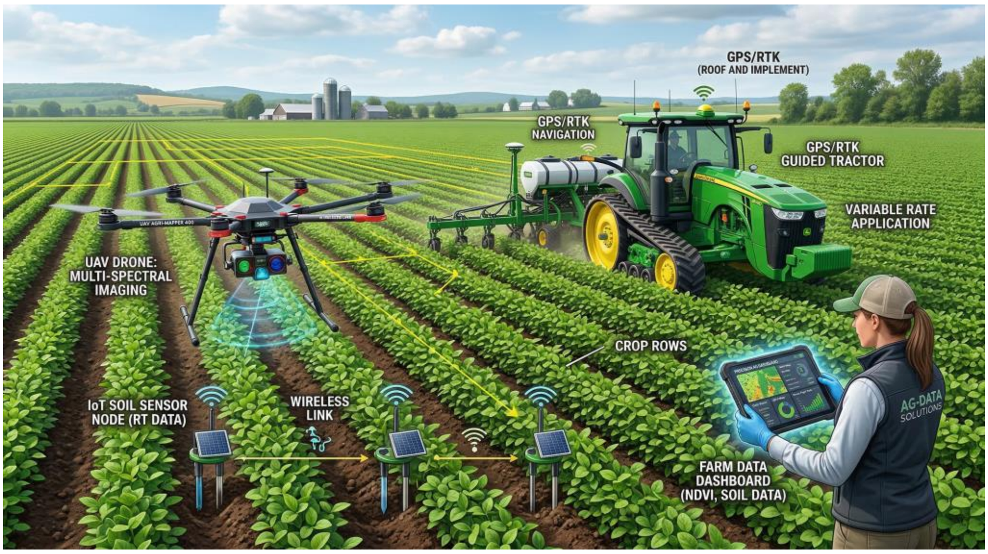

Figure 5: Integrated Precision Agriculture Technologies in Modern Farming. Illustration showing UAV drones, IoT soil sensors, GPS-guided tractors, and farm data dashboards working in concert

Key applications of drone technology in agronomy include crop health assessment through vegetation index analysis, precision spraying of pesticides and fertilizers, cover crop seeding, irrigation management, and yield estimation (University of Maryland Extension, 2024). Research has shown that drone-based multispectral imaging combined with AI analysis can forecast leaf water content and enable efficient soil moisture inversion, improving the speed and accuracy of irrigation decisions (AgWeb, 2024). The integration of artificial intelligence with drone-collected data has demonstrated significant improvements in early disease detection and resource optimization, with potential annual savings of USD 1.3 billion for corn, soybean, and wheat farmers through improved yields and reduced input costs (Doering, 2015, as cited in University of Maryland Extension, 2024).

5. CRISPR/Cas9 Genome Editing in Crop Improvement

CRISPR/Cas9 technology has revolutionized agricultural biotechnology by enabling precise, targeted modifications to plant genomes without introducing foreign DNA, making it a more publicly acceptable approach compared to traditional genetic modification techniques (Ali et al., 2023). This genome editing tool has been applied extensively to enhance crop tolerance to abiotic and biotic stresses, improve yield-related traits, and enhance nutritional quality.

In the domain of abiotic stress tolerance, CRISPR/Cas9 has been used to develop drought-resistant rice varieties through editing of osmotic stress-responsive genes, salt-tolerant crops by targeting susceptibility genes such as OsDSG1 and OsbHLH024 in rice, and UV-tolerant varieties through modification of the OsCOP1 gene (Hu et al., 2024; Alam et al., 2022; & Ly et al., 2024). For biotic stress resistance, CRISPR technology has enabled the development of crops resistant to viral, bacterial, and parasitic threats. Editing the LGS1 gene in sorghum conferred resistance to the parasitic weed Striga by disrupting strigolactone production essential for parasite seed germination (Makaza et al., 2023).

Nutritional enhancement through CRISPR-mediated biofortification represents another transformative application. Researchers have increased pro-vitamin A content in rice and maize through targeted editing of PSY1, CrtI, and LCYB genes, creating “Golden Maize” varieties that address vitamin A deficiency (Sobrino-Mengual et al., 2024). In soybeans, CRISPR editing of the GmIPK1 gene has reduced phytic acid content, thereby enhancing the bioavailability of iron and zinc (Song et al., 2022). Furthermore, novel Cas proteins such as LrCas9 from Lactobacillus rhamnosus have demonstrated improved editing efficiency across multiple crop species including rice, wheat, and tomato (Innovative Genomics Institute, 2024).

6. Nanotechnology Applications in Crop Production

Nanotechnology has emerged as a promising interdisciplinary approach to address challenges in crop production, including nutrient management, pest control, and stress mitigation (Usman et al., 2021). The unique physicochemical properties of nanomaterials, such as their high specific surface area and excellent biocompatibility, make them effective carriers for agrochemicals with enhanced efficacy and controlled release characteristics (Shang et al., 2019).

Nanofertilizers have demonstrated substantial improvements in nutrient use efficiency. Field trials have shown that nanohybrids of urea and hydroxyapatite increase agronomic nitrogen use efficiency by approximately 30% compared to conventional urea applications (Usman et al., 2021). Loading nitrogen, phosphorus, and potassium into chitosan nanoparticles has been shown to increase their acquisition by 17.04%, 16.31%, and 67.50%, respectively, in coffee plants (Usman et al., 2021). The application of carbon nanoparticles combined with fertilizers has increased grain yields by 10.29% in rice, 10.93% in spring maize, 16.74% in soybean, and 28.81% in winter wheat (Shang et al., 2019).

Nanosensors represent another critical application, enabling real-time monitoring of soil conditions, nutrient levels, plant hormone concentrations, and disease presence at the molecular level (Usman et al., 2021). Additionally, nano-enabled delivery systems for CRISPR/Cas components, such as cationic arginine gold nanoparticles, have achieved approximately 30% gene editing efficiency in plant cells, facilitating future crop improvement research (Shang et al., 2019).

7. Climate-Smart Agriculture

Climate-smart agriculture (CSA) has gained significant global attention as a holistic approach that simultaneously addresses three critical objectives: increasing agricultural productivity, enhancing resilience to climate change, and reducing greenhouse gas emissions (World Bank, 2024). The framework integrates diverse practices and technologies tailored to specific agro-ecological and socio-economic contexts.

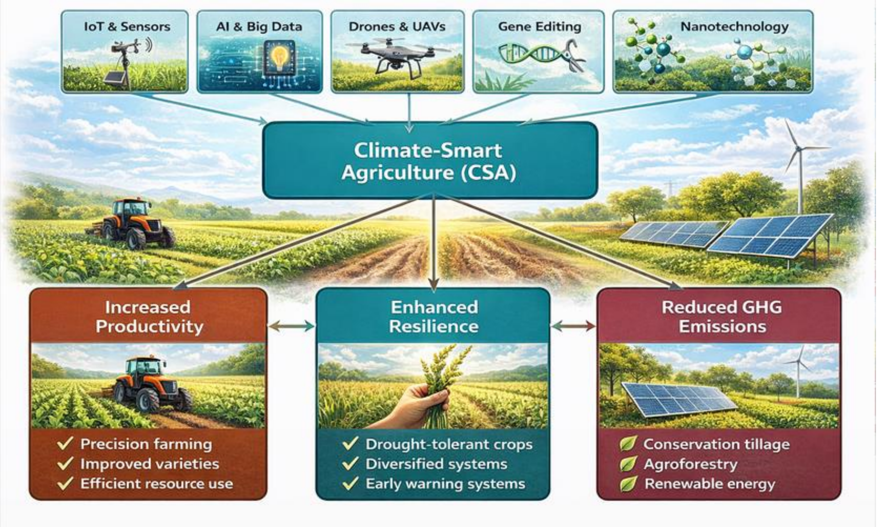

Figure 4: Framework of Climate-Smart Agriculture (CSA) Showing the Three Pillars and Enabling Technologies

Conservation agriculture practices, including minimal tillage, crop rotation, and cover cropping, form the foundation of CSA by improving soil health, enhancing carbon sequestration, and reducing erosion (Earth.Org, 2025). Agroforestry, which integrates trees alongside crops, plays a crucial role in carbon storage and biodiversity conservation. In Kenya, the adoption of CSA practices under the Kenya Climate-Smart Agriculture Strategy (2017–2026) has resulted in a 20% increase in crop yields, a 15% reduction in greenhouse gas emissions, and the training of more than 500,000 farmers in CSA techniques (Alliance Bioversity-CIAT, 2024).

The World Bank has significantly scaled up its investment in CSA, increasing financing by eight times since the adoption of the Paris Agreement to nearly USD 3 billion annually (World Bank, 2024). Precision irrigation systems in drought-prone regions such as California have demonstrated water savings of up to 33% while maintaining optimal crop yields, illustrating the potential of technology-driven CSA approaches (Earth.Org, 2025).

8. Future Prospects and Emerging Technologies

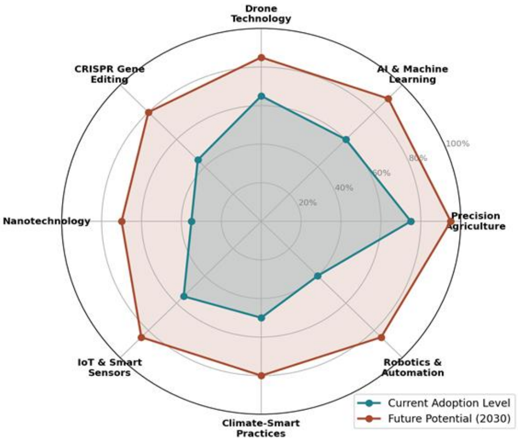

Figure 2: Key Technologies in Modern Agronomy – Current Adoption Levels vs. Future Potential (2030)

8.1 Autonomous Robotics and Automation

The global agricultural robots market is projected to grow from USD 10.18 billion in 2025 to USD 28.20 billion by 2030, at a CAGR of 22.60% (Yahoo Finance, 2025). Autonomous robotic platforms such as Solinftec's Solix are equipped with solar panels, AI, and IoT capabilities, performing tasks including plant health analysis, weed detection, and nutritional assessment autonomously around the clock (Kadence International, 2025). The 2025 Crop Robotics Landscape reveals continued traction in row-crop autonomy, with weeding and spraying robotics emerging as the most active areas for both venture investment and commercial deployment (Mixing Bowl Hub, 2025).

8.2 Digital Twins and Smart Farming

Digital twin technology, which creates virtual replicas of physical farming systems for real-time simulation and optimization, represents a frontier in precision agriculture (Awais et al., 2025). By integrating IoT sensor data, drone imagery, weather models, and crop growth simulations, digital twins enable predictive management of irrigation, fertilization, and pest control with unprecedented accuracy. Autonomous greenhouse systems have demonstrated yield increases of 12–20% and energy reductions of 15–20% compared to human-managed systems (Produce Grower, 2026).

8.3 Vertical Farming and Controlled Environment Agriculture

Vertical farming and controlled environment agriculture (CEA) offer year-round crop production in urban settings with minimal land and water use (Robovision, 2025). AI-automated CEA systems, showcased extensively at CES 2025, enable localized food production that reduces transportation emissions while eliminating the need for pesticides and herbicides. Hybrid vertical farms combining the best aspects of vertical and greenhouse production are emerging as the most economically viable model for 2026 and beyond (Eden Green, 2026).

8.4 Synthetic Biology and Advanced Breeding

The integration of CRISPR technology with synthetic biology and machine learning is expected to yield transformative advances in crop development. Future research directions include developing synthetic promoters for efficient editing in polyploid crops, combining CRISPR with metabolic engineering to produce bioactive compounds, and creating machine learning algorithms capable of optimizing multi-gene trait modifications for complex polygenic characteristics (Frontiers in Plant Science, 2024). The agricultural biotechnology sector is projected to grow at a CAGR of approximately 9% through 2029, driven by the convergence of AI and biotechnological innovation (Robovision, 2025).

CONCLUSION

The field of agronomy is undergoing a transformative evolution, driven by the convergence of digital technologies, biotechnological innovations, and sustainable farming paradigms. This comprehensive review has highlighted the remarkable advancements across multiple domains including precision agriculture, artificial intelligence, drone technology, CRISPR genome editing, nanotechnology, and climate-smart agriculture.

Precision agriculture, supported by IoT sensors and AI analytics, has demonstrated significant potential in optimizing resource use and improving crop yields, with the global market projected to exceed USD 24 billion by 2030. AI and machine learning applications have achieved remarkable accuracy in disease detection (up to 95%), weed identification, and yield prediction, while reducing chemical inputs by up to 90% through precision spraying technologies. The rapid expansion of agricultural drones, growing from 1,000 to 5,500 registered units in the United States within 18 months, underscores the accelerating adoption of aerial monitoring technologies.

CRISPR/Cas9 genome editing has opened unprecedented possibilities for developing climate-resilient, nutritionally enhanced, and higher-yielding crop varieties without introducing foreign DNA. Nanotechnology applications in nanofertilizers and nanopesticides have shown improvements of 17–68% in nutrient acquisition efficiency, while climate-smart agriculture frameworks have delivered measurable impacts including 20% yield increases and 15% emission reductions in implementation regions.

Looking ahead, the integration of autonomous robotics, digital twins, vertical farming, and synthetic biology will further reshape agronomic practices. However, the successful translation of these technologies from research to widespread field adoption requires addressing critical challenges including high implementation costs, digital divide in rural areas, regulatory frameworks for genome-edited crops, data privacy concerns, and the need for farmer training and capacity building. Interdisciplinary collaboration among researchers, technologists, policymakers, and farming communities will be essential to realize the full potential of modern agronomy in achieving global food security and environmental sustainability.

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