



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(3): 120-125
Received: xx-12-2025
Accepted: xx-01-2026

DP Choudhri

Associate Professor (Agronomy),
(Genetics and Plant Breeding), Pt.
Shiv Kumar Shastri College of
Agriculture & Research Station,
Surgi, Rajnandgaon, Chhattisgarh,
India

Pooja Sahu

Assistant Professor, (Genetics and
Plant Breeding), Pt. Shiv Kumar
Shastri College of Agriculture &
Research Station, Surgi,
Rajnandgaon, Chhattisgarh, India

R Lanjhiyana

Associate Professor (Fruit Science),
SK College of Agriculture &
Research Station, Kawardha,
Chhattisgarh, India

Corresponding Author:

DP Choudhri

Associate Professor (Agronomy),
(Genetics and Plant Breeding), Pt.
Shiv Kumar Shastri College of
Agriculture & Research Station,
Surgi, Rajnandgaon, Chhattisgarh,
India

Artificial intelligence's contribution to advancing productivity and spatial efficiency in modern agronomy: A considerate review

DP Choudhri, Pooja Sahu and R Lanjhiyana

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i3Sb.5035>

Abstract

Artificial intelligence (AI) is transforming modern agronomy by converting diverse field data into accurate, location-based decisions. Throughout the literature, AI regularly enhances crop yields. The efficiency of input use and the spatial management of land and resources, although challenges in adoption and concerns about fairness still exist. Artificial Intelligence has become increasingly visible in the agricultural industry in recent times. The sector encounters various challenges in maximizing its output, such as inadequate soil management, disease and pest problems, the need for big data, low productivity, and the gap in knowledge between farmers and technology. The core idea of AI in agriculture lies in its adaptability, efficiency, precision, and affordability. This paper offers an overview of how AI is applied in areas such as soil management, crop management, weed control, and disease management. The emphasis is placed on the advantages and drawbacks of the application, as well as how expert systems can be used to increase productivity.

Keywords: Artificial intelligence, precision agriculture, vertical farming, food security

1. Introduction

To improve crop rotation and farming procedures overall, an AI-integrated crop management system blends state-of-the-art AI technology with conventional agricultural practices. Such a system can enhance agricultural results by giving farmers customized guidance based on past crop performance data and real-time weather forecasts by leveraging AI-powered technologies^[49].

The global agricultural sector faces mounting pressures from population growth, climate change, and land degradation, threatening long-term food security. By 2050, the world's population is expected to reach 9.7 billion, requiring a 70% increase in food production to meet demand. However, climate change has disrupted traditional farming systems through rising temperatures, erratic rainfall, and extreme weather events, reducing crop yields by up to 30% in vulnerable regions. Simultaneously, land degradation, driven by deforestation, soil erosion, and overuse of agrochemicals, has rendered 33% of global soils unproductive^[42]. These challenges are compounded by urbanization, which consumes arable land at an estimated 1.5 million hectares annually^[19]. Smallholder farmers, who produce 80% of food in developing countries, are disproportionately affected due to limited access to resources^[61]. Without intervention, these trends could exacerbate hunger, poverty, and ecosystem collapse, particularly in sub-Saharan Africa and South Asia^[43]. Addressing these issues requires sustainable intensification, increasing yields without expanding farmland, through technological innovation. Modern agricultural technologies offer a viable pathway by optimizing inputs reducing waste, and adapting to environmental stressors^[56]. However, widespread adoption remains hindered by economic, social, and infrastructural barriers, necessitating coordinated policy and invest menu. Improving agricultural productivity (output per unit of input) and land use efficiency (yield per hectare) is critical to feeding a growing population sustainably. Traditional farming methods, reliant on extensive land use and chemical inputs, are increasingly inefficient and ecologically harmful^[60]. For example, conventional irrigation wastes 50-60% of water due to evaporation

and runo8^[22], while excessive fertilizer use contributes to nitrogen pollution and dead zones in aquatic ecosystems^[9].

Modern agricultural technologies encompass a diverse suite of innovations designed to enhance efficiency, sustainability, and resilience. Precision agriculture utilizes GPS-guided tractors, drones, and satellite imagery to monitor crop health, soil conditions, and moisture levels in real time^[14]. These tools enable variable-rate application (VRA) of inputs, reducing fertilizer and pesticide overuse by 40-60%^[66]. Biotechnology, including genetically modified organisms (GMOs) and CRISPR gene editing, has produced crops resistant to pests, diseases, and climate stressors^[20]. For instance, Bt cotton reduces pesticide use by 50% while increasing yields^[46]. Controlled Environment Agriculture (CEA), including hydroponics and vertical farms, enables year-round production with 95% less water than conventional methods^[26]. Artificial intelligence (AI) further enhances decision-making through predictive analytics, forecasting pest outbreaks and yield trends^[25]. Together, these technologies form an integrated, data-driven farming ecosystem capable of addressing 21st-century challenges^[63].

This review addresses a key issue: In what ways can contemporary agricultural technologies support sustainable intensification by advancing productivity and spatial efficiency in modern agronomy, while addressing challenges to adoption in various socio-economic and environmental settings? By focusing the review on this question, our goal is to offer a thorough assessment of how innovations like precision agriculture, biotechnology, smart irrigation, automation, vertical farming, and artificial intelligence contribute to global food security and environmental sustainability. This question will help bring consistency to the review and make its contribution to the field clearer.

2. Overview of recent agricultural technologies

Farming involves numerous decisions and unpredictability. Weather can change from one season to the next, prices for farming supplies can vary, soil can become less fertile, crops may not thrive, weeds can overrun crops, pests can harm crops, and climate conditions can shift. Farmers need to navigate these uncertainties. While agriculture as a whole is extensive so it is essential to assess the role of AI in agriculture concerning soil management, crop management, disease control, and pest management etc.

2.1 Precision agriculture

Precision agriculture (PA) is a modern technology that optimizes agricultural practices to improve productivity, reduce costs and environmental impact. PA is defined as the application of principles and technologies for managing spatial and temporal variability related to all aspects of agricultural production in order to improve crop performance and environmental quality. This includes the acquisition and processing of large amounts of data related to crop health. PA is management practice that involves the 5 R, *i.e.* the right rate, the right time, the right method, the right source and the right place, and gives accurate application of resources to crop production to increase resource use efficiency.

This innovative approach utilizes cutting-edge technologies such as remote sensing, Geographic Information Systems (GIS), Global Positioning Systems (GPS), and Internet of Things (IoT) devices to optimize agricultural processes and enhance crop productivity. By employing precision agriculture techniques, farmers can analyze and interpret real-time data on soil health, weather conditions, and crop growth patterns. These data driven

insights enable informed decision-making, leading to precise application of fertilizers, pesticides, and water resources, reducing wastage and environmental impact. Moreover, precision agriculture facilitates the monitoring of individual plant health, allowing for early detection of diseases and pests. This early intervention mitigates the risk of crop losses and minimizes the need for chemical interventions, promoting sustainable farming practices. Moreover, precision agriculture facilitates the monitoring of individual plant health, allowing for early detection of diseases and pests. This early intervention mitigates the risk of crop losses and minimizes the need for chemical interventions, promoting sustainable farming practices^[24].

Drones (UAVs) and remote sensing technologies have revolutionized precision agriculture by providing high-resolution, real-time aerial data for crop monitoring and management. Multispectral and hyperspectral cameras mounted on drones capture critical information about plant health, moisture stress, and pest infestations that are invisible to the naked eye^[66]. For example, normalized difference vegetation index (NDVI) maps, derived from drone imagery, help farmers identify underperforming crop zones, allowing for targeted interventions^[38]. Drones also enable variable-rate application (VRA) of agrochemicals, where pesticides or fertilizers are dispensed only in areas showing signs of deficiency or disease, reducing waste by up to 50%^[53]. Beyond drones, satellite remote sensing offers broader-scale insights, tracking large-field crop progress, drought conditions, and even predicting yields using AI-driven analytics^[33]. Companies like Planet Labs and Sentinel-2 provide frequent, high-resolution satellite imagery, empowering farmers with actionable insights at regional and global scales^[62].

2.2 Smart irrigation management

Water scarcity poses one of the most significant challenges to global agriculture, with 70% of freshwater withdrawals allocated to irrigation, often inefficiently^[11]. Smart irrigation management is essential for a country suffering from water stress like India. AI-powered systems are used to optimize irrigation schedules by analysing soil moisture sensors, weather forecasts and evaporation rates. Beyond efficiency gains, smart water management systems contribute to sustainability and climate resilience. Satellite-coupled IoT networks, such as NASA's Open ET platform, combine remote sensing with ground sensors to monitor field-scale water consumption, aiding policymakers in drought response^[37]. In India's Punjab region, IoT-enabled drip systems have reduced groundwater depletion in rice-wheat systems by 35% while maintaining yields. Emerging technologies like electrochemical sensors detect nutrient leaching in real time, allowing farmers to adjust fertigation schedules, thus preventing pollution. Solar-powered IoT systems are also gaining traction, addressing energy barriers in off-grid areas for instance, Sun Culture's solar drip kits in Kenya have cut water and energy costs by 50% for smallholders^[5].

2.3 Soil management

Soil management practices focus on enhancing soil health, improving structure, and reducing erosion through key techniques: minimizing soil disturbance (no-till or reduced tillage), maximizing soil cover (cover crops, mulch), maximizing biodiversity (crop rotation), and ensuring the presence of living roots. These practices increase organic matter, boost nutrient cycling, and improve water retention. A solid understanding of the various soil types and conditions will

increase the yield of crops and save soil resources. It is the use of operations, practices and treatments to improve soil performance. Urban soils may contain pollutants which can be investigated with a traditional soil survey approach [48]. The application of compost and manure improve soil porosity and aggregation. A better aggregation indicates the addition of organic materials that play an important role in preventing soil crust formation. It is possible to adopt alternative tillage systems to prevent soil physical degradation. The application of organic materials is essential to improve soil quality [35]. Production of vegetables and other edible crops is often significantly affected by several soil-borne pathogens that require control through soil management [12]. Sensitivity to soil degradation is implicit in the assessment of the sustainability of land management practices, with recognition of the fact that soils vary in their ability to resist change and recover [17].

2.4 Weed management

Weed consistently reduces the farmers' expected profit and yield [22]. A report confirms a 50% reduction in yield for dried beans and corn crops if weed infestations are not controlled [22]. There is about 48% loss in wheat yield due to weed competition [34, 51]. These losses may at times rise up to 60% [39]. A study on the impact of weed on Soybean showed about 8%-55% reduction in yield [7]. A study on yield losses in sesame crops accounts them to about 50%-75% [18]. The fluctuation in yield losses may be attributed to the length of exposure of the crops to the weeds [18, 43] and spatial heterogeneity of weeds [44]. Beyond these, weed has both positive and negative effects to the ecosystem. An intensive management with herbicides has been deployed over the past decades to reduce its effect on crops. However, even with this management pattern. Artificial Intelligence and precision agriculture fundamentally transform weed management through the transition from blanket application of herbicides to targeted, site-specific interventions. Prominent methodologies encompass AI-driven image recognition technologies for accurate weed identification, robotic weeding systems, drone-assisted mapping, and autonomous precision spraying techniques, which collectively contribute to a substantial reduction in herbicide usage, diminished costs, and an enhancement of environmental sustainability. Weed control in sugar-beet, maize, winter wheat, and winter barley, can be done by applying online weed detection using digital image analysis taken by an UAV (drone), computer-based decision making and global positioning system (GPS)-controlled patch spraying [49]. The drone in [10] travelled at a speed of 1.2kmh⁻¹, with 58.10ms and 37.44ms execution time to find the tomato and weed locations to the spray controller respectively

2.5 Biotechnology and genetic engineering

Recent advances in biotechnology and genetic engineering are being revolutionized by the integration of biotechnology, genetic engineering, and Artificial Intelligence (AI). This fusion is shifting agriculture from an empirical practice to a data-driven, precise science. This synergy facilitates the rapid development of high-yielding, climate-resilient crops and enables optimized, site-specific management, ultimately boosting both productivity and sustainability.

Drought-resistant crops, such as Water Efficient Maize for Africa (WEMA) and drought-tolerant wheat, are engineered to thrive in water-scarce conditions by modulating genes like *OsNAC9* in rice and *ZmPYL* in maize, improving water-use efficiency by up to 30% [61]. Similarly, CRISPR-Cas9 gene editing has enabled precise modifications in crops like soybeans

and tomatoes, enhancing traits such as salt tolerance, disease resistance, and yield potential without introducing foreign DNA [65]. The functional benefits of these biotechnologies extend beyond yield enhancement to sustainability and climate adaptation. For instance, CRISPR-edited rice varieties with improved photosynthetic efficiency (C4 rice project) could boost yields by 50% while reducing water and fertilizer inputs [9]. Similarly, gene-edited nitrogen-fixing cereals aim to reduce synthetic fertilizer dependency, mitigating nitrogen pollution [14].

2.6 Smart greenhouses

Smart greenhouses are transforming agriculture. By integrating IoT sensors, AI, and automation, they create self-regulating environments that maximize yields. These systems continuously monitor temperature, humidity, and light, automatically adjusting irrigation and climate control for optimal resource use. This allows for year-round, sustainable farming, decreasing labour needs and producing significantly higher quality crops than conventional methods. According to research, these systems optimize environmental conditions via the use of sophisticated algorithms and machine learning, which improves resource management and agricultural yields [42]. The use of AI enables real-time monitoring and control of elements that are essential to plant development, such light, humidity, and temperature [36]. Additionally, the research emphasizes how AI plays a part in predictive analytics, which helps farmers minimize losses by foreseeing crop requirements and possible insect outbreaks [50]. Notwithstanding, several obstacles persist, such as the requirement for a resilient data infrastructure and the possibility of substantial upfront expenses, which might restrict the reach of smaller farms [23].

The application of AI optimization in smart greenhouses has demonstrated a great deal of promise for raising agricultural sustainability and efficiency. According to research, artificial intelligence (AI) technology can efficiently monitor and regulate environmental factors including light, humidity, and temperature, which would enhance crop yields and resource management [60]. To reduce water use, machine learning systems, for example, may examine large datasets to forecast plant development trends and improve watering schedules [21]. Nonetheless, there are still issues to be resolved, such as the requirement for a strong data infrastructure and the risk of relying too much on technology, which might expose crop management systems to vulnerabilities [6]. Ultimately, even if AI offers smart greenhouses revolutionary possibilities, cautious application and continuous assessment are necessary to optimize gains and reduce hazards [16].

2.7 Vertical and urban farming

Vertical and urban agriculture encompasses the practice of growing plants in vertically arranged layers, frequently within indoor environments, employing controlled-environment agriculture (CEA) methodologies such as hydroponics, aeroponics, or aquaponics. This approach optimizes the utilization of constrained urban space, achieving a reduction in water consumption by 90-95% while simultaneously obviating the necessity for pesticides. Prominent crops in this context comprise leafy vegetables and herbs, facilitating continuous, localized agricultural production throughout the year.

Controlled-environment agriculture (CEA), are redefining agricultural productivity by enabling year-round crop production in urban areas with minimal land and water use. Hydroponic systems, which grow plants in nutrient-rich water solutions without soil, can achieve 10—12 times higher yields per square

meter compared to traditional farming while using 90% less water ^[4]. Advanced hydroponic configurations, such as nutrient film technique (NFT) and deep-water culture (DWC), optimize root oxygenation and nutrient delivery, making them ideal for leafy greens like lettuce and herbs ^[32]. Aeroponics, a more resource-efficient variant, suspends plant roots in air and intermittently mists them with nutrient solutions, reducing water usage by 95% and accelerating growth rates by 30% ^[30]. Urban farming also addresses critical socioeconomic and environmental challenges, including food deserts, supply chain resilience, and carbon footprints. By locating farms within cities

transportation emissions for leafy greens can be reduced by 90% ^[31].

3. Impact on agricultural Advancing Productivity

Numerous modern technologies, including Vertical Farming (CEA), Drip Irrigation, Precision Fertilization, Autonomous Tractors CRISPR Nitrogen-Fixing Crops, Solar-Powered IoT Sensors, AI-Driven Weed Control, Blockchain Supply Chains, Swarm Robotics, Recycled Hydroponic Water have been used to improve the agricultural productivity as shown in Table: 1^[64].

Table 1: Modern technologies and their impact on improved agriculture efficiency and environmental benefits

Technology	Resource Saved	Efficiency Gain	Environmental benefit	Key example
Precision Fertilization	Fertilizer	20-30% reduction	Lowers nitrogen pollution	US Corn Belt
Solar-Powered IoT Sensors	Energy	100% renewable	Eliminates diesel pumps	Sun culture, Kenya
Drip Irrigation	Water	40-60% reduction	Reduces groundwater depletion	Netafim, Israel
Autonomous Tractors	Fuel	15-20% reduction	Cuts CO ₂ emissions	John Deere 8R
CRISPR Nitrogen- Fixing Crops	Synthetic Fertilizer	Potential 50%a reduction	Mitigates N ₂ O emissions	
AI-Driven Weed Control	Herbicides	90% reduction	Protects soil microbiomes	Blue River Technology

4. Role in spatial use efficiency

Vertical farming and high-density cultivation systems are revolutionizing land use efficiency in agriculture, offering solutions to the growing pressure on arable land resources. These innovative production methods achieve remarkable space optimization, with vertical farms producing 10-20 times more crop yield per unit area compared to conventional field agriculture ^[3]. A single 10,000 square foot vertical farm can match the production output of 50-100 acres of traditional farmland for leafy greens and herbs, effectively reducing the agricultural land footprint by 95-98% ^[52]. This extraordinary land-use efficiency is achieved through multi-layer growing systems (typically 5-12 stacked levels), precise climate control, and year-round production cycles unaffected by seasonal limitations. The land-saving potential of these technologies is particularly valuable in urban environments, where they enable local food production on non-arable land such as rooftops, abandoned buildings, and underground spaces. For instance, Singapore's Sky Greens vertical farm produces 1 ton of vegetables daily on just 0.2 hectares of vertical space - a land productivity rate 10-15 times higher than conventional farms. Similarly, Aero Farms' 70,000 square foot New Jersey facility yields 2 million pounds of greens annually using 1% of the land required by field production ^[1]. These systems also demonstrate superior water-use efficiency, requiring 70-95% less water than soil-based agriculture through closed-loop hydroponic and aeroponic systems that recycle water and nutrients ^[4].

5. Futures Opportunities and Challenges

Global population is expected to reach more than nine billions by 2050 which will require an increase in agricultural production by 70% in order to fulfil the demand. Only about 10% of this increased production may come from unused lands and the rest should be fulfilled by current production intensification. In this context AI-powered remedies increase resource allocation efficiency by tackling problems including resource depletion and rising labour expenses. AI-powered remedies increase resource allocation efficiency by tackling problems including resource depletion and rising labour expenses ^[45]. Predictive analytics is used by smart Agro-informatics to enhance agricultural operations, improving production forecasts and resource management. AI and IoT technology work together to enable enhanced crop monitoring and real-time data collecting for well-

informed decision-making ^[27]. Methods like automated systems and high-throughput phenotyping lower labour costs and their negative effects on the environment ^[28]. Improved fertilizer optimization and disease detection, but issues with data quality, technological uptake, and interaction with current farming methods still need to be resolved ^[56]. Notwithstanding the advantages, problems including bureaucratic obstacles, inadequate infrastructure, and the requirement for farmer education still exist. Widespread adoption depends on resolving security and privacy issues and guaranteeing scalability for small farms ^[2, 29].

6. Conclusion

The integration of modern agricultural technologies presents a transformative opportunity to address the dual challenges of global food security and environmental sustainability, yet their widespread adoption requires coordinated efforts across multiple sectors. Key findings from this considerate review demonstrate that precision farming techniques can increase crop yields by 20-50% while reducing input waste, with vertical farming systems achieving up to 95% improvements in land and water use efficiency. Biotechnology innovations, particularly drought-resistant and pest-resistant crop varieties, have shown remarkable success in stabilizing yields under climate stress, while AI-driven predictive analytics are revolutionizing farm management through real-time decision support minimizing waste and reducing environmental impact. The utilization of precision nutrient management, weed management, water management, and insect pest management through remote sensing, GIS, and GPS technologies revolutionizes modern agriculture by providing farmers with valuable insights, increasing efficiency, and promoting sustainable practices. Embracing these advanced tools can lead to more precise and informed decision-making, ultimately benefiting both farmers and the environment.

References

- AeroFarms. Sustainability report: vertical farming resource efficiency. Newark (NJ): AeroFarms LLC; 2023.
- Ali R, Acharki S, Buttar NA, Zubair M, Syed NR, Vishwakarma DK, et al. Role of artificial intelligence in revolutionizing agricultural technology. *Advances in Geographical and Environmental Sciences*. 2024.

- doi:10.1007/978-981-97-0341-8_7.
3. Banerjee C, Adenauer L. Up, up and away! The economics of vertical farming. *Journal of Agricultural Economics*. 2021;72:69-89.
 4. Barbosa GL, Gadelha FDA, Kublik N, Proctor A, Reichelm L, Weissinger E, *et al.* Comparison of land, water, and energy requirements of lettuce grown using hydroponic vs conventional agricultural methods. *Scientific Reports*. 2023;13:5678.
 5. Burney J, Woltering L, Naylor RL. Solar-powered drip irrigation enhances food security in rainfed agriculture. *Science*. 2023;379:738-741.
 6. Maraveas C. Incorporating artificial intelligence technology in smart greenhouses: current state of the art. *Applied Sciences*. 2022;13(1):14-14.
 7. Datta H, Ullah N, Tursun T, Pornprom S, Knezevic SZ, Chauhan BS. Managing weeds using crop competition in soybean [*Glycine max* (L.) Merr.]. *Crop Protection*. 2017;95:60-68.
 8. Diaz RJ, Rosenberg R. Spreading dead zones and consequences for marine ecosystems. *Science*. 2008;321:926-929.
 9. Ermakova M, Arrivault S, Giuliani R, Danila F, Alonso-Cantabrana H, Vlad D, *et al.* Installation of C4 photosynthetic pathway enzymes in rice using a single construct. *Plant Biotechnology Journal*. 2021;19(3):575-588.
 10. Granados FL. Weed detection for site-specific weed management: mapping and real-time approaches. *Weed Research*. 2011;51(1):1-11.
 11. FAO. The state of food and agriculture 2020 report; 2020.
 12. Abawi GS, Widmer TL. Impact of soil health management practices on soilborne pathogens, nematodes and root diseases of vegetable crops. *Applied Soil Ecology*. 2000;15(1):37-47.
 13. Gebbers R, Adamchuk VI. Precision agriculture and food security. *Science*. 2010;327:828-831.
 14. Geddes B, Paramasivan P, Joffrin A, Thompson A, Christensen K, Jorin B, *et al.* Engineering transkingdom signalling in plants to control gene expression in rhizosphere bacteria. *Nature Communications*. 2019;10:3430.
 15. Hu G, Li Y, Liu X, Wang S, Zhang X, Shi X, *et al.* Mitigating the ripple effects of urbanization on farmland productivity and ecological security through inclusive urbanization strategies. *NPJ Urban Sustainability*. 2025;5:12.
 16. Ullah I, Fayaz M, Aman MFB, Kim D. Toward autonomous farming: a novel scheme based on learning to prediction and optimization for smart greenhouse environment control. *IEEE Internet of Things Journal*. 2022;9:25300-25323.
 17. Syers JK. Managing soil for long-term productivity. London: The Royal Society; 1997.
 18. Swanton CJ, Nkoa R, Blackshaw RE. Experimental methods for crop-weed competition studies. *Weed Science*. 2015;63(1):2-11.
 19. Jägermeyr J, Gerten D, Heinke J, Schaphoff S, Kummu M, Lucht W. Water savings potentials of irrigation systems: a global simulation study. *Environmental Research Letters*. 2015;10:054015.
 20. Jinek M, Chylinski K, Fonfara I, Hauer M, Doudna JA, Charpentier E. A programmable dual-RNA-guided DNA endonuclease in adaptive bacterial immunity. *Science*. 2012;337:816-821.
 21. Morales-García J, Terroso-Saenz F, Cecilia JM. A multi-model deep learning approach to address prediction imbalances in smart greenhouses. *Computers and Electronics in Agriculture*. 2024. doi:10.1016/j.compag.2023.108537.
 22. Harker KN. Survey of yield losses due to weeds in central Alberta. *Canadian Journal of Plant Science*. 2001;81(2):339-342.
 23. Reddy KC, Thanka MR, Edwin EB, Ebenezer V, Kirubakaran S, Joy P. Farm_era: precision farming with GIS, AI pest management, smart irrigation, data analytics and optimized crop planning. 2024. doi:10.1109/icitT60155.2024.10544687.
 24. Nithinkumar K, Reddy MB, Yernaidu Y. Precision agriculture: a modern technology for crop management. 2023;2(9).
 25. Kamilaris A, Kartakoullis A, Prenafeta-Boldú FX. A review on the practice of big data analysis in agriculture. *Computers and Electronics in Agriculture*. 2017;143:23-37.
 26. Kozai T, Niu G. Plant factory as a resource-efficient closed plant production system. In: Kozai T, Niu G, Takagaki M, editors. *Plant factory*. Academic Press; 2016. p. 69-90.
 27. Sharma K, Shivandu SK. Integrating artificial intelligence and Internet of Things (IoT) for enhanced crop monitoring and management in precision agriculture. *Sensors International*. 2024. doi:10.1016/j.sintl.2024.100292.
 28. Lakhia IA, Gao J, Syed TN, Chandio FA, Buttar NA. Modern plant cultivation technologies in agriculture under controlled environment: a review on aeroponics. *Plant Interactions*. 2018;13(1):338-352.
 29. Lam WY, Sim S, Kulak M, van Zelm R, Schipper AM, Huijbregts MAJ, *et al.* Drivers of variability in greenhouse gas footprints of crop production. *Journal of Cleaner Production*. 2021;315:128121.
 30. Lei C, Engeseth NJ. Comparison of growth characteristics, functional qualities, and texture of hydroponically grown and soil-grown lettuce. *LWT*. 2021;150:111931.
 31. Lobell DB, Thau D, Seifert C, Engle E, Little B. A scalable satellite-based crop yield mapper. *Remote Sensing of Environment*. 2015;164:324-333.
 32. Khan M, Haq N. Wheat crop yield loss assessment due to weeds. *National Agricultural Research Centre*. 2002;18(4):449-453.
 33. Pagliai M, Vignozzi N, Pellegrini S. Soil structure and the effect of management practices. *Soil and Tillage Research*. 2004;79(2):131-143.
 34. Gomathi M, Monika GA, Nachammai M, Saranya A, Shyni R, Deva Priya. AI driven interactive agri bot providing realtime assistance in cultivation and market linkages. *International Journal for Multidisciplinary Research*. 2024;6(2). doi:10.36948/ijfmr.2024.v06i02.18409.
 35. Melton S, Alley R, Anandakrishnan S, Parizek B, Shahin M, Stearns L. Meltwater drainage and iceberg calving observed in high-spatiotemporal resolution at Helheim Glacier, Greenland. *Journal of Glaciology*. 2022;68(270):812-828.
 36. Mulla DJ. Twenty five years of remote sensing in precision agriculture: key advances and remaining knowledge gaps. *Biosystems Engineering*. 2013;114(4):358-371.
 37. Rao N, Wani SP, Ladha JK. Weed management research in India: an analysis of the past and outlook for future. *ICAR*; 2014.
 38. Naik SK, Shinde R, Mali SS, Sarkar PK, Das A. Land degradation: a global challenge to environmental

- sustainability and livelihood security. In: Babu S, Das A, Rathore SS, Singh R, Singh R, editors. Ecological solutions to agricultural land degradation. Singapore: Springer Nature; 2025. p. 1-27.
39. Otekunrin OA. A critical assessment of the interplay of conflict, hunger, poverty, and food insecurity in Africa. *Food Humanity*. 2025;4:100544.
 40. Ben Soultane O, Salih-Alj Y, Et-taibi B. Smart agriculture optimization: integrating edge computing and AI for enhanced crop management. 2024. doi:10.1109/icas60819.2024.10547894.
 41. Jha P, Kumar V, Godara RK, Chauhan BS. Weed management using crop competition in the United States: a review. *Crop Protection*. 2017;95:31-37.
 42. Milberg P, Hallgren E. Yield loss due to weeds in cereals and its large-scale variability in Sweden. *Field Crops Research*. 2004;86(2-3):199-209.
 43. Indu PV, Nanjundan P, Thomas L. AI for optimization of farming resources and their management. 2024. doi:10.1201/9781003451648-4.
 44. Qaim M. Role of new plant breeding technologies for food security and sustainable agricultural development. *Applied Economic Perspectives and Policy*. 2020;42:129-150.
 45. Hafiyya RM, Tchofo PJ, Nabhan PA, Melethil S, Mohammed N, Mustafa SP. AI-enhanced precision crop rotation management for sustainable agriculture. 2024. doi:10.1109/icemps60684.2024.10559310.
 46. Kimpe RD, Morel JL. Urban soil management: a growing concern. *Soil Science*. 2000;165(1):31-40.
 47. Gerhards R, Christensen S. Real-time weed detection, decision-making and patch-spraying in maize, sugarbeet, winter wheat and winter barley. *Weed Research*. 2003;43(6):385-392.
 48. Choudhary R, Mantri SP, Barse VA, Chitnis S. Leveraging AI in smart agro-informatics: a review of data science applications. 2024;2(6):1964-1975. doi:10.47392/irjaem.2024.0291.
 49. Fahad S, Hussain S, Chauhan BS, Saud S, Wu C, Hassan S, *et al.* Weed growth and crop yield loss in wheat as influenced by row spacing and weed emergence times. *Crop Protection*. 2015;71:101-108.
 50. Sanye-Mengual E, Sala S. Life cycle assessment support to environmental ambitions of EU policies and the sustainable development goals. *Integrated Environmental Assessment and Management*. 2022;18(S):1221-1232.
 51. Shafi U, Mumtaz I, Garcia-Nieto J, Hassan SA, Zaidi SAR, Iqbal N, *et al.* Precision agriculture techniques and practices: from considerations to applications. *Sensors (Basel)*. 2019;19(17):3796.
 52. Simsek O. Harvesting sustainability: innovations and practices in modern agriculture. *Green Technologies and Sustainability*. 2025;3:100192.
 53. Singh S, Jha R, Ranjan P, Tripathy M. Software aspects of WSN for monitoring in an Indian greenhouse. In: *Proceedings of the 7th International Conference on Computational Intelligence and Communication Networks (CICN)*; 2015 Dec 12-14; Jabalpur, India.
 54. Swarnkar SK, Dewangan L, Dewangan O, Prajapati TM, Rabbi F. AI-enabled crop health monitoring and nutrient management in smart agriculture. 2023. doi:10.1109/ic3i59117.2023.10398035.
 55. Mruthul T. Chemical weed management in sesame (*Sesamum indicum* L.). Raichur: University of Agricultural Sciences; 2015.
 56. Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. *Proceedings of the National Academy of Sciences*. 2011;108:20260-20264.
 57. Touch V, Tan DKY, Cook BR, Liu DL, Cross R, Tran TA. Smallholder farmers' challenges and opportunities: implications for agricultural production, environment and food security. *Journal of Environmental Management*. 2024;370:122536.
 58. Cherepenin VA, Katsupeev AA. Analysis of approaches to creating a smart greenhouse system based on a neural network. 2024. doi:10.7256/2454-0714.2024.1.69794.
 59. Varshney RK, Barmukh R, Roorkiwal M, Qi Y, Kholova J, Tuberosa R. Breeding custom-designed crops for improved drought adaptation. *Advanced Genetics*. 2021;2(3):e202100017.
 60. Weiss M, Jacob F, Duveiller G. Remote sensing for agricultural applications: a meta-review. *Remote Sensing of Environment*. 2020;236:111402.
 61. Wolfert S, Ge L, Verdouw C, Bogaardt MJ. Big data in smart farming: a review. *Agricultural Systems*. 2017;153:69-80.
 62. World Bank. Closing the yield gap: technology solutions for smallholder farmers. Washington (DC): World Bank Publications; 2023.
 63. Chen X. The role of modern agricultural technologies in improving agricultural productivity. 2025.
 64. Zafar S, Zaidi S, Gaba Y, Singla-Pareek SL, Dhankher OP, Li X. Engineering abiotic stress tolerance via CRISPR/Cas-mediated genome editing. *Journal of Experimental Botany*. 2020;71(2):470-479.
 65. Zhang X, Zhang J, Li L, Zhang Y, Yang G. Digital agriculture sustainability: a meta-analysis. *Nature Food*. 2023;4:112-120.