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Artificial intelligence for sustainable agriculture: Transforming productivity and environmental stewardship

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Abstract

Artificial Intelligence (AI) is transforming agriculture by offering data-driven solutions to enhance productivity, conserve resources, and mitigate environmental challenges. Applications such as smart irrigation, precision agriculture, and climate risk prediction enable efficient resource use and informed decision-making, promoting sustainability. AI-powered solutions allow farmers to make data-driven decisions, predict and mitigate risks, and adopt sustainable practices. However, widespread AI adoption faces barriers, including limited infrastructure, technical expertise, and social acceptance, particularly in developing regions. This study highlights successful AI applications in agriculture, their role in reducing environmental impacts, and the need for collaborative frameworks to overcome adoption challenges. By integrating AI, agriculture can achieve sustainable development goals, balancing productivity with ecological preservation.

Keywords: Artificial intelligence, sustainable agriculture, precision agriculture, predictive analytics, resource optimization

Introduction

Sustainable development is a critical global agenda aimed at addressing climate change, environmental degradation, and resource sustainability (Vinuesa *et al*., 2020) [47]. Agriculture, a key sector underpinning food security and the global economy, is central to achieving these goals but faces significant challenges. These include increasing land productivity, efficient resource utilization, and mitigating negative environmental impacts such as greenhouse gas emissions and soil degradation (Gillespie and van den Bold, 2017) [13].

Artificial Intelligence (AI) brings transformative solutions to these challenges by introducing innovative approaches in sustainable agriculture (Alreshidi, 2019) [4]. AI-powered tools enable precise weather prediction, disease detection, and resource optimization. For instance, AI-based smart irrigation can save up to 30% of water while promoting crop yields (Wani *et al*., 2020) [48]. Nonetheless, the mass adoption of AI is hindered by some factors such as inadequate infrastructures, poor technical knowledge, and social resistance to the change (Dwivedi *et al*., 2021) [9].

In agriculture, AI is actually transforming traditional farming into better practices for sustainable development. Its precision agriculture approach utilizes all data from sensors, drones, and satellite imagery toward providing actionable insights on conditions of the soil, the health of crops, or even weather patterns (Lakshmi and Corbett, 2023) [25]. Hence, farmers can make decisions accordingly about irrigation, fertilization, or pest control, thus massively increasing productivity and minimizing loss of resources (Zhang *et al*., 2020) [50]. AI-based predictive analytics also help farmers predict climate change-related risks, such as droughts or floods, and prepare for them in advance and adapt accordingly (Gupta *et al*., 2021b) [16]. AI also helps optimize resource use. AI systems analyse soil moisture, nutrient levels, and crop water requirements and deliver water and nutrients with precision, reducing wastage and environmental impact (Jha *et al*., 2019) [18]. Advanced AI algorithms will help target pesticide application, reducing the chemical run-off and protection of biodiversity (Chlingaryan *et al*., 2018) [7].

This study investigates the dual role of AI in sustainable agriculture, including opportunities for innovation and barriers to adoption. The study uses case studies and expert insights to highlight successful implementations of AI and provide practical recommendations for stakeholders. For example, AI-based farming tools in developed countries have demonstrated strong environmental and economic benefits, while developing economies are exploring scalable AI solutions that fit local conditions (Jha *et al*., 2021) [19].

AI has significant potential to revolutionize agriculture, paving the way for a greener and more sustainable future. Through the integration of AI into these critical sectors, societies can address the dual challenges of resource efficiency and environmental sustainability, ensuring a balance between economic growth and ecological preservation (Singh *et al*., 2020) [42]. The continuous development of AI technology further highlights its capacity to transform industries and contribute meaningfully to global sustainable development goals (Vinuesa *et al*., 2020) [47].

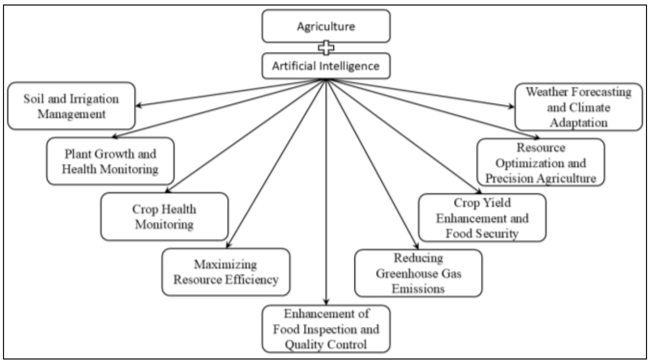

Fig 1: Schematic representation illustrating the role of AI in sustainable agriculture

1. Applications of AI in sustainable agriculture

Artificial Intelligence (AI) technologies are transforming agricultural practices, making farming more efficient, sustainable, and resilient to environmental challenges. Machine learning, remote sensing, and data analytics are being applied to optimize irrigation scheduling and nutrient management, leading to improved productivity and resource conservation (Kumar *et al*., 2023a) [23]. The integration of AI and IoT devices is enabling data-driven farming practices, including the use of robotics, drones for crop monitoring, and smart irrigation systems that leverage real-time data for optimized agricultural operations (Issa *et al*., 2024) [17]. By leveraging data-driven insights, AI-driven AgriTech is reshaping agricultural operations to improve decision-making, optimize resource utilization, and enhance productivity (Jha *et al*., 2019) [18].

1.1. Soil and Irrigation Management

AI technologies play a pivotal role in monitoring soil health and optimizing irrigation practices. By using sensors and IoT devices, AI systems collect real-time data on soil moisture, nutrient levels, and temperature (Rasheed *et al*., 2022) [36]. Advanced machine learning algorithms analyse this data to provide precise recommendations on when and how much water to apply, ensuring optimal irrigation (Chlingaryan *et al*., 2018) [7]. For instance, AI-powered irrigation systems have reduced water usage, while improving crop yields by efficiently delivering water only where needed (Jiménez *et al*., 2022) [20]. Such systems not only conserve water but also reduce energy costs and mitigate soil erosion caused by over-irrigation.

1.2. Weather forecasting and climate adaptation

Accurate weather prediction is essential for mitigating risks associated with climate variability, such as droughts, floods, and storms. AI-driven weather forecasting tools use big data and machine learning to analyse historical weather patterns and current atmospheric conditions (Lakshmi and Corbett, 2023) [25]. These models provide farmers with accurate, localized weather forecasts, enabling them to plan their planting, harvesting, and irrigation schedules effectively (Gupta *et al*., 2022) [15]. Additionally, AI can help farmers adapt to climate change by recommending crop varieties suited to changing weather patterns and developing strategies for disaster preparedness.

1.3. Plant Growth and Health Monitoring

AI technologies are instrumental in monitoring plant growth and detecting diseases at an early stage. Using drones and satellite imagery, AI-powered platforms analyse visual data to assess crop health and identify signs of stress caused by pests, diseases, or nutrient deficiencies (Vardhan and Swetha, 2023) [46]. For example, convolutional neural networks (CNNs) can classify diseases in plants with high accuracy by analysing images of infected leaves (Shoaib *et al*., 2023) [40]. Early detection allows for timely interventions, reducing crop losses and minimizing the use of chemical pesticides, which contributes to environmental sustainability.

1.4. Resource Optimization and Precision Agriculture

Precision agriculture is a cornerstone of AI applications in farming. By integrating data from sensors, drones, and satellites, AI platforms provide actionable insights into field conditions, enabling farmers to make precise decisions about planting, fertilization, and harvesting (Mgendi, 2024) [30]. This approach minimizes resource wastage, reduces greenhouse gas emissions, and enhances overall efficiency (Chlingaryan *et al*., 2018) [7]. For example, AI-based fertilizer management systems analyse soil nutrient data and recommend optimal application rates, reducing environmental pollution caused by excessive fertilizer use (Gangwani, 2024) [10].

AI applications in sustainable agriculture are revolutionizing traditional farming methods, offering data-driven solutions to address critical challenges such as resource scarcity, environmental degradation, and climate change. By optimizing resource use, enhancing productivity, and minimizing environmental impacts, AI technologies pave the way for a more resilient and sustainable agricultural sector (Jha *et al*., 2019) [18].

2. Advantages of AI in agriculture

Artificial Intelligence (AI) is emerging as a transformative tool in modern agriculture, capable of dealing with important challenges in the field related to productivity, resource efficiency, and sustainability (Aggarwal *et al*., 2024) [1]. Integration of advanced technologies into farming practice allows AI to enhance agricultural productivity, improve crop health monitoring, and facilitate intelligent decision-making processes (Kumar *et al*., 2023b) [24]. The said development also leads to a decrease in environmental impact and to general food production systems' sustainability (Zhang *et al*., 2020; Jha *et al*., 2019) [18, 50].

2.1. Maximizing Resource Efficiency

AI-based agriculture has also helped farmers optimize their resource usage (Sharma *et al*., 2020) [39]. They have machines that read sensors, drones, and satellites and yield data analysis that offers exact guidance on when to use water, fertilizer, and pesticides (Khan *et al*., 2024) [22]. For example, AI-based irrigation systems monitor soil moisture and weather conditions to supply the right quantity of water at the right time, which reduces wastage by as much as 30% (Wani *et al*., 2020) [48]. Likewise, AI-based nutrient management tools analyse soil conditions and advise optimal fertilizer usage, thus preventing chemical runoff and preserving ecosystems (Chlingaryan *et al*., 2018) 7[]. These resource-efficient practices not only increase productivity but also reduce the input costs of farmers (Kumar *et al*., 2023a) [23].

2.2. Crop Health Monitoring

The use of AI in improving crop health monitoring is significant, in that it can utilize techniques such as computer vision and machine learning as well as remote sensing. (Sornalakshmi *et al*., 2022) [44] The AI-based algorithms process the data extracted from drones and satellite imagery to identify crop diseases, pests, and nutrient deficiencies (Ai *et al*., 2021). Early detection of these problems allows for timely interventions, thereby reducing crop losses and the use of excessive pesticides (Liakos *et al*., 2018) [27]. For instance, CNNs have been applied to identify particular plant diseases with high accuracy, enabling farmers to apply targeted corrective measures (Zhang *et al*., 2020) [50]. These capabilities enhance the quality and quantity of agricultural produce while minimizing environmental impact.

2.3. Facilitating Intelligent Decision-Making

AI-powered platforms are empowering farmers to make informed decisions based on weather, soil, market trends, and crop performance data. These platforms provide actionable insights in terms of planting schedules, crop rotation, and harvest timing that help the farmer maximize yield and reduce risks (Gupta *et al*., 2021b) [16]. For example, predictive analytics powered by AI can forecast potential weather disruptions, enabling farmers to take preventive measures against droughts or floods (Jha *et al*., 2019) [18]. AI's ability to process and interpret complex data fosters precision agriculture, ensuring optimal use of resources and improved profitability for farmers.

2.4. Reducing Greenhouse Gas Emissions

By optimizing farming practices, AI contributes significantly to reducing agriculture's environmental footprint. AI technologies minimize waste, enhance energy efficiency, and decrease the amount of greenhouse gas emissions related to farming. For example, AI-equipped precision planting and harvesting machinery causes the least possible soil disturbance and, consequently, minimizes carbon in the soil loss and associated emissions (Wani *et al*., 2020) [48]. Moreover, AI-based waste management systems in agriculture convert organic waste into bioenergy, thus supporting circular economy practices and reducing methane emissions from decomposing waste (Singh *et al*., 2020) [42].

2.5. Crop Yield Enhancement and Food Security

AI improves agricultural productivity by making farmers grow more with fewer inputs. AI-based precision farming techniques have been proven to increase crop yields by optimizing input use and improving field conditions (Chlingaryan *et al*., 2018) [7]. Furthermore, AI enables climate-resilient crop variety development through the analysis of genetic and environmental data, ensuring food security in the context of climate change (Gupta *et al*., 2021b) [16].

2.6. Enhancement of Food Inspection and Quality Control

Agricultural applications of AI are seen in improving food inspection and quality control. AI enables systems that can detect the defects, contamination, and variability in the quality of products using computer vision and machine learning. Such systems ensure high-quality products at the market outlets, which reduces food waste as well as enhances the effectiveness of supply chains (Liakos *et al*., 2018) [27]. Further to reducing quality control costs, the automated process also reduces operational cost that contributes to more sustainable food value chains for food processing and packaging industries (Zhang *et al*., 2020) [50].

2.7. Encouraging Sustainability-Focused Farming Practices

Through its varied applications, AI encourages sustainable agriculture by lowering input wastage, increasing efficiency, and enhancing environmental stewardship. AI technologies allow for the adoption of conservation agriculture techniques, such as minimum tillage and cover cropping, which protect soil health and biodiversity (Wani *et al*., 2020) [48]. By applying AI to farming operations, it is possible to balance the productivity and sustainability of an agricultural system in a manner that ensures long-term viability for farmers and ecosystems alike.

Table 1: Categorization of AI-Based Software and Tools for Agricultural Applications

Category	Software	Description
Crop Health Monitoring & Disease Detection	Plantix	Identifies plant diseases and suggests treatments using AI image recognition.
	Taranis	Uses high-resolution imagery and machine learning to detect crop diseases and pests.
	DeepMind Plant Disease Detector	AI-based system for identifying crop diseases with high accuracy.
	DroneDeploy	Uses drones and AI for aerial crop imaging and health analysis.
	Skymet	Predicts weather-related risks for crop protection.
	Ceres Tag	Combines AI with sensor technology for tracking crop stress and health.
	PEAT	AI-based image recognition tool for identifying crop diseases and pests.
	Scarecrow AI	Detects and deters birds from crops using intelligent systems.
Precision Agriculture	Granular	Farm management software for data-driven decision-making.
	Climate FieldView	Monitors and analyses field data for optimizing farm operations.
	Trimble Ag Software	AI-based tools for soil health, crop planning, and yield analysis.
	John Deere Operations Center	Combines AI and IoT for optimizing farm equipment and operations.
	Agremo	AI-based tool for mapping, crop counting, and analytics.
	SenseFly	Drone-based AI for precision farming and field monitoring.
	Precision Hawk	Combines machine learning with drone imagery for crop insights.
	Hummingbird Technologies	AI-powered crop analytics and yield mapping platform.
	Prospera Technologies	Provides real-time insights into crop health using AI.
Soil & Irrigation Management	CropX	AI-powered soil monitoring platform for efficient water and nutrient management.
	Agribotix	Uses drones and AI for monitoring soil conditions and crop health.
	Aquacrop	FAO's AI-based tool for simulating crop productivity under different water conditions.
	Sentek Technologies	AI tools for soil moisture monitoring and irrigation planning.
	FarmLogs Soil Health	AI-based predictions for soil fertility and management.
	Arable	AI-based platform for weather, soil, and crop data integration.
	HydroBio	AI-driven irrigation management system using satellite imagery.
Pest & Weed Management	Blue River Technology (See & Spray)	AI-based weed control system.

	AgroSense	Pest and weed detection using machine learning.
	WeedSpotter	AI-based weed identification and management tool.
	Ecorobotix	Autonomous robots powered by AI for targeting and removing weeds.
	Strider	Uses AI to manage pests and diseases at large-scale operations.
	Plantix Pro	Advanced pest and disease detection for commercial farms.
	Precision Weed Management (Syngenta)	AI for detecting and addressing weed problems.
Yield Prediction & Crop Planning	FarmLogs	Provides AI-driven yield prediction and planting recommendations.
	Harvest AI	Predicts yield outcomes and analyses crop patterns.
	Ceres Imaging	AI and aerial imagery for yield optimization.
	AgriChain	AI for planning crop cycles and market analysis.
	Geosys Crop Insights	Uses AI for satellite-based crop forecasting.
	Pix4Dfields	AI tools for precision crop monitoring and yield prediction.
	KisanHub	AI-powered platform for crop and yield tracking in real-time.
	EOS Crop Monitoring	Remote sensing platform with AI-driven analytics for yield estimation.
Market Analysis & Farm Economics	AgriSync	AI-driven support platform for farm advisory services.
	Farmbrite	Tracks expenses, revenue, and crop yields using machine learning.
	FarmLead	AI marketplace platform for buying and selling crops.
	Agrio	AI-powered platform for connecting farmers to markets and advisors.
	Traive	AI-based financial planning and risk assessment for farmers.
	CIBO Impact	AI platform for sustainable farming and carbon credit management.
	Agrimap	Farm management software for market forecasting.
Robotics & Automation	Naïo Technologies	AI-enabled autonomous robots for weeding and harvesting.
	Abundant Robotics	Robotic systems for fruit harvesting.
	Harvest CROO Robotics	AI-powered harvesting systems for strawberries.
	Fendt Xaver	AI-enabled robotic systems for precision seeding.
	FarmWise	Autonomous weeding robots with machine learning.
	Agrobot	AI-powered robots for fruit picking and sorting.
	Blueberry Picking Robot (Dogtooth Technologies)	AI-driven harvesting robots.
	EcoRobotix	Uses AI to identify and target weeds in fields precisely.
Climate & Weather Prediction	aWhere	Uses machine learning for hyper-local weather predictions.
	IBM Watson Decision Platform for Agriculture	Offers AI-driven weather insights for agricultural decision-making.
	Climacell	AI-powered weather insights tailored for farming.
	Cropmetrics	Combines AI with weather data for irrigation planning.
	Tomorrow.io	AI-driven hyper-local weather predictions for agricultural operations.
	Sencrop	Uses AI to provide microclimate insights to farmers.
	Agroweather	Predicts extreme weather patterns and crop risks using AI.
Livestock & Aquaculture Management	Connecterra	AI-powered dairy farming platform that monitors herd health and productivity.
	Cowlar	Smart collars with AI to track livestock health.
	FARM360	Tracks livestock behaviour, feed consumption, and health using AI.
	Moocall	Uses AI to monitor cattle health and calving.
	WellCow	AI tools for dairy and beef cattle monitoring.
	Smartbow	Ear tags with AI to track livestock movement and health.
	eFishery	AI-powered automated feeders for aquaculture.
	Aqua Manager	AI-driven aquaculture software for optimizing fish farming.
General Farm Management	CropIn SmartFarm	AI-powered farm management software.
	Smart Yields	AI for data-driven decisions on farms and greenhouses.
	Agrivi	Comprehensive AI farm management platform for small and large farms.
	Grownetics	Smart farming solutions for greenhouses and hydroponic systems.
	Agroptima	Mobile-based AI app for real-time farm tracking.
Emerging Innovations	OneSoil	AI-powered platform for precision agriculture via satellite imagery.
	Resson	AI and big data for predicting agricultural outcomes.
	Tarfin	AI-powered agri-fintech platform to support farmers' financial needs.
	iUNU	AI and computer vision for greenhouse management.
	TensorField	Uses AI for automating and optimizing farming processes.

3. Challenges in applying AI in agriculture

The promising integration of Artificial Intelligence (AI) into agriculture is facing significant challenges that hinder its more widespread application. These include technological, infrastructural, economic, ethical, and social dimensions (Atapattu *et al*., 2024) [6]. It is important to address these challenges to realize the potential for AI in transforming agriculture to become a more efficient and sustainable sector (Oliveira *et al*., 2023) [33].

3.1. Technological Adoption Obstacles

The primary barrier to the adoption of AI in agriculture is the lack of technological awareness and expertise among farmers, especially in developing regions (Tzachor, 2021) [45]. Most farmers are unaware of advanced technologies like machine learning, IoT devices, and data analytics, which are a part of AI-driven solutions (Liakos *et al*., 2018) [27]. Moreover, the deployment of AI tools is often complex and requires knowledge and skills that are scarce in rural areas. Even if these tools are available, the lack of proper training programs hinders their use (Anusha and Kunte, 2024) [5].

3.2. Infrastructure and Investment Requirements

AI in agriculture requires massive investment in digital infrastructure such as high-speed internet, sensors, drones, and data storage facilities (Gikunda, 2024) [12]. However, many rural areas, particularly in low-income countries, lack the infrastructure to support these technologies (Atapattu *et al*., 2024) [6]. This challenge is further compounded by the digital divide between urban and rural regions, where connectivity for farmers in remote areas often remains poor and modern technology is not readily available (Marie, 2022) [28]. High upfront costs associated with AI tools are another deterring factor to smallholder farmers who operate on very tight budgets and cannot afford such innovations if not supported externally (Tzachor, 2021) [45].

3.3. Data Privacy and Security Concerns

AI-driven agricultural systems mostly depend on data collection via sensors, drones, among other devices (Ongadi, 2024) [34]. This introduces issues related to data ownership and privacy, as well as security (Wilgenbusch *et al*., 2022) [49]. Farmers are slow to share their data in fear of misuse, access without authorization, or corporations exploiting them (Kaur *et al*., 2022) [21]. Moreover, the absence of standardized regulations on managing data in agriculture makes it complex to guarantee transparency and fair play in AI applications (Wilgenbusch *et al*., 2022) [49].

3.4. Variability in Field Conditions

Farm operations are highly influenced by conditions like soil type, climate, crop type, and farming practices among others (Atapattu *et al*., 2024) [6]. This variability can make it difficult to generalise AI tools across all circumstances. The performance of AI also largely depends on the training data quality and quantity involved, and inconsistent field conditions may lead to poor reproducibility of results (Geli *et al*., 2019) [11]. For instance, an AI system learnt in one region may fail in other regions because of regional-specific factors related to the environment or agronomy (Anusha and Kunte, 2024) [5]. The AI solutions are hence constrained in their scalability, thereby not being implemented globally.

3.5. Ethical and social considerations

The development and use of AI in agriculture face also some ethical and social implications. For example, AI-based equipment automates certain farm activities and potentially puts farm workers out of a job (Munnisunker *et al*., 2022) [31]. This brings about significant socioeconomic concerns about the AI adoption, especially in economies that depend heavily on farming as an occupation (Ryan, 2023) [37]. In addition, the design of AI tools must be based on cultural and social considerations to ensure that it aligns with the needs and values of local communities (Dara *et al*., 2022) 8[].

3.6. Lack of standardization and collaboration

The lack of standard procedure and collaborative framework for agriculture in AI applications complicates its implementation (Atapattu *et al*., 2024) [6]. Various parties such as developers of technology, policy makers, and farming operators often work in disjointed ways leading to partial and inconsistent efforts. Common standards setting and cooperation among parties is crucial to the effectiveness of AI technology in farming systems (Dara *et al*., 2022) [8].

3.7. Environmental and sustainability challenges

Though AI promises much in terms of sustainability, designing tools that balance productivity with environmental stewardship is a very complex task (Nishant *et al*., 2020) [32]. For instance, over-reliance on AI-driven precision farming techniques may inadvertently result in monoculture practices that degrade soil health and biodiversity (Gikunda, 2024) [12]. Careful planning and monitoring are necessary to ensure AI applications meet broader sustainability goals.

4. Future directions and research opportunities in AI for sustainable agriculture

The potential of Artificial Intelligence in revolutionizing sustainable agriculture is tremendous (Smith and Jones, 2019) [43]. However, unlocking the full benefits requires a concerted effort to overcome existing barriers and pave the way for future advancements (Gupta *et al*., 2021b) [16]. These efforts focus on developing scalable AI solutions (Jha *et al*., 2021) [19], fostering collaborative initiatives among stakeholders (Lee and Park, 2019) 26[], and addressing socio-economic and ethical considerations (Dara *et al*., 2022) [8]. The future of AI in agriculture lies in innovation, inclusiveness, and appropriate technology with respect to human and environmental values (Gupta *et al*., 2021b) [16]

4.1. Scalable AI solutions

Most focus will be on the next-generation scalable AI solutions compatible with multiple farming environments for various farm operations. (Ahmed *et al*., 2020) [2], Current AI applications suffer from non-replicability in most cases due to regional variability in soil, climate, and agricultural practices (Liakos *et al*., 2018) [27]. Future research would look to design AI tools that could generalize effectively across different conditions but with the option to customize it according to local needs. For instance, AI models that are trained on global datasets can be fine-tuned using region-specific data for enhancing their applicability and accuracy (Chlingaryan *et al*., 2018) [7].

Scalable AI solutions should also address the needs of smallholder farmers, who are the backbone of agriculture in many developing countries. (Zhang *et al*., 2020) [50]. These tools must be affordable, easy to use, and work well even in low-resource environments. Developments in lightweight AI algorithms that can run on simple hardware, such as smartphones, will help democratize access to AI-driven agricultural technologies (Jha *et al*., 2019) [18].

4.2. Socio-economic and ethical implications

Socio-economic and ethical implications of AI adoption in agriculture are critical areas for future research and policy development. While AI can boost productivity and reduce labour-intensive tasks, it raises job displacement concerns, especially in regions heavily dependent on agricultural labour (Wani *et al*., 2020) [48]. Research is needed to explore strategies for workforce transition, such as reskilling programs and the creation of new roles that complement AI technologies. Studies have suggested that fostering collaboration between policymakers, educators, and industry stakeholders is key to developing sustainable frameworks for this transition (Lee and Park, 2019) [26].

Ethical considerations also relate to data ownership and privacy. As AI systems gather and analyse large amounts of data, it is essential to establish regulatory frameworks that protect the rights of farmers and ensure fair sharing of data (Gupta *et al*., 2021a) [14]. These frameworks should address algorithmic transparency and work to avert biases that may disproportionately affect small-scale or marginalized farmers. Additionally, researchers argue that inclusivity in AI design and policy development can help bridge the digital divide and ensure equitable benefits from technological advancements in agriculture (McKinsey Global Institute, 2018) [29].

4.3. Collaborative efforts and stakeholder engagement

The integration of AI into agriculture requires collaboration among stakeholders such as governments, private companies, research institutions, and farmers. (Lee and Park, 2019) [26] Policymakers have a critical role to play in fostering an enabling environment through investment in digital infrastructure, subsidies for AI technologies, and incentives for innovation (Liakos *et al*., 2018) [27]. Acceleration of the development and deployment of AI solutions might be facilitated by public-private partnerships, fostering knowledge exchange between researchers and practitioners.

Another significant stakeholder engagement in investment is in the aspect of digital literacy. The farmers should be trained in their ability to apply the AI technologies. (Patel *et al*., 2022) [35] There should be training programs, outreach community initiatives, and friendly farmer interfaces that help to narrow the digital divide in achieving an inclusive adoption of AI in agriculture (Zhang *et al*., 2020) [50].

4.4. Integration of human-centered AI approaches

Future research is increasingly focused on human-centered AI approaches, which emphasize collaboration between humans and machines. These systems focus on augmenting human expertise rather than replacing it so that farmers are in control of decision-making processes (Chlingaryan *et al*., 2018) [7]. For example, AI tools may suggest irrigation or pest management, but the final decision could be left to the farmer, based on experience and contextual knowledge.

Human-centred AI pays attention to ethical imperatives, such as aligning AI-driven practices with sustainability requirements (Dara *et al*., 2022) [8]. This encompasses developing biodiversity-enhancing algorithms, developing natural resource-saving algorithms and reducing the impact of climatic changes. AI is likely to be applied to assisting in regenerative agriculture, particularly crop rotation and soil carbon sequestration that improves on ecosystem health and productivity increases (Gupta *et al*., 2021b) [16].

4.5. Interdisciplinary research and innovations

Interdisciplinary research combining expertise from agronomy, computer science, economics, and social sciences would open up avenues for innovations addressing technical, economic, and social dimensions simultaneously. AI in combination with genomics could help accelerate the development of climate-resilient crop varieties. Similarly, by integrating AI with behavioural science, one could design tools that are more intuitive and culturally relevant for farmers (Jha *et al*., 2019) [18].

5. Conclusion

Artificial intelligence has the prospect of revolutionizing agriculture by working to address critical challenges linked to sustainability, productivity, and resource efficiency. The combination of AI technologies in farms' practices, such as precision agriculture, weather forecasts, crop health monitoring, and resource optimization, transforms traditional agricultural methods into highly sustainable and resilient farming systems. AI supports this global agenda for sustainable development by enhancing decision-making processes, bringing improved crop yields, and reducing environmental impacts.

However, the adoption of AI in agriculture is not without its challenges. Technological barriers such as limited awareness and expertise among farmers, inadequate infrastructure, and high investment costs are still significant obstacles, especially in low-income and rural areas. Data privacy concerns, variability in field conditions, and ethical implications add to the complexity of AI solutions. Addressing these challenges through targeted investments, capacity building, and collaboration among stakeholders is very essential in fully harnessing the potential of AI in agriculture.

AI can play a pivotal role in advancing agricultural sustainability and mitigating the negative impacts of climate change, soil degradation, and resource scarcity. Optimizing resource use, improving efficiency, and reducing waste are some of the ways AI-driven technologies will contribute to a more sustainable and equitable agricultural sector. As AI continues to evolve, its potential to shape the future of farming remains immense, offering a path toward greener, more resilient food production systems that can meet the needs of a growing global population while protecting the environment for future generations.

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