

E-ISSN: 2618-0618

P-ISSN: 2618-060X

© Agronomy

NAAS Rating (2026): 5.20

www.agronomyjournals.com

2026; SP-9(7): 31-41

Received: 25-04-2026

Accepted: 28-05-2026

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AI-Driven Regenerative Agriculture for Climate Resilience: A Review

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i7Sa.5900>

Abstract

Agriculture is being impacted by climate change with a multitude of challenges to address, such as increasing temperatures, unpredictable precipitation, soil erosion, biodiversity decline, and more frequent extreme weather events. Regenerative agriculture has been recognized as a more sustainable agricultural practice with regard to restoring soil health, increasing biodiversity, enhancing ecosystem services, and sequestering carbon. Meanwhile, the development of technologies such as Artificial Intelligence (AI), machine learning, deep learning, remote sensing, Internet of Things (IoT), and big data analytics are revolutionizing the management of agricultural resources and decisions. The convergence of AI and regenerative agriculture is a viable potential solution for climate resilient food production systems. AI-enabled interactive tools also allow dynamic monitoring of soil and crop health, simulation of climate risks, nutrient and water management precision, carbon accounting, and farm management adaptation. This review integrates emerging trends in AI-enabled RA, considers its potential to promote climate resilience, assesses challenges and barriers, and suggests possible research directions. The review demonstrates that AI could greatly enhance the speed at which the regenerative practices are adopted and how effective they are at improving productivity, sustainability and ecosystem restoration.

Keywords: Artificial Intelligence, Regenerative Agriculture, Climate Resilience, Precision Agriculture, Soil Health, Carbon Sequestration, Sustainable Farming, Digital Agriculture

1. Introduction

Climate change is now a major threat considered to be the greatest challenge for agriculture worldwide. Droughts and floods are becoming more common, as are heat waves and changing patterns of pests, all of which are impacting world agricultural output and food security. Direct non-CO₂ GHG emissions from agriculture, including land use change and deforestation for agricultural expansion, play a vital role in the global environment and are related to conventional farming practice, which involves high rates of tillage, monoculture, and overapplication of synthetic fertilizers and pesticides (Kabato *et al.*, 2025; Basheer *et al.*, 2024; Yuan *et al.*, 2024) [26, 10, 63]. Regenerative agriculture is a comprehensive farming system that attempts to enhance ecosystem services without compromising agricultural productivity. Key principles are reduction in soil disturbance, maintenance of soil cover, diversification of crops, incorporation of livestock, and increasing biological activity. These activities favor soil organic carbon (SOC), water infiltration, nutrient cycling and biodiversity (Rai *et al.*, 2025; Khangura *et al.*, 2023; Jayasinghe *et al.*, 2023) [47, 29, 24]. Recent progresses in Artificial Intelligence (AI) provide unprecedented chances to enhance the regenerative agriculture. AI algorithms can analyze enormous datasets from satellites, drones, sensors, weather stations and farm records in order to assist decision-making in real time. The Intersection of AI and regenerative agriculture has the potential to produce climate smart production systems that maintain productivity as climate variability increases (Ali *et al.*, 2025; Sajjad *et al.*, 2026) [5, 49].

2. Concept of Regenerative Agriculture**2.1 Minimize Soil Disturbance**

Conservation tillage and no-till farming are essential regenerative ag practices that reduce or avoid soil disturbance along with the number of times the soil in a field is tilled. These practices contribute to moisture conservation in the soil, help reduce erosion, increase water penetration into the soil and stimulate activity of the good types of organisms in the soil. Through residue retention and minimal soil disturbance, they conserve soil aggregation and soil pore space,

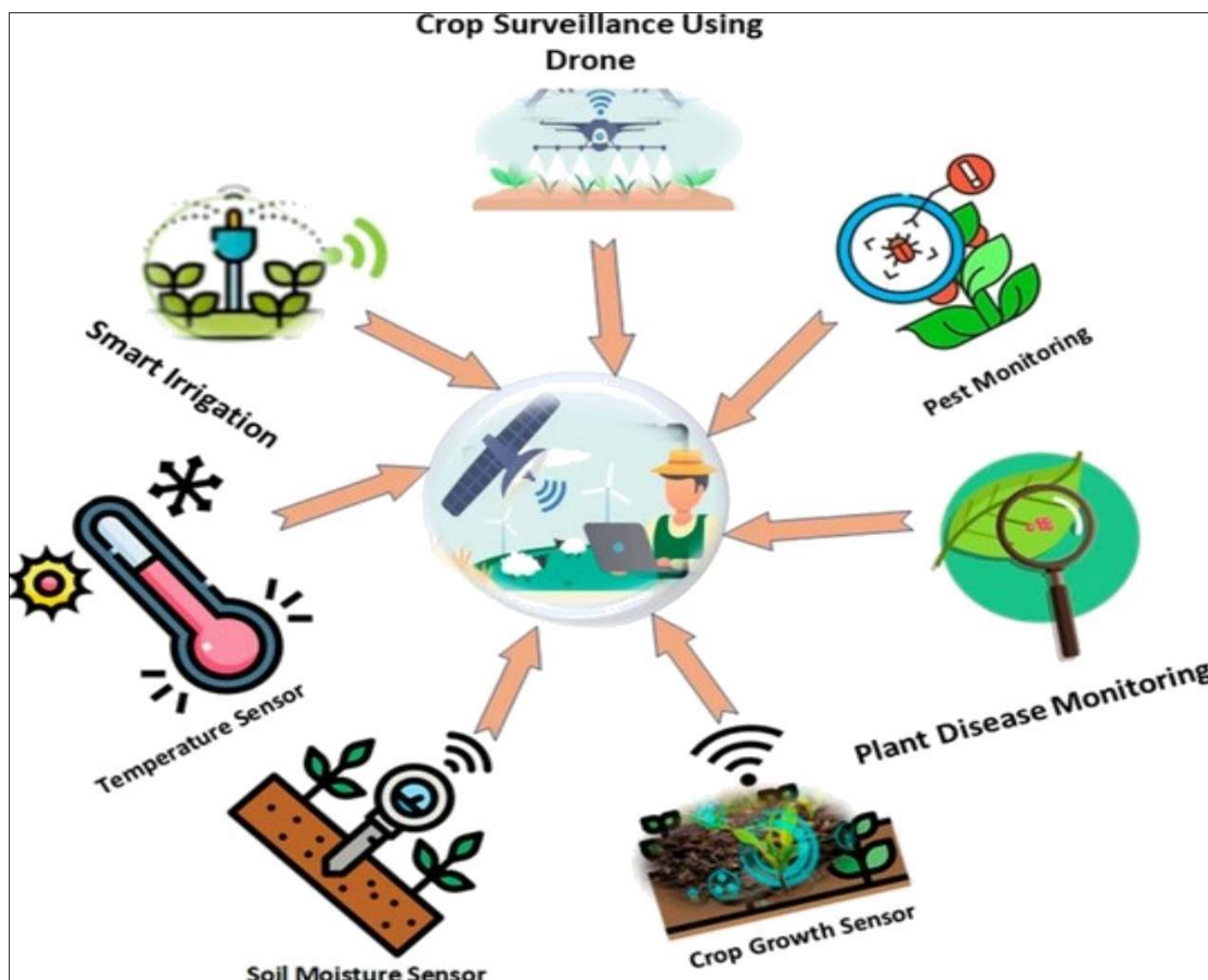


Fig 1: Smart Agriculture Monitoring Using Drone and IoT Sensors

allowing for improved root growth, aeration, nutrient availability, and ultimately improved soil productivity. In addition, reduced soil disturbance impedes the decomposition of soil organic matter, mitigates carbon dioxide emission and enhances soil organic carbon sequestration. As a result, conservation tillage and no-till practices promote carbon sequestration, soil health, and agricultural climate change mitigation/adaptation (O'donoghue *et al.*, 2022; Sher *et al.*, 2024; Zhao *et al.*, 2025) [52, 66, 41].

2.2 Permanent Soil Cover

Cover crops, crop residue retention, and mulching are regenerative agricultural practices that preserve soil cover, prevent erosion, retain moisture, and mitigate soil temperature (Lal, 2015) [68]. These practices contribute to the build-up of soil organic matter, stimulate microbial activity, suppress weeds, improve water-use efficiency, and enhance the resilience of agricultural systems toward climate change (Zhang *et al.*, 2023; Gomide *et al.*, 2026) [64, 19].

2.3 Crop Diversification

Crop rotations, intercropping and agroforestry systems are sustainable land management practices that improve soil fertility, enhance nutrient cycling, suppress pests and diseases, increase biodiversity,

and promote efficient use of natural resources, contributing to higher agricultural productivity and environmental sustainability (Zheng *et al.*, 2024; Al-Musawi *et al.*, 2025; Toker *et al.*, 2024) [67, 6, 56].

2.4 Livestock Integration

Sustainable grazing and nutrient cycling, coupled with better interactions among ecosystem functions, improve soil fertility, nutrient availability, and eco-environmental stability, beneficially affecting biodiversity and resource use efficiency within sustainable agriculture. These managements enhance soil quality and water productivity, they contribute to ecosystem resilience and they reduce reliance on off-farm inputs and on degradation of the environment (Morales-Reyes *et al.*, 2025; Mabhaudhi *et al.*, 2023) [38, 34].

2.5 Soil Biological Enhancement

Organic amendments, application of compost and biofertilizers or microbial inoculants enhance the physical, chemical and biological characteristics of soils by increasing organic matter content, nutrient availability, microbial population, and overall soil structure. These practices enable sustainable nutrient management, sustainable crop productivity and sustainable soil health and environmental quality (dos Reis *et al.*, 2024; Tomar *et al.*, 2026) [16, 58].



Source: <https://www.shutterstock.com/image-vector/regenerative-agriculture-principles-diagramdo-not-2660453793>

Fig 2: Principles of Regenerative Agriculture

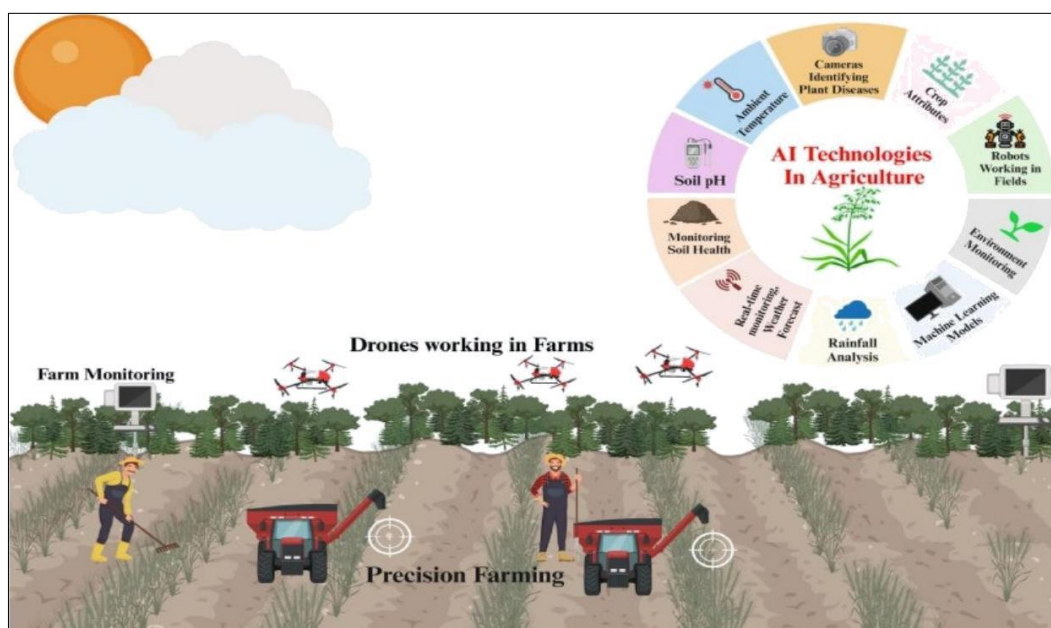
3. Climate Resilience in Agriculture

Climate resilience is the ability of agricultural systems to survive, adapt to, and recover from climate related stresses and disturbances while still maintaining its basic functions of production and provision of ecosystem services. It includes adaptive capacity (the ability to change management practices in response to climate variability), resistance (the ability to maintain productivity during unfavourable conditions), recovery capacity (the ability to recover productivity after disturbances), and transformative capacity (the ability to undergo long-term transformations according to changing climatic conditions). Regenerative agriculture practices improve climate resilience by building soil organic matter, enhancing water holding capacity and soil water infiltration, supporting biodiversity, bolstering ecosystem functions, and reducing reliance on external inputs, resulting in farming systems that are more able to withstand climate-related stressors (Sharma *et al.*, 2025) ^[51].

4. Artificial Intelligence in Agriculture

AI is currently being developed as a computational system that can learn by itself from the data, reason about things, make predictions, and potentially-even support an agent in making autonomous decisions. AI in agriculture is a combination of

multiple high-end technology to bring revolution in productivity, efficiency and sustainability. ML algorithms examine massive data collections to support decisions relating to yield prediction, soil classification, and climate forecasting (Jabed and Murad, 2024) ^[23]. Deep Learning (DL), a branch of AI, employs intricate neural networks, among other things, to achieve remarkable accuracy in disease detection, weed detection, and image-based crop monitoring (Kumar *et al.*, 2026; Pai *et al.*, 2024) ^[31, 43]. Applications of Computer Vision techniques to analyze and interpret digital images (2D or 3D) for canopy analysis, detecting nutrient deficiencies, and crop phenotyping are now well established. The convergence of AI and Internet of Things (IoT) enables sensing environmental, soil and plant parameters in the real-time, automated irrigation scheduling, and environmental monitoring using connected sensors and devices (Abdelmoneim *et al.*, 2025) ^[1]. Moreover, Remote Sensing (RS) and GIS offer spatial data on vegetation mapping, soil moisture estimation, and terrestrial carbon monitoring, which contribute to the implementation of site-specific management of agricultural resources (Li *et al.*, 2024) ^[33]. All of these AI-enabled technologies are transforming the way we grow food, building more resource-use efficient, risk-reduced and climate-resilient farming systems to feed the future (Madhav, 2025) ^[35].



Source: Aijaz *et al.*, 2025

Fig 3: AI-Driven Precision Agriculture System

5. Integration of AI with Regenerative Agriculture

5.1 AI-Based Soil Health Monitoring

Soil Organic Carbon

Soil organic carbon (SOC) is commonly used as an indicator of soil fertility and soil quality since it represents the amount of organic matter in soil. Its level is monitored to evaluate carbon sequestration potential and the efficacy of regenerative management practices (Patil *et al.*, 2025) ^[45].

Soil Moisture

Soil moisture is the amount of water contained in the soil, which is a key factor affecting plant growth and nutrient absorption. Continuous monitoring of soil moisture contributes to the optimization of irrigation scheduling and the enhancement of water use efficiency (Tripathi *et al.*, 2025) ^[59].

Microbial Activity

Microbial activity is the measure of the population and the activity of beneficial soil microbes that participate in nutrient cycling and the decomposition of organic materials. Greater microbial activity is representative of healthy, biologically active soil for plant production (Badagliacca *et al.*, 2024) ^[8].

Nutrient Availability

Nutrient availability is the extent to which essential nutrients are accessible for plant uptake. Nutritional status evaluation is useful for accurate fertilization and to avoid nutrient deficiency or toxicity (Bhatia and Sindhu, 2024) ^[11].

Continuous Monitoring

Monitoring continuously supplies data on soil states and ecosystem activities in real-time. It facilitates decision-making at the right time and early identification of soil health problems (Colombi *et al.*, 2025) ^[16].

Site-Specific Interventions

Site-specific management is the application of management practices to portions of a field, rather than the entire field, to address the specific needs of each area (Sharma, 1996) ^[69]. This

leads to greater efficiency of utilization of inputs and better farm level productivity (Thakur and Subba, 2026) ^[55].

Improved Soil Restoration Strategies

Precise information on soils enables scientists to develop efficient soil restoration measures adapted to the local conditions. These practices contribute to restoring soil fertility, enhancing ecosystem services, and ensuring agricultural sustainability in the long run (Patil *et al.*, 2025) ^[45].

5.2 Precision Nutrient Management

Variable-Rate Fertilizer Application

Variable-rate fertilization is one of the precision agriculture techniques which consist of fertilizing at different rates within a field according to the conditions of soil fertility and crop needs. This leads to nutrient supply at the right place and right time (where in field in field or farm) resulting in increased fertilizer use efficiency and reduction of wastage (Pawase *et al.*, 2023; Kabato *et al.*, 2025) ^[46, 26].

Nutrient Demand Forecasting

Forecasting of nutrient demand uses information derived from soil testing, plant growth stages, environmental condition, and from model based on AI to estimate future nutrient needs. This provides more precise prediction of the timing, and rates of N application for improved crop production (Tomar *et al.*, 2026) ^[58].

Nutrient-Use Efficiency Improvement

Enhancement of nutrient-use efficiency is based on the principle to utilize maximum nutrient among the applied nutrient under crop root environment. Balanced nutrition, precision nutrient management, and use of biofertilizers are some of the approaches which reduce nutrient losses and enhance productivity (Singh *et al.*, 2025) ^[54].

Reduced Fertilizer Losses

Precision nutrient management decreases nutrient losses owing to leaching, runoff, volatilization and fixation. The fertilizer

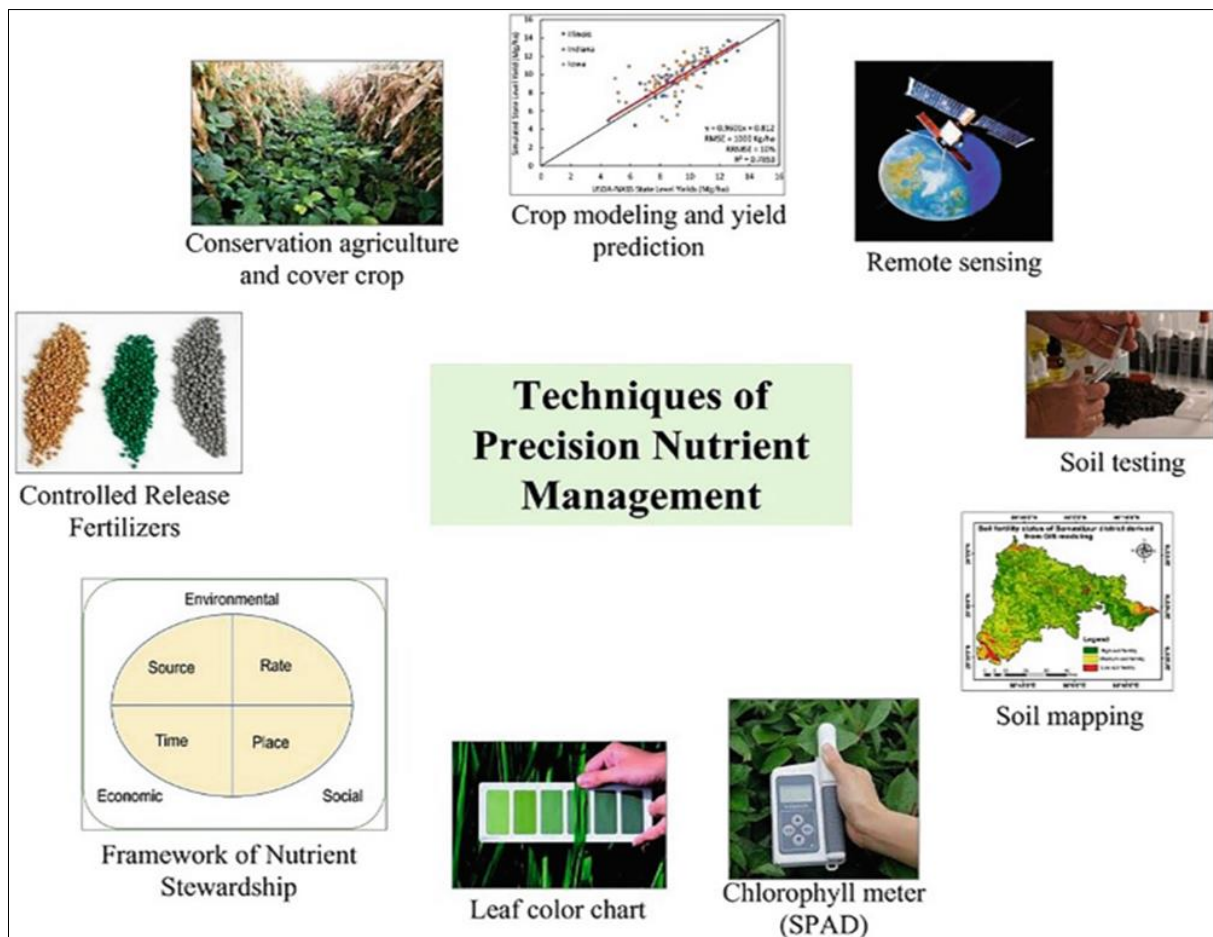
efficiency is increased with less environmental pollution (Bhatia and Sindhu, 2024) ^[11].

Lower Greenhouse Gas Emissions

Efficient fertilization reduces emissions of greenhouse gases, especially nitrous oxide (N₂O), from the soil under agricultural use. This leads to climate change abatement and improved sustainable agricultural practices (Patil *et al.*, 2025) ^[45].

Enhanced Soil Biological Activity

The result of balanced nutrient management is a thriving community of beneficial soil microbes, actively engaged in the cycling of nutrients and decomposition of organic matter. High microbial activities can enhance soil physical properties, fertility and sustainable productivity of soils (Tomar *et al.*, 2026) ^[58].



Source: Shidayaichenbi *et al.*, 2025

Fig 4: Techniques of Precision Nutrient Management

5.3 Smart Water Management

Weather Forecasts

Expectations about rainfall, temperature, humidity, and other weather conditions are given by weather forecasters. Such forecasts enable the farmers to better organize their irrigation and field work, and mitigate the risk of weather variability (Wang *et al.*, 2024) ^[62].

Soil Moisture Sensors

Soil moisture sensors continuously monitor soil moisture and give real-time information of the availability of water to crops. This allows a control- led irrigation management, by applying water only when needed and avoiding both underand over-irrigation (Urdanigo-Zambrano *et al.*, 2025) ^[60].

Crop Growth Models

Cropping growth stages use weather, soil, and crop information to represent plant development and water needs at different growing periods of the crop. These models enable better decisions in irrigation and crop management (Tolomio and Casa, 2020) ^[57].

Improved Water-Use Efficiency

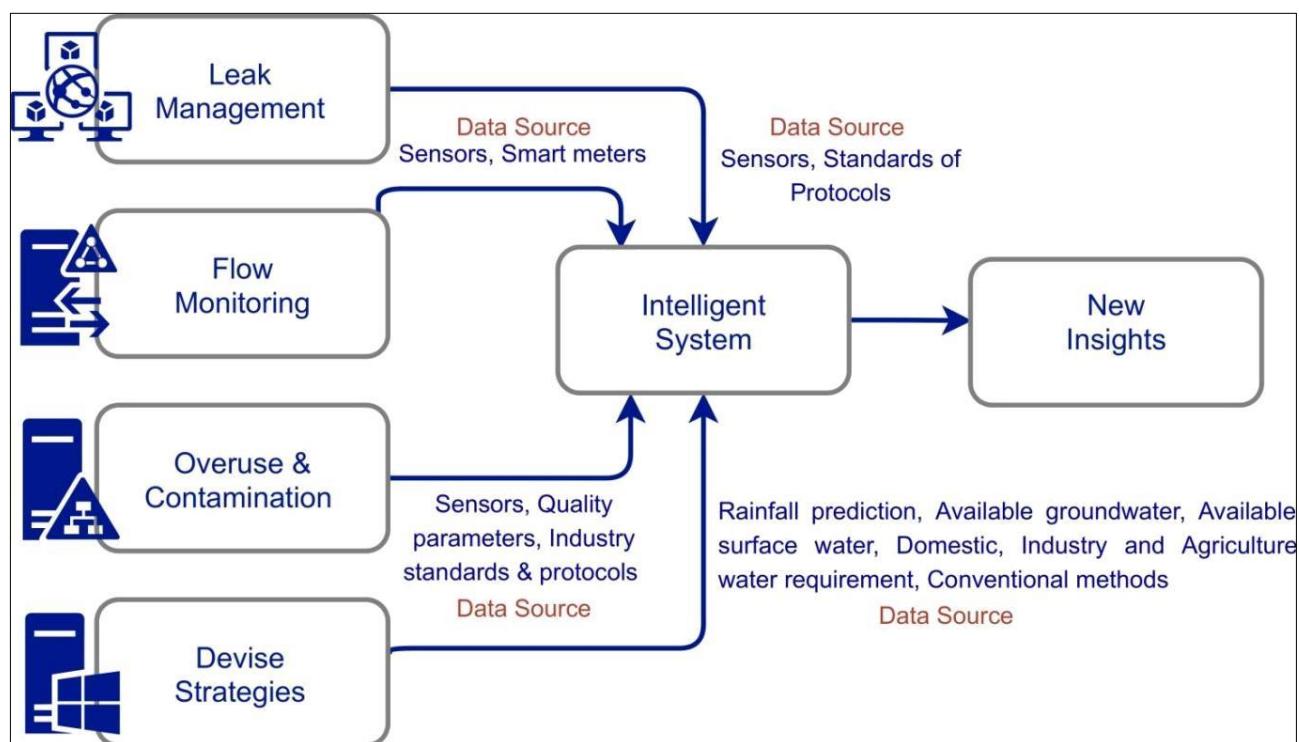
Weather forecasts, soil moisture sensors and crop growth models can be integrated to enable more precise water application in relation to crop requirements. This is to enhance the efficiency of water use and curtail wasteful consumption of water (NK and Ga, 2024) ^[40].

Reduced Drought Vulnerability

Current and predicted soil moisture status and weather conditions enable farmers to take a proactive stance on water shortages. As a consequence, crops gain in drought stress tolerance and yield loss is minimized (Islam *et al.*, 2025) ^[22].

Better Groundwater Conservation

Precision irrigation practices mitigate over-exploitation of groundwater through optimization of water application rates and timing. This contributes to groundwater resource conservation and sustainable water management in agriculture.



Source: Krishnan et al., 2022

Fig 5: Intelligent Water Management System Using Smart Sensors

5.4 Carbon Sequestration Assessment

Soil carbon storage, carbon sequestration possibilities, and greenhouse gas offset effects are widely employed indices in assessing the contribution of agricultural soils to climate change mitigation. Soil carbon stock is used to define the amount of carbon stored in the soil, while the carbon sequestration potential is the ability of the soil to absorb and retain carbon dioxide from the atmosphere for a period of time. Enhanced carbon storage contributes to the mitigation of greenhouse gases and to climate resilience. Such metrics are increasingly being used in carbon credit validation, climate smart agriculture certification and sustainability reporting, allowing farmers and organisations to measure environmental gains, prove sustainable land management and engage in carbon markets and climate related programs (Zhang et al., 2024; Munna et al., 2025) [65, 39].

5.5 Biodiversity Monitoring

Pollinator abundance, plant diversity, and habitat quality are recognized as key components of ecosystem functioning and biodiversity within agroecosystems. Pollinator abundance can be monitored to gauge the delivery of essential ecosystem services, such as crop pollination, and vegetation diversity represents the diversity of plant communities. Habitat quality reflects how well the environment can support a variety of organisms and ecological processes. Evaluation of these indices facilitates the monitoring of restoration of the ecosystem, assists in conservation planning, and fosters biodiversity preservation by pinpointing management strategies that improve ecological resilience and sustainability (Aizen et al., 2019; Katumo et al., 2022) [3, 27].

6. Role of AI-Driven Regenerative Agriculture in Climate Resilience

6.1 Drought Resilience

Prediction of soil moisture, adaptive irrigation scheduling, and water-saving technology are the main aspects that encompass

precision water management in sustainable agriculture. Soil moisture prediction integrates sensor readings, weather data and predictive models to predict future soil water status, so as to make appropriate decisions on irrigation. Adaptive irrigation scheduling differs from conventional irrigation in the timing and quantity of water application based on crop needs and environmental conditions with efficient water use. These methods collectively facilitate the saving of water by curtailing the over-irrigation, reducing the water losses, enhancing crop water use efficiency, and ensuring the sustainable management of the scarce water resources (Lakhari et al., 2024; Balamurali et al., 2025) [32, 9].

6.2 Heat Stress Management

Crop stress prediction, monitoring of microclimates, and advice on heat-tolerant crops are hightech climate-smart agriculture methods that enable producers to adapt to new environmental realities. Using weather data, crop models, and AI-based analytics, Crop Stress Forecasting predicts potential stress from drought, heat, or other harmful factors before widespread damage takes place. Microclimate monitoring is useful for receiving real-time localized temperature, humidity and solar radiation and other environmental factors that influence the growth of crops. These data can be utilized for development of heat-tolerant crop and variety recommendations to enhance productivity, to reduce climate-related risk, and for climate-resilient farming systems amidst escalating temperature extremes (Akwabeng et al., 2026) [4].

6.3 Flood Risk Reduction

Analysis of landscape hydrology, runoff estimation, and water retention optimization will greatly contribute to sustainable land and water resources management. Landscape hydrology analyses the transport, fate, and storage of water across agricultural landscapes, while runoff prediction provides estimates of the volume and flow rate of water exiting fields during precipitation events. These evaluations contribute to the

development of water retention optimization strategies, such as better drainage, conservation structures and soil management, thereby increasing water supply, reducing soil losses, minimizing nutrient losses, and boosting the adaptive capacity of agricultural systems to climatic variability (Sene, 2024) ^[50].

6.4 Pest and Disease Resilience

Early warning systems, predictive modeling of diseases and reduction of pesticide dependency are important elements of intelligent crop protection. Early warning systems are based on realtime weather, crop, and environmental data to detect conditions that may promote pest and disease outbreaks prior to causing significant damage. Predictive disease models use the data to predict when and how severe a potential infection could be, allowing producers to intervene in a timely and targeted manner. This enables farmers to use preventive and precision management practices for a reduced pesticide dependence, less production costs, less environmental impacts, and a more sustainable agriculture system (Biswal *et al.*, 2025) ^[12].

7. Emerging Technologies Supporting Regenerative Agriculture

Digital Twins

Digital Twins are digital representations of farms, fields, or agricultural systems that incorporate live data from sensor networks, weather stations, and management records. They provide the opportunity to simulate alternative management scenarios, evaluate climate and production risks, and even assist in the optimization of farming decisions prior to field application (Manivasagam, 2025) ^[36].

Explainable AI

Explainable AI (XAI) is a class of AI systems that provide their

recommendations and predictions in a way that is accessible and understandable to users. By enhancing transparency and interpretability, the confidence of farmers is increased, decision-making may be more informed, and the diffusion of AI-based agricultural technologies is facilitated (Chettri *et al.*, 2026) ^[15].

Edge Computing

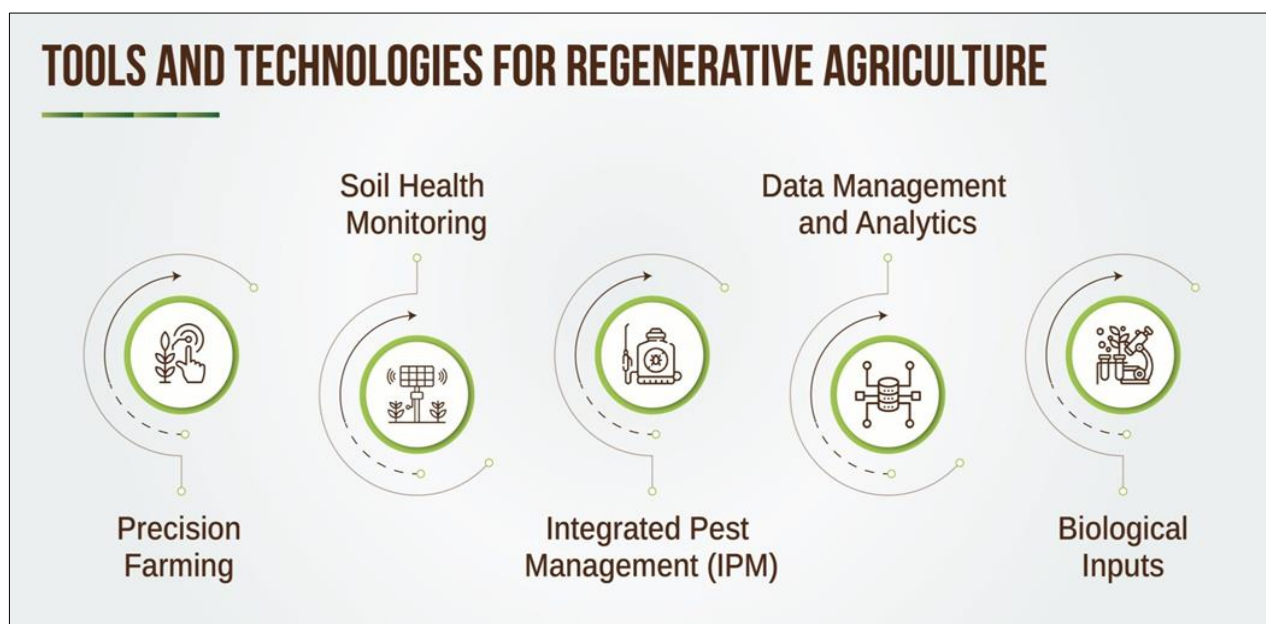
Edge computing is a distributed computing paradigm that brings computation and data storage closer to the location where it is needed, such as on-site with a sensor or an instrument, on a drone, or a farm machinery, rather than sending all the data to cloud servers. This allows for real-time processing and decision-making, as well as reducing the lag time associated with data transmission and dependence on the internet (Khan *et al.*, 2026) ^[28].

Blockchain Integration

Blockchain technology allows for a safe, transparent, and immutable digital record of farm activities and transactions. In regenerative farming, it enables tracking of sustainable agricultural practices, soil carbon sequestration, and carbon credit trading, promoting accountability and market trust (Parhamfar *et al.*, 2024) ^[44].

Autonomous Robotics

Autonomous robotics is the use of automated machines with sensors, AI, GPS navigation, and other technologies to carry out farming operations with little human intervention. Robots can now perform precision planting, selective weeding, crop monitoring and field scouting, enhancing efficiency, minimizing labour needs and enabling sustainable crop management (Botta *et al.*, 2022) ^[13].



Source: KhetiBuddy. <https://khetibuddy.com/blogs/innovative-tools-and-technologies-supporting-regenerative-agriculture/?utm>

Fig 6: Tools and Technologies for Regenerative Agriculture

8. Challenges and Limitations

Technical Challenges

Data limitations, inadequate interoperability, and model uncertainty are significant impediments in applying advanced digital technology and artificial intelligence in agriculture. Data scarcity is related to the fact that high quality, standardized and

long term datasets are scarcely available to develop accurate models and make sound decisions. Bad interoperability is the existence of problems related to data and communication interoperability in different sensors, platforms, software systems and agriculture technologies within which each side wants exchange information to its own peculiar format. In

addition, model uncertainty is induced by environmental conditions, quality of data and assumptions made in predictive models that may cause errors in predictions and recommendations. It will be important to overcome these challenges to enhance the reliability, scale and impact of digital agriculture solutions (Hossen *et al.*, 2025; Challinor *et al.*, 2018) [21, 14].

Economic Constraints

High capital expenditure, burden of infrastructure and low affordability for small farms constitute major impediments for enhancement of adoption level of high-tech agriculture. Various digital tools, precision farming machinery, sensors, drones, and automated systems demand significant initial investment and supporting infrastructure such as dependable electricity, internet access, and technical assistance. These costs may be prohibitive for small-scale and resource-poor farmers, limiting their access to cutting-edge technologies and producing disparities in technology adoption. It is essential to handle these limitations by means of affordable options, financial support modalities and capacity building schemes to ensure for the inclusive and sustainable agricultural development (Erike *et al.*, 2025; John *et al.*, 2023; Mizik, 2023) [17, 25, 37].

Social Challenges

The digital literacy divide, farmer acceptance, and trust in *AI-based* suggestions are all significant social issues influencing the diffusion of digital agriculture technologies. A lack of technical expertise and skill may impede a farmer's ability to take advantage of sophisticated tools and analyze digital data. Furthermore, hesitation in embracing new technologies and doubts about the accuracy of *AI-based* advice may erode farmer trust and hinder progress. 3 Environmental and ethical questions have also been raised as a result of the growing use of *AI*: these include the energy requirements of *AI* systems, which can be a source of carbon emissions, and issues surrounding data privacy and ownership, in which concerns about the collecting, storing, sharing, and controlling of farm data must be confronted to promote transparency, security, and responsible use of technology (Vedamurthy *et al.*, 2026; Gardezi *et al.*, 2024; Atapattu *et al.*, 2024) [61, 18, 7].

9. Research Gaps

Future work on *AI-enabled* regenerative agriculture should prioritise long-term field-based validation of *AI-enabled* regenerative systems, to test effectiveness in a range of agricultural environments and over time. The development of *AI* models for smallholder systems, which are specific to their resource-constrained environment and management practices is required. Developing a standard set of indicators for the assessment of regenerative agriculture will provide a baseline against which soil health, biodiversity, carbon sequestration and sustainability can be regularly quantified. There is a call for research focusing on so-called techno-socio-environmental data integration to enable 'holistic' decision-making that serve environmental and livelihood outcomes. In addition, the advancement of interpretable and transparent *AI* models is critical for the enhancement of user trust, accountability, and acceptance. Lastly, development of regional climate resilience models will enable farmers to tailor regenerative principles to local climates, increasing the relevance of, and success in implementing, climate-smart agricultural practices (Omotayo *et al.*, 2025; Rajbongshi *et al.*, 2026) [42, 48].

10. Future Prospects

Digital twins powered by *AI*, climate forecasting systems, autonomous drones and robots, carbon accounting platforms, multi-source sensor networks, and generative *AI* advisory systems constitute a newer generation of smart agricultural technologies. *AI-based* digital twins generate virtual farm representations for scenario analysis and decision-making support and climate forecasting systems deliver improved predictions for better climate resilience and risk management. Unmanned air vehicles and robots can perform precision surveillance, planting, weeding, and crop care with little human involvement. Carbon accounting platforms enable quantification, reporting and verification of the benefits of carbon sequestration and greenhouse gas mitigation. Integrating data from soil, crop, weather and environmental sensors, multi-source sensor networks deliver detailed, real-time farm intelligence. Generative *AI* advisory systems have the potential to process large volumes of agricultural information and provide individualized advice, contributing to the efficient use of resources, enhanced productivity, and the adoption of sustainable regenerative agriculture practices (Gund *et al.*, 2025) [20].

11. Conclusion

AI-enabled digital twins build virtual farm models that interact with live data to simulate management strategies, forecast results, and enhance decision-making. Climate prediction products employ sophisticated analytics and *AI*, yielding weather and climate predictions that inform farmers on managing risk and adapting to evolving environmental conditions. Drones and robots autonomously execute a variety of agricultural activities including crop monitoring, precision spraying, seeding, and weeding, with little to no human supervision, optimizing productivity while minimizing labor needs. Platforms for carbon accounting facilitate measuring, monitoring, and verifying sequestration of carbon and greenhouse gas emissions, contributing to carbon credit systems and sustainability reporting. Heterogeneous sensor networks aggregate information from soil sensors, weather stations, drones, satellites, and farm equipment to deliver integrated real-time data about crop and environmental conditions. Generative *AI-based* advisory systems process extensive, heterogeneous datasets, including crop management, resource optimization, and sustainable agriculture best practices, to provide tailored recommendations that can increase productivity, resilience, and environmental sustainability.

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