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Reinventing Conservation Agriculture with Artificial Intelligent Systems: A Review

Kuldeep Kumar[1], Raj Kumar[2], Vineet Kumar[3], Vimal Kumar[4], Rajbir Singh[2], Saurabh[5], Vijay Kumar[6]

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ABSTRACT

Conservation Agriculture (CA) has become a new sustainable management model, which improves the health of soils, increases the efficiency of resource use and guarantees the agricultural productivity in the long run. None the less, the agricultural sector is becoming the victim of the climate change, soil erosion, water shortages and food insecurity. Machine learning and computer system vision are the core features of Artificial Intelligence (AI), which can offer new data-driven solutions to these issues and reinforce sustainable agriculture systems. A systematic literature review was conducted through the process of locating peer-reviewed articles and reports, which were published in 2015-2024. The Artificial Intelligence, Conservation agriculture and precision farming keywords had been used to get the related studies in dataset like Scopus, google scholar and web of science. The literature chosen was examined in terms of theme to evaluate the implementation of AI in soil management, crop production and climate resilience. The results reveal that conservation Agriculture as represented by limited soil disturbance, crop and permanent soil cover rotation practice has good implications on soil sustainability. The PI technologies also introduce precision to the systems of resource management, real-time crop monitoring, detection of diseases and pests, yield prediction, as well as climate-directed decision-making. An AI-CA system will render the process more efficient and less destructive to the environment and will result in data-driven farming.

Key words: Artificial intelligence, Conservation agriculture, Machine learning, Precision agriculture, Sustainable agriculture.

Conservation agriculture is increasingly being promoted as sustainable farming based on a high emphasis on soil security, low use of external inputs and an increase in long-term productivity (FAO, 2017).

Such practices enhance the soil structure, erosion and resource management, Climate variability, soil degradation, water and food shortages are some of the significant issues that agriculture is currently experiencing due to decreased soil fertility, water shortages and increased food demand worldwide. The conventional methods of farming are in most cases not able to mitigate these problems.

Artificial Intelligence as a terminology can be considered a set of calculation techniques (machine learning, deep learning and computer vision) that enable machines to process large volumes of data, identify trends and support decision-making. Agriculture is under pressure because of climatic changes, soil erosion, water scarcity and the increasing world population. The major features of its practices include minimal mechanical disturbance on soil, cover on the soil and crop rotations. The AI has found use in the agricultural sector to manage crops, predict crop yield, identify diseases and pests and augment climate resilience (Kamilaris and Prenafeta-Boldu, 2018).

Agricultural applications of AI, such as yield prediction, disease detection, intelligent irrigation and others are already starting to provide agricultural systems with a sustainable existence (Mohanty *et al.*, 2016). These technologies are quite aligned with CA ideas because of the higher efficiency and the reduction of the effect on the environment.

[1]Department of Agronomy, IIMT University, Meerut-250 001, Uttar Pradesh, India.
[2]School of Agricultural Sciences, IIMT University, Meerut-250 001, Uttar Pradesh, India.
[3]Department of Soil Science, IIMT University, Meerut-250 001, Uttar Pradesh, India.
[4]Department of Horticulture, IIMT University, Meerut-250 001, Uttar Pradesh, India.
[5]Department of Agronomy, Major S.D. Singh University, Farrukhabad-209 601, Uttar Pradesh, India.
[6]Department of Genetics and Plant Breeding, IIMT University, Meerut-250 001, Uttar Pradesh, India.

Corresponding Author: Kuldeep Kumar, Department of Agronomy, IIMT University, Meerut-250 001, Uttar Pradesh, India.
Email: agronomy.kk@gmail.com
ORCIDs: https://orcid.org/0000-0002-9273-1083, https://orcid.org/0000-0002-3777-3424, https://orcid.org/0009-0001-1991-2742, https://orcid.org/0009-0001-6006-3084, https://orcid.org/0009-0004-1418-0580, https://orcid.org/0009-0007-4144-2744, https://orcid.org/0000-0003-1531-7126

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Secondly, recent studies state that AI-driven agriculture can be used to improve the soil and crop productivity and assist in supporting agricultural methods to get sustainable yield (Selvaraj and Vinod, 2023; Mohan, 2023).

The combination of AI and CA will help to offer efficient, sustainable and accurate solutions to current farming problems (Fig 1).

Research gap

Irrespective of these extraordinary advances in AI and CA there has been little attempt to unite the two. The possibilities of learni ng such areas are widely researched in separate spheres, yet not combined in a comprehensive way.

Objective

This review will look at the ways AI can be applied in enhancing Conservation Agriculture and areas where future studies ought to be based.

This paper uses a systematic literature review methodology.



Fig 1: Data-to-decision pipeline in intelligent conservation agriculture**.**

Data sources

Literature was collected from Scopus, Google Scholar, Science Direct and Web of Science.

Search strategy

Keywords included:

- Artificial intelligence in agriculture.
- Conservation agriculture.
- Precision farming.
- Machine learning in crop management.

Inclusion criteria

- Peer-reviewed articles.
- Publications from 2015-2024.
- Studies related to AI or CA.

Exclusion criteria

- Irrelevant or duplicate records.

Data analysis

A thematic analysis was conducted focusing on:

- AI applications in CA.
- Benefits and limitations.
- Future research opportunities.

The AI systems analyse data with the sensors, drones and satellites to make decisions in agriculture. The prediction of crop harvest, moisture of soil and pests' infestations is conducted through the machine learning, but model-based disease detection is carried out with assistance of deep learning strategy, like convolutional neural-networks (Mohanty *et al.*, 2016). Remote sensing technologies also enhance real-time monitoring of crops (Liakos *et al.*, 2018; Wolfert *et al.*, 2017).

These insights are pooled together by decision support tools and are used to suggest sustainable and conservation focused interventions (Wolfert *et al.*, 2017) (Fig 2).

AI applications in conservation agriculture

Precision resource management

AI-based decision support systems optimize irrigation, fertilization and pesticide use by analyzing soil, crop and

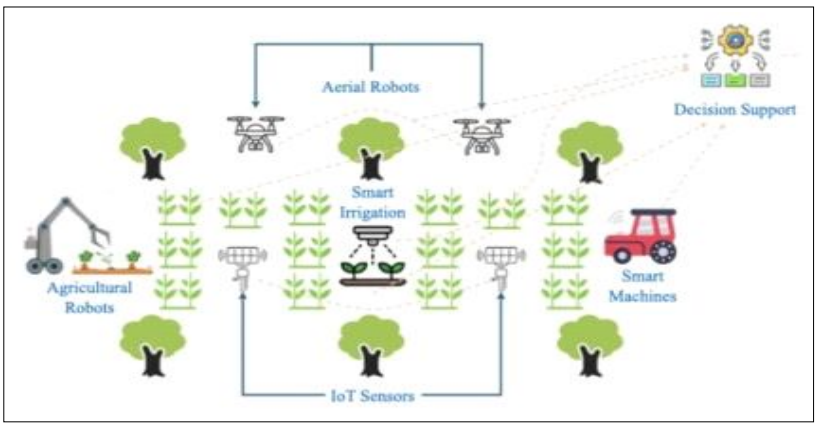


Fig 2: AI use throughout the conservation agriculture cycle.

weather data. This reduces resource wastage and improves efficiency (Kamilaris and Prenafeta-Boldu, 2018; Ramesh *et al.*, 2020; Manonmani, 2022).

Table 1 presents a detailed overview of these AI applications in the context of soil resource optimization. It quantifies the application of new technologies, like machine learning, remote sensing and decision-support tools for tracking soil health conditions; managing irrigation; optimizing nutrient inputs, *etc*. These strategies together promote input efficiency with sustainable soil management.

Monitoring of crop health and crop disease detection

The deep learning processing of images provides an opportunity to detect diseases in plants early enough, to restore crops when it is still in time, to minimize losses (Mohanty *et al.*, 2016; Singh *et al.*, 2023; Mohan, 2023).

An organized overview of the AI-based solutions used for crop monitoring and protection is illustrated in Table 2. It illustrates the use of methods like deep learning and computer vision to evaluate crop status, detect pests and diseases and estimate yield. These tools result in timely and informed decision-making processes, vital in order to minimize damage and enhance the general crop performance.

Soil health and moisture management

AI tools monitor soil moisture, nutrient levels and organic matter to support CA practices such as mulching and reduced tillage, improving soil fertility and water retention (Pathak *et al.*, 2019; Sahil and Bishnoi, 2023).

These practices increase soil stability, minimize erosion and enhance the capacity to retain water (Sahil and Bishnoi, 2023; Pathak *et al.,* 2019) (Fig 3).

Weed and pest management

AI-enabled robotics can identify crops, weeds and pests accurately so that herbicides and pesticides can be applied precisely in the exact locations. This targeted method lowers chemical-intensive agriculture in the field and facilitates sustainable agricultural methods (Slaughter *et al.,* 2008; Basa, 2024).

AI-supported field operations and automation is illustrated in Table 3. The technologies listed encompass robotic systems, autonomous vehicles, precision application methods for inputs that can have a role in effective weed and pest control. These innovations allow them to rely less on chemical treatments and practice more sustainable agriculture.

Climate-adaptive farming

Climatic variability presents a serious threat to the agricultural industry. Predictor models used by AI use historical and real-time weather data to help in crop selection, planting and rotation of crop decisions.

Table 1: AI for soil and resource management in conservation agriculture.

Application area	AI techniques	Role in conservation agriculture	Key benefits	Tools/Use
Soil health assessment	ML, remote sensing, GIS	Monitors soil nutrients, organic carbon, moisture	Improves soil fertility management	Satellite-based soil maps
Precision irrigation	IoT + predictive analytics	Schedules irrigation based on real-time needs	Saves water, reduces runoff	Smart drip systems
Nutrient management	Decision support systems	Recommends optimal fertilizer doses	Minimizes chemical inputs	Variable rate fertilizer applicators
Residue cover estimation	Computer vision, drones	Tracks crop residue retention	Prevents erosion, improves carbon sequestration	Drone imagery analysis
Carbon sequestration modeling	AI simulations	Estimates soil carbon storage	Supports climate-smart farming	Carbon accounting platforms

Table 2: AI for crop monitoring and protection.

Application area	AI techniques	Role in conservation agriculture	Key benefits	Tools/Use
Crop growth monitoring	Image analytics, deep learning	Tracks crop health and vigor	Early stress detection	Multispectral drone imaging
Pest detection	CNNs, computer vision	Identifies pest infestation hotspots	Reduces pesticide use	AI pest recognition apps
Disease diagnosis	Neural networks	Detects plant diseases early	Minimizes crop losses	Smartphone diagnosis tools
Weed detection	Vision-based robotics	Enables site-specific weeding	Reduces herbicide application	Robotic weeders
Yield estimation	Regression models, ML	Predicts harvest output	Better planning and marketing	Yield forecasting systems

This enhances the strength of CA systems with dynamic environmental conditions (Pathak *et al.*, 2019; Wolfert *et al.*, 2017).

The overview of AI-based decision-making tools for climate resilience is given in the Table 4. These range from predictive weather analysis and risk assessment models to crop planning systems and market forecasting tools. These enable farmers to adapt through the environmental data wave, while ensuring that conservation agriculture becomes sustainable and economically viable.

Data-driven decision support systems

The use of AI can integrate data at farms and regions to facilitate decision-making and policy generation (Ramesh *et al.*, 2020; Bharvey and Sharma, 2024).

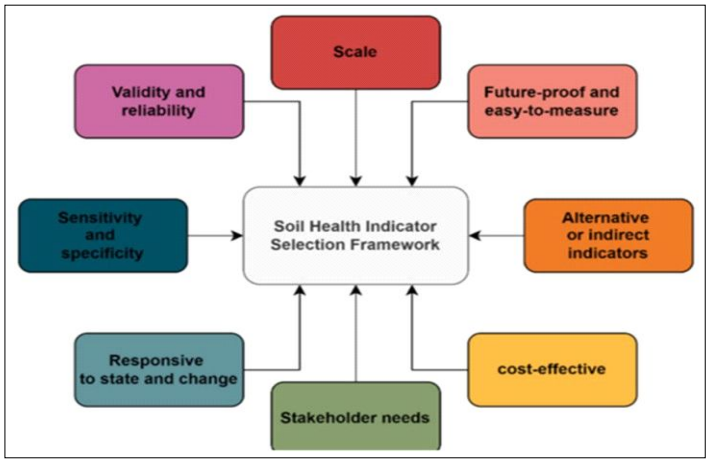


Fig 3: Intelligent systems framework on conservation agriculture.

Table 3: AI for machinery, automation and field operations.

Application area	AI techniques	Role in conservation agriculture	Key benefits	Tools/Use
Autonomous tractors	Robotics, reinforcement learning	Supports minimal tillage operations	Reduces soil compaction	Self-driving tractors
Precision seeding	GPS + AI optimization	Ensures accurate seed placement	Improves germination and yield	Smart seed drills
Variable rate technology (VRT)	ML algorithms	Site-specific input application	Cuts input costs and waste	Smart spreaders/ sprayers
Smart harvesting	Sensor-based automation	Optimizes harvest timing	Reduces losses	AI harvesters
Fuel efficiency optimization	Predictive analytics	Plans efficient machinery routes	Lowers emissions	Route planning software

Table 4: AI for decision support and climate resilience.

Application area	AI techniques	Role in conservation agriculture	Key benefits	Tools/Use
Weather forecasting	Predictive modelling	Provides localized forecasts	Improves planning	AI weather advisories
Climate risk analysis	Simulation models	Assesses drought /flood risks	Enhances resilience	Risk alert systems
Crop rotation planning	Optimization algorithms	Suggests sustainable sequences	Improves biodiversity and soil health	Rotation planners
Farm advisory systems	Expert systems, chatbots	Offers real-time recommendations	Supports informed decisions	Digital farm assistants
Market prediction	Data mining, ML	Forecasts price trends	Improves profitability	Price forecasting tools

The implementation of AI in Conservation Agriculture will be a paradigm shift to the sustainable agricultural system. AI is helping to use resources more efficiently, minimize the environmental effects and be more productive, as it makes interventions more precise and data-driven.

However, there are other aspects such as high cost of implementation, data and technical skills, particularly in developing countries and a host of others that have also contributed to non-adoption. The AI systems need strong datasets and infrastructure, which is not always available.

The future research has shown that farmers, the development of infrastructure and favourable policy frameworks should be the key to success (Manonmani, 2022; Bharvey and Sharma, 2024). These limitations are to be addressed to size AI-based CA systems.

CONCLUSION

The potential of AI to make inputs more efficient and sustainable is massive as it enables to monitor the state of soil and crops and advance practices that can resist climate changes. Despite such flaws as the costs, access to data and technical skills, the integration of AI and CA practices can be discussed as the worthy solution to improve efficiency and environmental accountability in the sphere of agriculture.

However, AI can be further developed and involve more policy so that it can be embraced by more individuals. AI and CA are yet another method of attaining sustainable agriculture and world food security.

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Disclaimers

The authors express their capacity to make opinions and conclusions that belong to them and it does not necessarily mean that they represent the opinion and conception of the organizations that they both participate in. Even though the authors are required to guarantee that the information is precise and full, they do not assume any responsibility of the losses that might be suffered as a result of using the information, both directly and indirectly.

Informed consent

The review study was carried out based on the use of secondary data on literature that was already published. Since no primary data collection was done, there was no need of ethical approval and informed consent.

Conflict of interest

The authors of this paper report that they do not have any conflicts of interest with respect to the publication of the same. None of the available funding and support affected the design of the study, data collection, analysis, publication decision, or the article preparation.

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