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REVIEW ARTICLE

Roles of artificial intelligence (AI) in the innovation of agriculture sector: A systematic review

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Abstract

This systematic literature review investigates the role of artificial intelligence (AI) in agriculture within emerging economies, with a focus on India. By analysing 211 scopus articles through the PRISMA protocol, the study explores how AI integrates with technologies like sensors, the internet of things (IoT) and big data analytics to drive sustainable agricultural development. Key themes identified include climate change resilience, precision farming, crop and yield management, natural resource conservation and digital agriculture. The study highlights four priority areas essential for adaptive agricultural strategies: climate-resilient crops, precision farming, sustainable practices (such as AI-driven irrigation and reduced agrochemical usage) and agricultural policy improvements. This review provides valuable insights for policymakers, researchers and practitioners, emphasizing AI's potential to transform Indian agriculture into a more efficient and sustainable system.

Keywords: agri policy; artificial intelligence; emerging economies; Indian agriculture; precision farming

Introduction

The swift expansion of agriculture is both a prerequisite and an adequate factor to initiate structural transformation, driven by advancements in technologies and innovations, leading to significant improvements in agricultural development (1). However, with the growing world population and shrinking resources, greater endeavours will be essential to achieve sustainable growth in agricultural production to meet global food needs and reduce food wastage (2). Study shows that the primary motivation for innovation in agri-tech arises from the necessity to enhance productivity to meet the rising demands of a growing global population (3). In such a scenario, the advent of technologies like artificial intelligence (AI), Internet of Things (IoT), blockchain and drones, coupled with crucial datasets, presents an unparalleled opportunity to enhance the efficiency and effectiveness of agricultural production systems (4).

In recent years, AI has gained increasing prominence in the domain of agriculture (5) to improve productivity and efficiency (6), crop yield prediction (7) data-driven smart farming for real-time operational decision and crop health management. The rapid evolution of AI technology in agriculture is required for better decision-making, leading to maximized efficiency in the agriculture sector (5, 8). AI techniques such as machine learning (ML) and computer vision have been used in agricultural management to optimize irrigation scheduling, predict disease outbreaks and enhance fertilization strategies (9). These studies highlighted the significant role of AI in making precise yield predictions and facilitating site-specific farming practices.

Although, there is a substantial literature available on AI in agriculture focusing on business model, benefits and challenges, dimensions of AI in agri-food sector and role of AI in agri value chain separately (5, 6, 10-12). Further, the literature on AI in sustainable agriculture has been comprehensively reviewed (3) and a productivity-focused review on AI (ML) in agriculture has also been conducted (7). However, to the best of the authors' knowledge, no comprehensive study has been commenced to date in sustainability and productivity in the Indian Agricultural domain. The following research questions are therefore proposed for this study.

RQ1: How has the research focus on AI applications in agriculture evolved over time in India?

RQ2: What are the major themes in the existing literature on AI and agriculture in the Indian context?

RQ3: What are the future research opportunities existing in the study area?

The arrangement of this research is structured as follows: The subsequent section provides an overview of the background of the review in the field of AI in agriculture, followed by the methodology section. The examination of the chosen literature contributes to the results and discussion section, where all research questions are addressed. Ultimately, the study is concluded in the conclusion section, which includes suggestions for future research and offers a roadmap to stakeholders.

Review of literature

In the past, few systematic reviews have been conducted by researchers in the domain of AI in agriculture. More recently, AI applications in agriculture, focusing on business model development, wherein 37 articles sourced from Scopus, EBSCO and WoS were examined through content analysis was reviewed in the previous research (10). The study suggested opportunities for farmers and entrepreneurs to support the decision-making process for profitability in agriculture. A review of AI literature in agriculture and allied sectors was carried out on the principal AI applications in agriculture, highlighting the main benefits and challenges of AI adoption in the sector (11). Similarly, a review was conducted to provide a broader understanding of the area, along with identifying potential areas for future research in a more holistic manner (13, 14). The review was carried out based on 17 high-quality studies (having high impact factors) during five years (2017-22). Similarly, 69 documents retrieved from the Scopus database, covering the timespan 2009-2022, were systematically reviewed to address the dimensions of AI in the agri-food sector (6). The same study utilized bibliometric coupling to identify some clusters under the domain and suggested an interpretive framework.

Furthermore, the challenges and opportunities associated with the integration of AI-driven advancements in agricultural systems and processes were reviewed using the Scopus and WoS databases, covering 10786 articles over a span of nearly 43 years (1978 to July 2021) (5). The study was more specifically about the adoption of AI in agriculture in the global space. It provided a theoretical framework for further examination of the factors responsible for adopting AI in agriculture. Similarly, with a focus on the agricultural value chain (AVC), the use of AI was reviewed through the analysis of 88 articles including journals, reviews, conference papers, books and newspaper articles from 1994 to 2020 using content analysis (12). In addition, a study pinpointed the primary research clusters within agri-food supply chain studies from the WoS database (90 documents) through bibliometric (co-occurrence) analysis and conducted an in-depth content analysis of 18 papers to determine specific AI applications and their role in improving supply chain efficiency (15). Their findings indicated a rapid surge in the influence of AI on food production. They underscored the significance of implementing these technologies throughout the supply chain, emphasizing stakeholder engagement and the utilization of diverse data sources to achieve sustainable outcomes in agri-food, such as reducing food waste and heightened awareness (15). Table 1 summarizes the major extent reviews.

Research gaps

In contrast to the existing reviews, the current study utilizes two science mapping techniques, namely co-occurrence and co-

Table 1. Extant literature review on AI in agriculture

Title	Methodology	Research Question(s)	References
Artificial intelligence-led innovations for agricultural transformation: A scoping study	SLR (Bibliometric Content analysis)	RQ1. What are the significant keywords, current trending topics and interconnections in the domain of AI and agriculture? RQ2. How has the research in this area and its underlying themes evolved over time? RQ3. What are the existing research gaps and potential areas for further investigation in this field?	(13)
Artificial intelligence and new business models in agriculture: a structured literature review and future research agenda	SLR (Content Analysis), 37 documents (Scopus)	RQ1. What can be the contribution of AI to the agricultural sector, especially in the creation of new business models? RQ2. What research implications emerge?	(10)
Artificial Intelligence in Agriculture: Benefits, Challenges, and Trends	SLR (Content Analysis), 17 documents (ScienceDirect; Scopus; Springer; IEEE Xplore; MDPI)	RQ1. What are the most influential countries, research institutions, journals and principal papers in AI techniques applied to agriculture? RQ2. What are the principal AI techniques applied for domains of agriculture tasks? RQ3. What are the main benefits and challenges of adopting AI for agriculture?	(11)
Unleashing the value of artificial intelligence in the agri-food sector: Where are we?	SLR (Bibliometric Analysis on 129 documents - bibliographic coupling method and Content Analysis with 69 documents) Scopus database	RQ1. What is the state-of-the-art in management studies on AI in the agri-food sector? RQ2. What are the dimensions of AI in the agri-food sector? RQ3. Which are the impacts of AI on value chain activities in the agri-food sector? Are they at firm or inter-firm level?	(6)
Artificial intelligence research in agriculture: a review	SLR (Bibliometric Analysis - Only performance analysis), 10786 documents, Scopus and Web of Science	RQ1. What is the status of research using AI in the agriculture domain? RQ2. When and where this research has been published? RQ3. What are the influencing factors for adopting AI in agriculture and how can these be classified? RQ4. What are the conclusions from existing research and directions to the future work?	(5)
Artificial intelligence in agricultural value chain: review and future directions	SLR (Descriptive Analysis using Nvivo) 88 documents indexed in Google scholar, Scopus and Web of Science	Not specified	(12)

citation analysis, to identify the relevant themes within the domain of AI in agriculture, which has only been briefly explored in previous research (13). However, the context of that study was broader, encompassing agriculture and allied fields (14). In comparison, the present study is unique in its specific focus on agriculture and farm-related aspects. Further, the existing reviews are more confined towards one specific agenda of agriculture, such as agribusiness model, agri value chain, challenges and opportunities in the domain of AI in agriculture, adoption of AI, application of AI in agriculture, marketing and supply chain. However, the present article aims to explore the complete domain knowledge of AI in a sustainable agriculture ecosystem. Moreover, the current study is focused on the Indian context, providing real examples from public and private institutions utilizing the application, thereby providing an overview and future directions for the researchers, practitioners and policymakers to understand the evolution of AI in the agriculture domain, more specific to the developing countries.

Methodology

Aligned with the research questions (RQs), we conducted a systematic literature review (SLR) to achieve a state-of-the-art synthesis of the literature, aiming to derive interpretations through sensemaking. This approach facilitates a deeper understanding and straightforward comprehension of emerging themes within the subject area, as recommended in the previous study (16). The PRISMA protocol was adopted for the SLR process.

PRISMA protocol

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method was chosen for its thoroughness and applicability across diverse fields, given its widely recognized and established nature (17). The detailed PRISMA method is depicted in Fig. 1 and summarized below for more clarity, providing a robust framework for our research.

The SCOPUS database was opted for in this research because of its comprehensive coverage and advanced search functionalities, surpassing other databases, as emphasized (14). The selection of keywords for the database search resulted from a thorough literature review, expert discussions and consultations. During this process, terms like Artificial Intelligence, Machine Learning, sensor, Agri*, farm and India were identified as promising keywords for retrieving relevant studies from the database. An advanced query search conducted on September 3, 2023, produced 952 documents. Articles published until August 2023 were included in this study to provide a thorough and current overview of the prevailing status of AI in agriculture.

The initial search for documents concentrated on the textual content found in titles, abstracts and keywords. This method was chosen based on the widely accepted belief that these elements efficiently communicate the central theme of an article (18). This thorough examination covered all pertinent subject areas in AI in agriculture to ensure the inclusion of the most relevant and impactful research. This study focused solely on publications in their final stage and only articles in the English language were included in the database search. In view of the above, the following search query was initiated.

Search query: (TITLE-ABS ("Artificial Intelligence" OR "Machine Learning" OR "ML" OR "DL" OR "sensor" AND ("Agri*" OR "farm") AND ("India")) AND (LIMIT-TO (DOCTYPE,"ar") OR LIMIT -TO (DOCTYPE,"re"))).

A crucial step in conducting a systematic literature review is data cleaning, which involves removing errors and inconsistencies from the data to ensure the reliability and accuracy of the findings (19). An initial screening was carried out to eliminate irrelevant or duplicate articles. This process excluded 205 articles with missing data and 256 with no associated impact factor. Furthermore, a comprehensive manual review was conducted, leading to the exclusion of 280 inappropriate articles. Following this meticulous process, a final set of 211 articles was chosen for further analysis. The rigor of the study was ensured by including articles published in high -quality journals with a Clarivate Impact Factor (IF). This process narrowed down the dataset to 211 articles for further analysis. To map the literature from the selected database, the VOS viewer, a computer program for bibliometric mapping was used as an analytical tool (20).

Results

This study section presents the results and discussions aligned with the pre-defined research objectives. The analysis begins by examining the chronological development of research in the application of AI in agriculture. It then proceeds to conduct a co -occurrence network and co-citation analyses within this domain. Finally, it outlines underlying themes in AI in agriculture and proposes potential areas for future research.

Evolution of studies on 'AI in agriculture'

The progression of scientific productivity in AI applications in agriculture is depicted in Fig. 2. In the late 1990s, the studies on the remote sensing and estimation of temperature, soil condition, yield and monitoring of crops and yield were the pattern of studies. However, during the 2000s, there was a limited number of research endeavours delving into AI applications in agriculture. Most of these investigations concentrated on assessing the impact of biomass burning on aerosol characteristics, employing remote sensing techniques in conjunction with AI in line with the existing study (21). A substantial surge in research related to AI applications in agriculture was recorded post covid with the significant expansion. In 2022, there was a three-fold increase in the research volume, with 81 studies conducted, compared to just nine studies in 2020. The COVID-19 pandemic played a pivotal role in driving the adoption of AI in agriculture by creating a pressing demand for innovative solutions to address challenges and ensure food security. In 2023, till September 2023, 60 articles were published. These remarkable growth in the use of AI in the agriculture sector can be attributed to advancements in technology, heightened awareness and a pursuit of efficiency.

Co-occurrence analysis

In this study, thematic analysis was performed to understand the themes under the domain of AI in agriculture with the help of keywords co-occurrence. Fig. 3 shows the clusters that emerged in the analysis. The themes analyzed in this section are described as below.

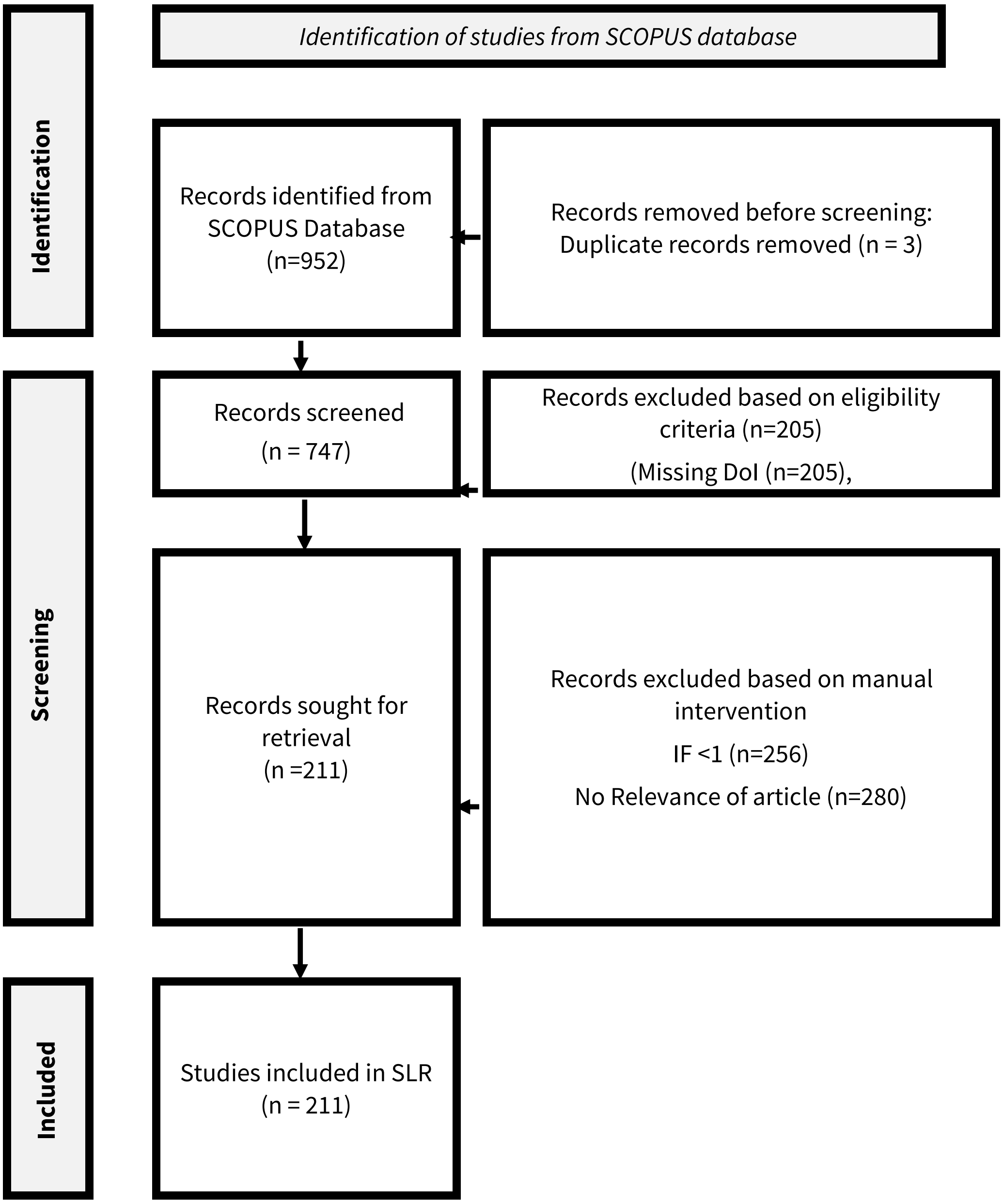

Fig. 1. PRISMA 2020 protocol for SLR.

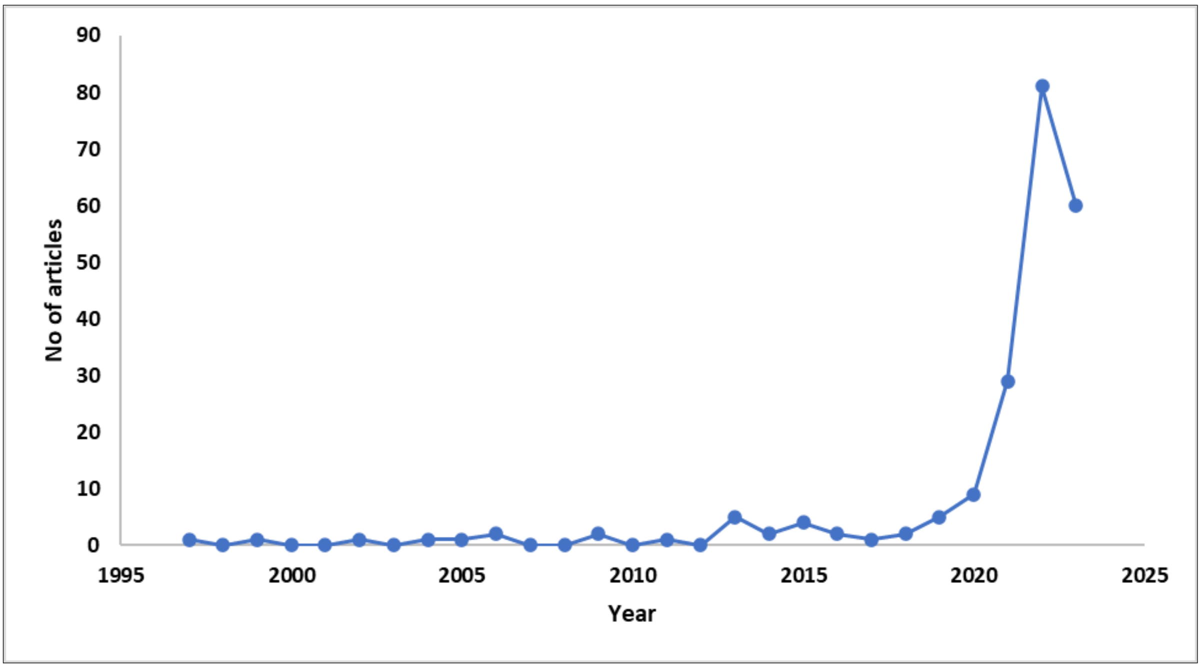

Fig. 2. Annual scientific production in the common area of AI and agriculture.

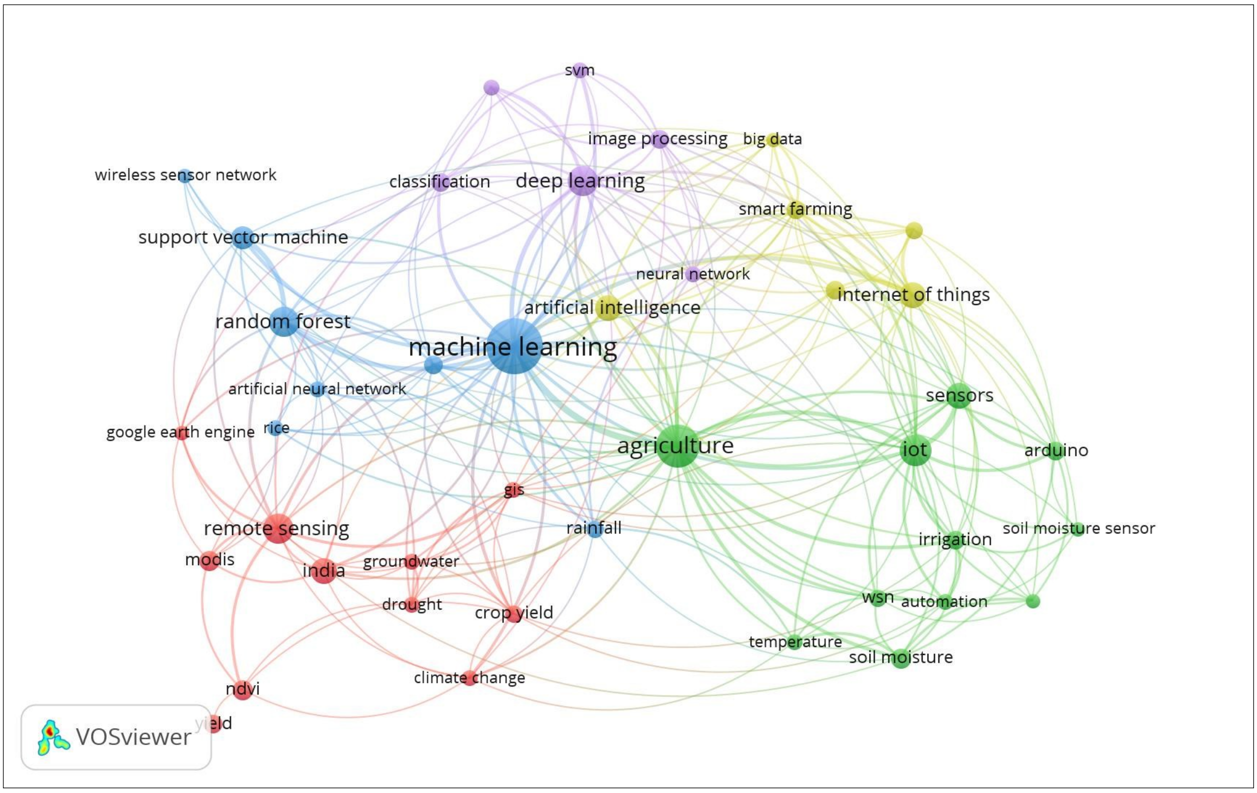

Fig. 3. Co-occurrence network of author's keywords (Cluster 1: Red, Cluster 2: Green, Cluster 3: Sky Blue, Cluster 4: Yellow and Cluster 5: Purple).

Theme 1: Climate change, agriculture and AI (cluster 1) : Cluster 1, in red, heavily focuses on climate change, remote sensing, yield, GIS, etc., hence named climate change, agriculture and AI. Climate change is a significant factor affecting agriculture. It leads to shifts in weather patterns, increased temperatures and alterations in precipitation, all which impact crop growth and production, resulting in yield differences. Further, droughts, often exacerbated by climate change, severely impact agriculture. Water scarcity affects crop growth and can lead to yield losses. Uses of AI and ML thus introduced in the agriculture sector to reduce the risk of unforeseen climate impact. Remote sensing technologies, including satellite imagery, are critical for monitoring climate-related changes in agriculture, such as crop health and land use. Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data is used to monitor changes in vegetation and land cover, providing insights into the impact of climate change on agriculture. Further, Normalized Difference Vegetation Index (NDVI), derived from satellite data, assesses vegetation health, which is closely tied to climate conditions and crop growth.

Theme 2: Innovation ecosystem (Clusters 1 and 5): Clusters in green depict the keywords, sensors, IoT, soil moisture, microcontroller, etc. This cluster encompasses integrating AI with various technologies to enhance agricultural practices, which is, therefore, named the Innovation Ecosystem. These keywords are related to each other, such as IoT is fundamental in collecting data from sensors and devices deployed in agriculture, Sensors are critical for collecting data on soil moisture (monitoring soil moisture level is essential for efficient irrigation), temperature, weather and crop health. Cluster 5 (in purple) is also clubbed with this theme. One of the finest examples in India is an initiative of the Government of Telangana and the World Economic Forum through its 'Saagu Baagu' Project, an AI-led Agricultural Innovation project benefiting several farmers in the region. Recently, a pilot project on cotton with 17000 farmers resulted in a 25 % higher income and a 17 % better yield for the connected farmers. The project benefits farmers through a data-driven precision farming approach such as managing soil micronutrients, temperature data, moisture data, pest historical data, crop images, micro weather historical data and forecasts through the mobile application (4).

Theme 3: Precision farming and crop management (Cluster 3): Based on the keywords grouped under this cluster, it is named 'Precision farming and crop management.' Artificial Neural Network (ANN) and Machine Learning are used for data analysis, enabling precise decision-making in farming. Random forests, Artificial Neuron Networks and support vector machines are machine learning techniques used for classification and prediction in agriculture, aiding in crop management decisions. Further, wireless sensor networks are deployed to collect data on soil moisture, temperature and other variables for precise crop management.

Theme 4: Digital agriculture and big data in agriculture (Cluster 4) : The theme 'Digital Agriculture' encompasses integrating artificial intelligence, big data analytics and IoT technologies to revolutionize traditional farming practices, improve efficiency and enhance agricultural sustainability. This theme aligns with the modernization of agriculture through cutting-edge technologies. AI is at the core of transforming agriculture by enabling smart decision-making, optimizing resource use and automating tasks. Big Data in agriculture increasingly relies on vast amounts of data for insights and predictions, driving the need for advanced data analytics. Similarly, IoT devices, such as sensors and drones, are instrumental in collecting real-time data from farms, enhancing precision in agriculture. A case study of Wangree Health Factory company of Thailand reveals that with the use of digital technology, the company can manage sustainability in the social, environmental and economic aspects with revolutionary performance such as almost 99 % reduction in water consumption, 80 % reduction in fertilizer cost, 30 % reduction in unit cost, higher quality of life due to controlled aerial environmental factors and better-quality grade than conventional agriculture (22).

Co-citation analysis

The co-citation analysis was conducted using VoS viewer software on the selected dataset. The analysis was based on a minimum citation threshold of four citations for a referenced source. Three of the 27 initially identified documents were repetitive, leaving 24 unique studies for further co-citation analysis (Fig. 4). The result of this analysis is categorized into four themes.

Theme 1: Machine learning and big data in agriculture (Cluster 1, 2 and 7) : The field of machine learning (ML) encompasses various approaches. Supervised learning leverages labelled data to make predictions, unsupervised learning identifies patterns within unlabelled data and semi-supervised learning combines both data types for learning purposes. Each approach has strengths and applications, making them valuable in data science and artificial intelligence.

In agriculture and land policy, ML algorithms play a crucial role in improving agricultural practices. These algorithms, including Random Forest (RF), Multivariate Adaptive Regression Splines (MARS), Flexible Discriminant Analysis (FDA) and Support Vector Machines (SVM), as highlighted in the former research (23), are driving significant advancements. We demonstrate substantial accuracy gains with bagging and advocates SVM as a robust predictor, as further supported in the previous study (24). Furthermore, an illustration was carried out using RF through R coding, open-source software for handling extensive and complex metadata in genomic experiments as mentioned in the previous study (25). Liaw's work also delves into various ML approaches used in Deep Learning (DL), encompassing supervised, unsupervised, reinforced and indirect search methods for encoding deep and large networks. Studies adopted ML for diagnosing plant diseases, proving AI's use in agriculture for best agri practices (26, 27).

Theme 2: Crop health management (Cluster 5): A deep convolutional neural network model was used to predict leaf disease in an experiment conducted on mango leaves with high accuracy (28), the researcher employed an MCNN model to predict anthracnose, a fungal disease affecting mangoes, achieving higher accuracy in their predictions. The adoption of AI, especially the DL aspect, in image and data processing to address various agricultural challenges such as leaf classification, disease detection, plant identification, fruit counting and growth measurement was conducted in the previous research (29). The case of FASAL (https://fasal.ai/), an Indian agri-business startup, utilizes AI to prevent diseases (downy and powdery mildew) by restricting extra spray in vineyards.

Theme 3: Yield prediction and forecasting (Cluster 3 and Cluster 6): Enhancing the productivity and quality of crop yields, alongside minimizing operational expenses and environmental impact, stands as a primary objective in precision agriculture. A previous study utilizes AI techniques for crop yield prediction and nitrogen status estimation in the soil (30). Further, a case analyzing the impact of extreme climate events on crop yield in southeastern Australia provided new insights by developing an AI-driven model for better crop yield prediction (31). The theme featured studies on ANN and vector regression techniques. Within the existing literature, AI methods like ANN and SVM have demonstrated successful applications in forecasting oilseed production in India (32). Research has made substantial contributions to the field of forecasting, providing a robust foundation for predictive learning and developing highly accurate models in the realm of AI (33).

Theme 4: Environmental and natural resource management (Cluster 4): Efficient water utilization in agriculture is a prominent challenge agricultural scientists face worldwide. In response to this challenge, a study proposed the adoption of proximity sensors or wireless sensors in agriculture to optimize crop irrigation (34). Consequently, integrating sensors into agriculture can provide technological support for the detection and prevention of various critical issues both on and off the farm. This integration fosters a more balanced relationship among soil, water and air ecosystems.

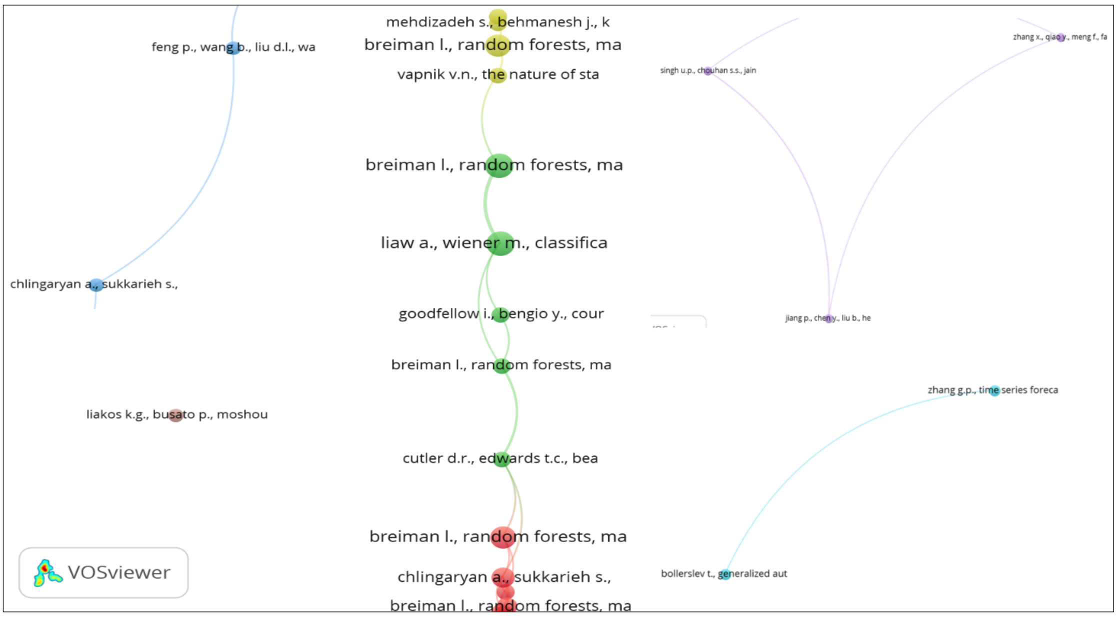

Fig. 4. Co-citation analysis (Cluster 1: Red, Cluster 2: Green, Cluster 3: Sky Blue, Cluster 4: Yellow, Cluster 5: Purple, Cluster 6: Cyan and Cluster 7: Brown).

Co-occurrence and co-citation analysis reveals commonality in themes such as crop management, precision farming, smart farming ecosystem and digital agriculture. Several startups in India have done Promising work in these areas (Table 2). Cropin, DeHaat, AGNEXT, aquaconnect, FarmERP and Xarvio are organizations working in farm management, crop monitoring, AI-based supply chain monitoring, advisory, consultancy to farmers and yield predictions. Further, analysis reveals that literature on yield prediction emerged as one of the areas of high concern for stakeholders ensuring farmers' income.

Scope for future research in the field of AI in agriculture

AI-based technologies have proven their effectiveness across various sectors, including agriculture. In the agricultural context, these technologies, such as AI-driven crop monitoring, irrigation optimization, soil analysis and weed management, have played a pivotal role in increasing crop yields and overall agricultural productivity (35). Additionally, AI-driven agricultural robots have emerged as valuable assets in the agricultural sector. These advancements are driven by integrating AI and digital technologies into farming practices. They enable real-time monitoring and data-driven decision-making, leading to more efficient and sustainable agricultural processes. The potential of AI in agriculture continues to expand, offering innovative solutions to address the challenges of modern farming, such as resource optimization, labor shortages and the need for sustainable practices. The Present study provides a view on the objectivity of agricultural development wherein sub-themes of AI in agriculture are categorized under Sustainability and Productivity (Table 3). Further, based on the results of co-occurrence and co-citation analysis, the future research areas are given under Fig. 5, which categorizes the scope under four major domains, namely climate change and Use of AI, Precision Agriculture, Sustainable Agri Practices and Agri policy and advisory.

Table 3. Broad objectives of agricultural development viz-a-viz areas of study under AI in agriculture

Sustainability	Productivity
Climate change	ML and Bigdata in Agriculture
Environment and natural resource management	Yield prediction and forecasting
Digital agriculture	Precision farming
Smart farming	Decision making in Agri production
Crop health management	Crop health management
Innovation ecosystem	Agriculture policy and advisory
Agriculture policy and advisory	Smart farming

Table 2. Most promising AI applications in Indian agriculture

AI Application	AI driven tech. solutions to agriculture	Features
Cropin	Farm Management, Crop Monitoring Precision Agriculture	Geotag farm plots, Monitor input usage, share weather-related advisory, Monitor crop health remotely, Set pest and disease alerts, Manage alerts and activity log, Set up workflows and tasks for the field team
DeHaat	Supply Chain and Farm Advisory	AI-powered advisory based on the crop, agro-climactic conditions and specific farming conditions of the farmer. Early-warning for crop protection
AGNEXT	Crop monitoring and post-harvest management	Provider of a platform for monitoring and improving agricultural food quality. It offers solutions for farmers to manage farm activities such as post-harvest procurement assessment and management, inventory monitoring and control, automated quality auditing, food traceability and more
Aquaconnect	AI-based end-to-end solutions for shrimp and fish farmers	It offers data-driven farm advisory by using the deep learning method. It provides context-aware alerts and suggestions regarding water quality and aquatic health. It also provides formal finance and insurance linkages and improves the market linkage of the farmers
FarmERP	Crop monitoring and Prediction of Yield	Pest Infestation Monitoring, Predictive Analytics, Soil Analysis, Disease Detection, Livestock Management, Real-time Visibility into Agri Supply Chain
Xarvio	Field monitor	Receive, upload and analyze all field-zone specific information in one place. Increase transparency and make better informed decisions for fields, all year long

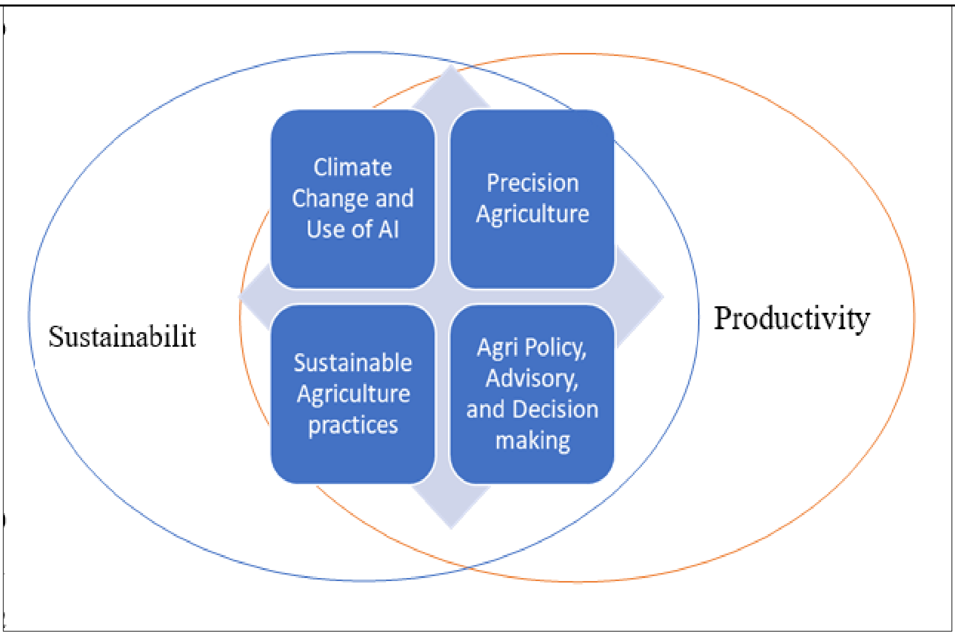

Fig. 5. Domain of AI driven agriculture development.

Climate change and AI

AI framework can handle large climate-related datasets, thus enhancing the precision of climate predictions and our understanding of future climate change impacts (36). In the realm of climate change, future research endeavours aim to develop adaptive strategies for agriculture, encompassing the study of climate-resilient crops, precision farming techniques to alleviate climate risks and a comprehensive assessment of the socio-economic impacts on farming communities. Concurrently, environmental and natural resource management research is poised to concentrate on sustainable practices, including efficient water and soil conservation methods. AI-driven models outperform traditional methods in forecasting extreme events, notably droughts and floods, thereby reducing risks to human lives (37, 38). AI's role in carbon capture and sequestration, exploring its applications in advanced materials and technologies crucial for reducing greenhouse gas emissions (39). Anticipated studies may delve into technologies such as conservation tillage and agroecological approaches to optimize natural resource utilization.

Precision agriculture

Precision agriculture, enabled by AI, is a game-changer for modern farming. AI-driven systems have the potential to enhance agricultural productivity while reducing environmental impact significantly. Farmers can anticipate crop yields more accurately by utilizing AI, enabling them to develop effective marketing strategies and mitigate potential risks (8). AI algorithms are crucial in identifying crop health, nutritional deficiencies and pest incidence through high-resolution images, leading to precise resource allocation and management (4, 40). Furthermore, AI systems can tailor input applications to specific field conditions, optimizing resource utilization and minimizing environmental effects (41). When coupled with the Global Positioning System (GPS), AI technologies ensure accurate seed positioning, resulting in consistent crop growth, improved nutrient utilization and reduced wastage (42, 43).

Real-time data and weather predictions, harnessed by AI-powered irrigation systems, facilitate optimal watering schedules, reducing water wastage and enhancing overall water efficiency (44-46). The application of AI in precision agriculture, specifically with the aid of unmanned aerial vehicles (UAVs), which involves optimizing agricultural inputs, cost reduction, judicious pesticide application and utilizing UAV-collected data processed through AI algorithms for decision-making in precision farming, with a particular emphasis on early stress detection, weed and pest identification, crop growth assessment linked to nutrient levels and yield prediction was examined (47). Future research in precision farming may involve the development of autonomous systems, robotics and data-driven decision-making tools. It may also include exploring the potential of drones, autonomous machinery and smart sensors to enhance farm efficiency and sustainability.

Sustainable agriculture practi*ces*

In addition to precision, AI also plays a crucial role in promoting sustainable agricultural practices. AI technology monitors soil health, allowing farmers to implement targeted soil management practices that enhance fertility and ensure long-term sustainability (48). The future scope in crop health management includes advanced disease detection, pest control and overall crop monitoring methods. Research may focus on integrating remote sensing, machine learning and biological control techniques for sustainable crop health management.

AI-powered irrigation systems have shown great promise in conserving water resources. For instance, the AI optimizes water consumption by dynamically adjusting irrigation plans based on real-time data, contributing significantly to water conservation and effective irrigation practices was emphasized in the previous study (49). Moreover, AI's ability to identify early indicators of diseases and insect infestations enables prompt action, reducing the need for excessive pesticide usage and promoting environmentally friendly pest and disease management (50, 51). But AI's potential in agriculture goes beyond this. It also holds promise in biodiversity conservation and ecological monitoring (52, 53). Additionally, the integration of AI-driven autonomous equipment into agriculture can boost resource use efficiency, aligning agricultural practices with sustainability goals. Future studies can explore strategies for fostering a robust innovation ecosystem in agriculture. This may involve understanding collaboration models, incentivizing knowledge-sharing and supporting technology transfer to ensure the sustained development and adoption of innovative agricultural practices.

Agri policy, advisory and decision making

Artificial intelligence (AI) has the potential to create simulation models that facilitate the assessment of the potential consequences of various agricultural policies before their implementation. AI holds vast promise in transforming the landscape of agricultural policy development and management practices. AI algorithms excel in identifying patterns, trends and correlations within datasets, thereby empowering policymakers to formulate policies rooted in empirical insights and enabling managers to optimize their operational strategies. Moreover, the use of AI, along with data-driven blockchain models, has been shown to address several important issues such as food safety, food quality and provision of remunerative prices for farmers, as concluded in the previous research (54). This reassures us of the significant benefits AI can bring to the agricultural sector. Furthermore, AI's capacity to assess the impacts of various policies and interventions assists governments in crafting effective strategies for mitigating and adapting to climate change challenges (36).

The integration of AI to supersede traditional forecasting techniques, like linear models, with more accurate predictions utilizing neural networks was studied (8). Improved forecasting, particularly in the determination of optimal sowing times, is envisioned through AI's capacity to analyze soil, pest and weather data. Such advancements in the Agri sector are expected to enhance decision-making (55), fostering a more scientific approach that could ultimately increase the profitability of agricultural practices. The future research scope in agricultural policy involves evaluating and refining policies to address current and emerging challenges. Research may focus on developing policies that incentivize sustainable practices, promote technology adoption and ensure fair and equitable outcomes for farmers in the face of evolving agricultural landscapes.

Conclusions and future directions

The current research provides valuable insights into the landscape of AI in agriculture in the Indian context. The analysis reveals a pronounced focus on sustainability and productivity aspects. Sustainability aspects, encompassing climate change, environmental dimensions, crop health, smart farming and innovation ecosystem. While productivity aspect including yield prediction and forecasting, precision farming, crop management and agriculture advisory. These major dimensions are need of the hour to address the prevailing concern of sustainable agriculture and food security among all the researchers and policy makers. However, the emphasis on productivity highlights a relative underrepresentation of AI applications in effective supply chain management in the review. The area of agricultural supply chain including procurement, warehousing and logistics is a promising area for future research in the field of AI in agriculture, underscoring the urgency and importance of this research.

AI research has the potential to drive innovative solutions, including unlocking the genetic potential of seeds, improving soil health and enhancing water use efficiency. The study underscores the significance of public-private partnerships in achieving desired objectives, particularly in leveraging real-time data for evidence-based policy formulation in agriculture. Nevertheless, high-value sectors such as livestock and fisheries have yet to receive adequate attention in AI research. Therefore, there exists substantial room for investment in exploring AI applications in these domains to unlock their growth and advancement potential. Dedicated AI research funding is critical for enhancing agricultural efficiency and addressing these gaps.

In conclusion, the intersection of climate change, agriculture and AI is a transformative force that has the potential to revolutionize the agricultural sector. The smart farming ecosystem, driven by AI technologies, has the potential to revolutionize agricultural practices. Precision farming and crop management, enabled by AI, empower farmers to optimize resource allocation and enhance crop yields. The digital transformation of agriculture heralds a new era of sustainable and efficient farming practices. Furthermore, the integration of AI -driven disease and soil management strategies enhances the resilience of agriculture in the face of environmental challenges. Machine learning approaches and yield prediction models not only boost productivity but also pave the way for data-driven decision-making. Together, these themes underscore the immense potential of AI in mitigating the impacts of climate change on agriculture, promoting sustainability and ensuring global food security.

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Authors' contributions

PS, NK[1] and NK[2] carried out conceptualization, writing - original draft, writing - revised, investigation, methodology and supervision. AK, BP and RK helped in writing - revised. All authors read and approved the final manuscript [NK[1]- Neelam Kumari; NK[2] - Nishant Kumar].

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