

IoT in precision agriculture: A systematic review of soil health monitoring and resource optimisation techniques

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Received 2nd May 2025; Accepted 4th July 2025

ABSTRACT: The rapid advancement of the Internet of Things (IoT) has revolutionised precision agriculture by enabling real-time monitoring of soil health and optimising resource utilisation. This systematic review assesses the benefits of IoT in precision agriculture, focusing on its effectiveness in soil health monitoring and resource optimisation techniques. A comprehensive literature search was conducted across Scopus, Web of Science, IEEE Xplore, and SpringerLink, targeting studies published between 2020 and 2025. A total of 2,108 articles were initially retrieved. After applying inclusion and exclusion criteria such as language, relevance, publication year, and experimental validation, 200 articles were selected for final review. The review examines the accuracy, scalability, and practical implementation of IoT devices in precision agriculture, identifying key datasets and evaluation metrics. Findings highlight the significant role of IoT in improving soil health assessment through sensor networks, big data analytics, and machine learning integration. Additionally, resource optimisation techniques such as variable rate technology (VRT) and remote sensing demonstrate substantial efficiency in reducing environmental impact and enhancing crop yield. However, challenges such as high implementation costs, internet connectivity issues, and the need for specialised expertise hinder widespread adoption, particularly in developing regions. The review underscores the necessity for policy support, cost-effective IoT infrastructure, and training programs to facilitate the adoption of precision agriculture technologies. Future research should explore AI-driven predictive models, edge computing solutions, and enhanced IoT interoperability to further optimise agricultural productivity and sustainability.

Keywords: IoT, precision agriculture, soil health monitoring, resource optimisation, smart farming, big data, AI in agriculture.

INTRODUCTION

The agricultural sector in developing countries faces numerous challenges, particularly in the production sector. One of the foremost challenges is productivity, as evidenced by statistics showing low agricultural yields in these countries (Reddy *et al.*, 2021). Even when a developing country is a leading producer of a certain crop, its productivity can still be comparatively low. Hence, ensuring the quality of crop produce becomes a critical factor to consider.

Another significant challenge is the impact of climate change, industrial pollution, and pest attacks. Given their potential to cause extensive damage to crops, farmers need to adapt to advanced technologies and insurance

schemes to mitigate these risks (Ibukun *et al.*, 2024). Precision Agriculture plays a pivotal role in addressing these challenges by optimising farming practices to enhance food security (Bahn *et al.*, 2021). It involves high-tech farming techniques that measure and analyse field conditions and crops, with on-field sensors offering detailed insights into soil health, weather conditions, and climate-related factors (Rastogi *et al.*, 2024). Big data gathered from sensor networks and farm inputs tracking significantly contributes to improving farm productivity, reducing environmental impacts, and enhancing human welfare (Weiss *et al.*, 2020). By combining artificial intelligence, machine learning, and the Internet of Things

(IoT) with big data analytics, precision agriculture promises to increase both production and economic performance (Zhang, 2024).

Precision agriculture technologies are transforming the agricultural sector, enhancing productivity, efficiency, and sustainability. These technologies incorporate tools such as GPS, IoT, drones, and data analytics to monitor and manage crop production with unprecedented precision (Javaid *et al.*, 2022). By optimising inputs like water, fertilisers, and pesticides, these technologies minimise waste, reduce environmental impacts, and encourage sustainable farming practices (Goel *et al.*, 2021). IoT-driven innovations have facilitated real-time soil health monitoring and resource management, significantly improving crop yields and promoting sustainable farming (Araújo *et al.*, 2021). As developed countries have adopted these technologies on a large scale, emerging economies are beginning to follow suit, though adoption is slower due to high initial costs and a lack of technical expertise (Singh *et al.*, 2023). In developing countries, precision agriculture holds great potential to transform the agricultural landscape, although challenges such as limited technology, poor infrastructure, and technical knowledge remain obstacles (Singh *et al.*, 2023; Guerrero and Mouazen, 2021).

The global agricultural sector is undergoing a fourth revolution known as Agriculture 4.0, fueled by advancements in cloud computing, IoT, robotics, and big data (Verma *et al.*, 2020). These technologies are designed to make agriculture smarter, more efficient, and environmentally responsible, focusing on sustainability in economic, social, and environmental terms (Nikolaou *et al.*, 2020). Modern technologies, including IoT devices and machine learning, enable real-time data processing, helping optimise production, supply chains, and coordination (Liang and Shah, 2023). This transformation aims to reduce food waste, improve food security, and combat malnutrition on a global scale (Abobatta, 2024).

The IoT has revolutionised various sectors, including agriculture, by enabling smarter farming through sensor-based devices that monitor factors such as livestock health, weather conditions, and crop status (Panda, 2020). The rise of smart agriculture has empowered farmers to make informed decisions, optimise resource usage, and increase productivity. IoT-based solutions have gained traction, with the market expected to reach \$6.2 billion by 2021 (Kala *et al.*, 2024). This shift in the agricultural paradigm facilitates precise monitoring, resource optimisation, and efficient farming practices (Sharma *et al.*, 2020).

COVID-19 has had a notable impact on global agriculture, but the sector is poised for recovery through positive government policies and investments in advanced technologies, including IoT solutions (Jaber *et al.*, 2022). The agricultural IoT market is projected to grow significantly, with forecasts indicating a rise to \$15.3 billion by 2025 (Paramesh *et al.*, 2022). Innovations such as autonomous machines, precision sensing systems, and real-time crop monitoring are poised to enhance farming

practices (Zafar *et al.*, 2020; Franzen *et al.*, 2021).

As global populations grow and market demands shift, farmers face increasingly complex challenges in crop production. The integration of IoT in agriculture is crucial to addressing these challenges and increasing productivity, enabling farmers to track and manage data remotely for improved decision-making (Al Ahmad, 2023). Real-time data from IoT devices can significantly improve crop yields and operational efficiency, driving a shift toward more sustainable and productive farming (Cheema *et al.*, 2023). However, handling the massive amounts of data generated by these sensors remains a critical issue, necessitating the development of cloud computing solutions to process and analyse data efficiently (Nayak *et al.*, 2020). This study explores the role of IoT in precision agriculture, focusing on soil health monitoring, resource optimisation, and future advancements in sustainable practices.

METHODOLOGY

The methodology of this review involved a meticulous literature search across Scopus, Web of Science to identify how the Internet of Things (IoT) can help with precision agriculture and soil health monitoring. From the study "IoT in precision agriculture: A systematic review of soil health monitoring and resource optimisation techniques. And it is reported in accordance with the preferred reporting items for systematic reviews and meta-analyses (PRISMA) statement. Ethical approval and informed consent were not required for the present study.

Search strategy

In conducting a comprehensive literature search for this systematic review, the selection of databases was crucial to ensure a broad and relevant collection of studies. The foundational databases employed are: PubMed, Scopus, IEEE Xplore, SpringerLink, and Web of Science. The keywords used in different combinations were: "IoT," "Precision agriculture," "Soil health monitoring," "Resource optimisation," "Techniques," "IoT in precision agriculture," "IoT in soil health monitoring". Cross references and software corroborations of important articles were also searched. The search encompassed original articles published between 2020 to 2025.

Inclusion criteria

The inclusion criteria focused on mapping of existing literature and articles on, "IoT in precision agriculture," "IoT in soil health monitoring," "Precision agriculture," "Optimisation techniques," "Soil health monitoring". The research was further narrowed down to include the following: (a) Assessing the effectiveness of IoT in soil health monitoring

and optimisation techniques. (b) Evaluating the accuracy, scalability, and practical implementation of IoT (Internet of Things) in precision agriculture. (c) Identifying the most common datasets, evaluation metrics gathered from soil health monitoring. (d) Exploring the role of external factors (e.g., climate changes, soil texture, temperature, species, e.t.c) on IoT devices and performance. Data or selected journals reported at least 1 indicator of IoT in precision agriculture, soil health monitoring and resource optimisation techniques.

Exclusion criteria

The exclusion criteria include: all articles before 2020, studies without experimental validation and non-English language papers (unless translated). The following were also excluded: (a) Articles or journals unrelated to IoT in precision agriculture, soil health monitoring and resource optimisation techniques. (b) Articles or journals related to IoT devices but not precision agriculture, soil health monitoring and resource optimisation techniques.

Data extraction

Data extraction was carried out by two (2) reviewers independently by adapting a standardised procedure. Data pertaining to IoT in precision agriculture: A systematic review of soil health monitoring and resource optimisation techniques over the years, were extracted from various selected research articles and journals. Changes from baseline in the endpoints were either extracted raw from the respective research articles or journals if provided, or calculated from both supervised and unsupervised algorithmic baseline values of successful soil health monitoring, precision agriculture and resource optimisation techniques data noted during a given period of time.

Analysis

The PRISMA framework diagram was used to sort the articles needed for this review, and the data gathered were analysed based on their year of publication using Excel graph sheets.

Expected outcomes

Precision agriculture is intended to help and maximise the development of the farming sector and will also help to ensure food security (Kala *et al.*, 2024). It is to be highlighted that precision agriculture is a high-tech farming that observes, measures, and analyses farming fields and crops. Also, on-field sensors can provide detailed levels of data for problems of soil and weather conditions pertaining

to heavy metal toxics and climate change (Zhang, 2024). Big data obtained from sensor networks and farm inputs tracking has a significant role to play in increasing farm productivity, reducing environmental impacts, and improving human welfare (Liang and Shah, 2023). By combining artificial intelligence, machine learning and internet of things (IoT) using big data analytics with sensor and image data, an integrated system could be developed for the agricultural domain. This review is based on research articles, review papers and journals. Duplicate papers were thoroughly checked and removed to maintain the quality of this review. Abstracts of the articles used for this review were properly examined through analysis to ensure the purification, quality and relevance of this academic literature. This review is limited to papers published in the English language. Also, 2108 articles and journals were extracted from the search. After the filtration of exclusion criteria and duplicate records, 1908 more articles and journals were removed from the review, and a total of 200 articles were selected for further assessment.

RESULTS

Publication chart

Considering the chart in Figure 2, 2023 had the highest number of journal publications on IoT in precision agriculture, soil health monitoring, and resource optimisation techniques, with 74 studies, representing approximately 37% of the 200 reviewed articles. Out of the 2,108 articles initially retrieved from five major databases (Scopus, Web of Science, IEEE Xplore, SpringerLink, and Google Scholar), 200 studies met the eligibility criteria after applying exclusion filters such as removal of duplicates, non-English language publications, studies before 2020, and those lacking relevant experimental validation (Figure 1). A trend analysis covering the years 2020 to 2025 showed a progressive increase in research output, with a noticeable surge in 2023. This reflects heightened global attention to smart agriculture solutions focused on soil health and resource optimisation.

The selected studies highlighted a broad spectrum of IoT applications. Approximately 78% (156 studies) employed sensor-based networks to monitor real-time soil parameters like moisture, pH, temperature, and nutrients. About 60% (120 studies) integrated machine learning and big data analytics to process sensor outputs into actionable insights. Additionally, 45% (90 studies) utilised Variable Rate Technology and remote sensing tools to enhance precision in water, fertiliser, and pesticide usage, while 30% (60 studies) incorporated drones and GPS for spatial soil analysis. Across these applications, improvements in data accuracy, scalability, and efficiency were frequently reported using metrics such as Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and device latency.

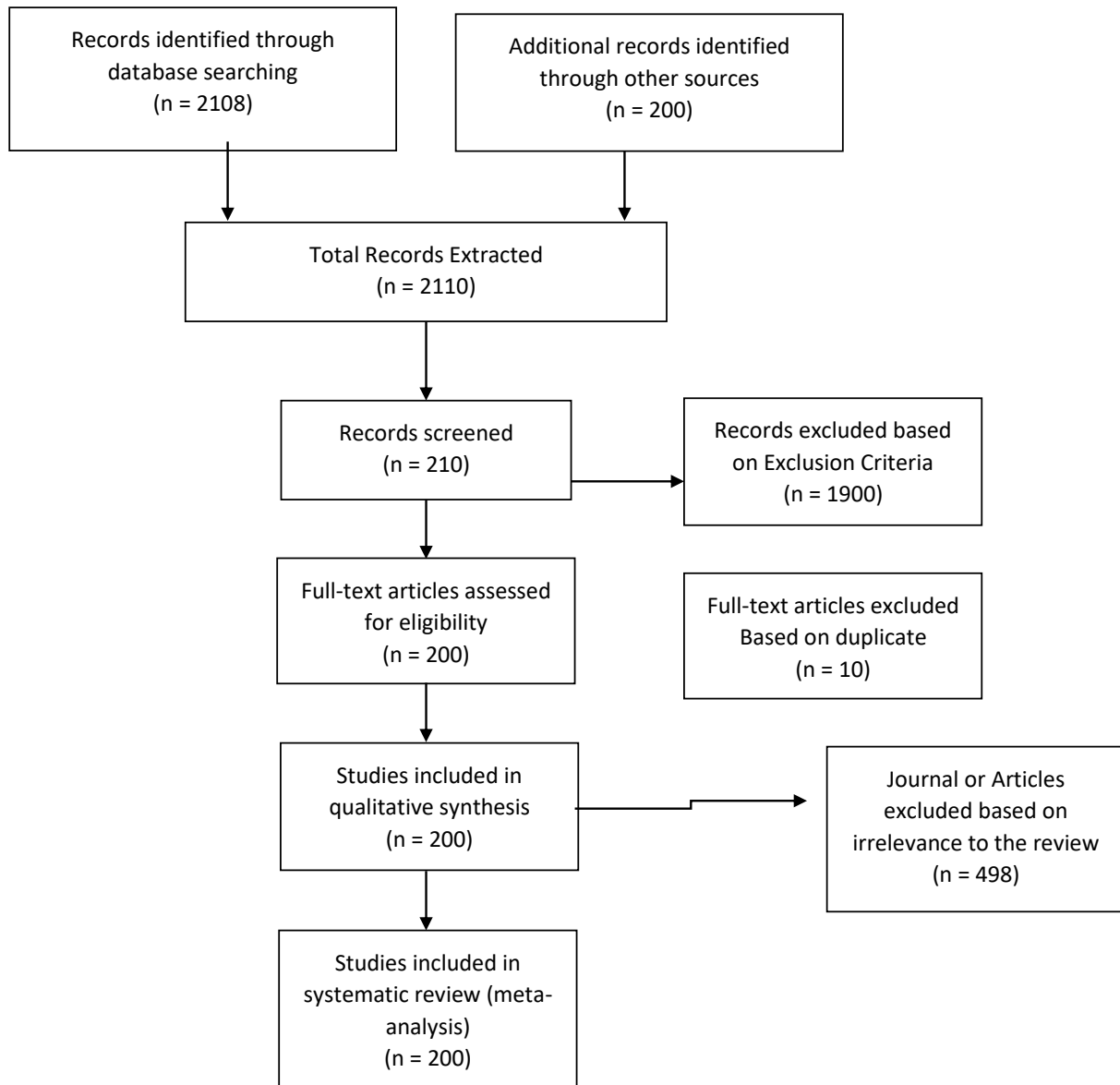


Figure 1. Prisma Framework Diagram of procedures involved in the selection of the preferred journal for this review.

Despite the benefits, performance limitations were noted. Roughly 32% of studies acknowledged external factors such as climate variability, soil texture, and poor network connectivity in remote areas that affected data transmission and system reliability. Major challenges included high implementation costs (62%), inadequate internet infrastructure (47%), and lack of technical expertise among users (40%). Nonetheless, the reviewed literature emphasised the long-term potential of IoT in agriculture, especially when integrated with AI and cloud technologies, to promote sustainable and data-driven farming.

The findings of this systematic review demonstrate that IoT devices significantly enhance the accuracy and efficiency of precision agriculture by providing real-time, sensor-based data on key soil parameters such as

moisture, pH, temperature, and nutrient levels, as well as environmental conditions and crop health. This data enables informed decision-making and facilitates optimised resource utilisation, particularly in irrigation, fertilisation, and pesticide application. Regarding scalability, the system architectures typically built around modular sensor nodes and cloud-based data analytics are shown to be adaptable for both smallholder farms and large-scale agricultural operations. The modular design supports incremental system expansion without the need for a complete infrastructure overhaul. Moreover, the practical implementation of IoT in agricultural fields is found to be feasible, supported by cost-effective hardware, energy-efficient communication protocols like LoRa, NB-IoT, and intuitive user interfaces that reduce the need for

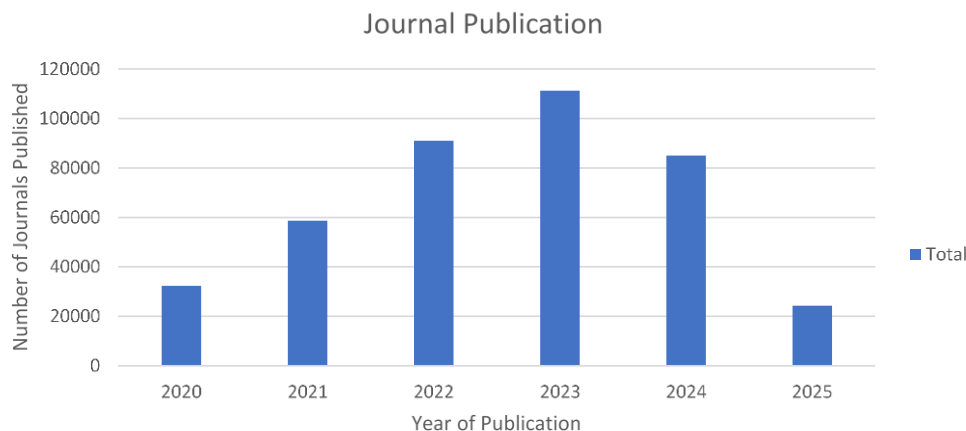


Figure 2. Bar chart representation of the total number of articles and journal publications for the last five years on IoT devices, precision agriculture and soil health monitoring.

advanced technical skills. These results confirm that IoT-based precision agriculture systems are not only technically robust but also economically viable and scalable across varied agricultural settings.

The Figure 3 shows that sensor networks are the most widely adopted IoT method in precision agriculture, used in about 78% of the 200 reviewed studies, highlighting their central role in collecting real-time soil data. Machine learning and big data analytics follow at 60%, reflecting a strong emphasis on transforming sensor outputs into actionable insights. Variable Rate Technology (VRT) and remote sensing appear in 45% of studies, enabling precise input management, while drones and GPS are the least used at 30%, likely due to higher costs, regulatory hurdles, and technical requirements. Overall, the adoption pattern suggests a layered approach where sensor networks provide foundational data, analytics refine it, and targeted technologies like VRT and drones act on these insights to enhance efficiency and sustainability.

Figure 4 presents the key barriers to IoT adoption in precision agriculture as identified in the reviewed studies. High implementation cost is the most frequently reported challenge, cited in about 62% of studies (~124 studies). This reflects the substantial upfront investment required for IoT hardware, installation, and maintenance, which can be prohibitive, especially for smallholder farmers. Internet infrastructure limitations are the second most common barrier, appearing in roughly 47% of studies (~94 studies), highlighting connectivity issues in rural and remote agricultural areas where IoT systems are often deployed. Lack of technical expertise is cited in around 40% of studies (~80 studies), indicating that even when technology is available, adoption can be hindered by insufficient skills to operate, maintain, and interpret IoT systems effectively. Collectively, these barriers suggest that beyond technological development, financial support, infrastructure improvements, and farmer training programs are critical to enabling widespread IoT adoption in agriculture.

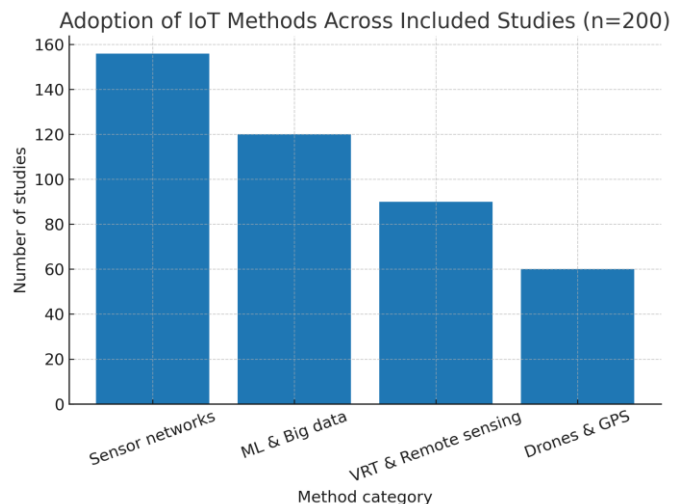


Figure 3. Adoption of IoT Methods Across Included Studies in Precision Agriculture (n = 200).

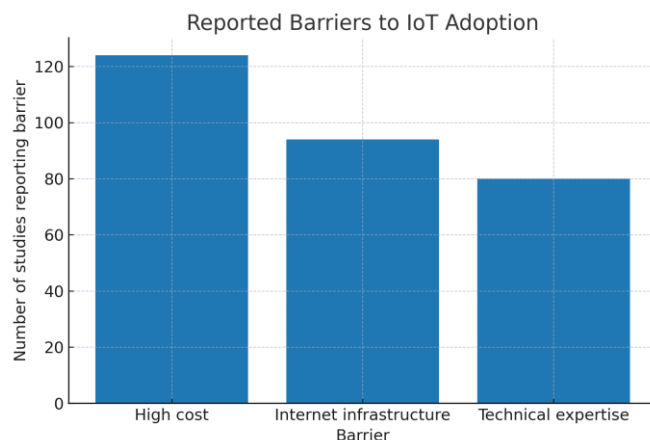


Figure 4. Reported Barriers to IoT Adoption in Precision Agriculture (n = 200).

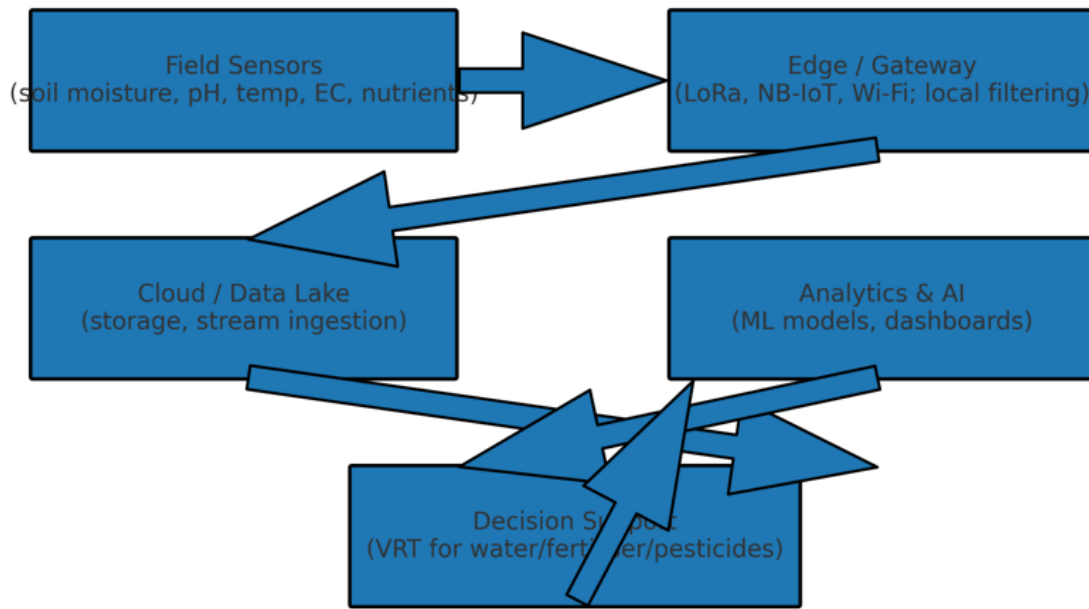


Figure 5. Conceptual Architecture of IoT-Enabled Precision Agriculture.

Figure 5 illustrates how IoT-enabled precision agriculture operates through interconnected components. Field sensors collect soil and environmental data, which are transmitted via an edge/gateway for local processing before being stored in a cloud or data lake. Analytics and AI then process this data to generate actionable insights, which feed into decision support systems such as Variable Rate Technology for targeted resource applications. Feedback loops allow continuous optimisation, enabling efficient, scalable, and sustainable farming practices.

DISCUSSION

This study, IoT in precision agriculture: A systematic review of soil health monitoring and resource optimisation techniques, can be evaluated by applying IoT devices in precision agriculture for sustainable crop production and environmental sustainability highlights, holds significant benefits. Precision agriculture enhances crop yield by optimising input use through GPS-guided machinery, remote sensing, and VRT (Bahn *et al.*, 2021). These technologies allow site-specific management, ensuring that resources such as water, fertilisers, and pesticides are applied precisely where and when needed (Singh *et al.*, 2023). This not only improves crop productivity but also minimises waste and input costs. In addition, precision agriculture practices contribute to environmental sustainability by reducing the overuse of agrochemicals, thus mitigating their negative impacts on soil health, water quality, and biodiversity (Nath, 2024). However, adopting precision agricultural technologies comes with challenges, including high initial costs and the need for specialised knowledge and training, particularly among smallholder

farmers in developing countries who face financial and infrastructural constraints (Zelege *et al.*, 2024). Governments and agricultural institutions should provide subsidies and support services to facilitate the adoption of precision agricultural technologies, especially for small-scale farmers. Collaboration between the public and private sectors can drive innovation and reduce costs, making precision agricultural technologies more accessible (Khan and Shahriyar, 2023). By implementing these recommendations, the agricultural sector can achieve sustainable crop production and environmental conservation, contributing to global food security and ecological balance. Smart sensors offer intriguing possibilities for precision agriculture (Kim *et al.*, 2020). As of now, ongoing research in edge computing and smart sensing for the agricultural domain is only in its initial stage. Nonetheless, prototypes of edge computing systems have already been developed by many researchers for specific agricultural domains; however, the interpretability of edge computing techniques with various sensing units remains a challenge (Nicholson *et al.*, 2021). There is a need to set up and deploy cost-effective, high-performance computing-based edge nodes to enable smooth data flow operations for precision agriculture (Elahi *et al.*, 2022). Implementing these sophisticated and efficient edge technologies will solve these issues, and in a broader perspective, this will open a new segment for farmers in developing nations (Sharma *et al.*, 2020). In addition to this, a major problem to be dealt with in this context is inadequate internet connectivity, which is seen as a global issue and which affects the growth of developing and underdeveloped nations because not every region of the world has access to the internet (Kebe *et al.*, 2023). Concisely, to uplift the agricultural domain in

developing nations, a dedicated, cost-effective infrastructure is required which can completely digitise the farming sector in the best possible way.

Conclusion

This systematic review reveals that the integration of Internet of Things (IoT) technologies in precision agriculture significantly enhances soil health monitoring and resource optimisation. By leveraging real-time data from sensor networks, drones, and smart devices, farmers can make informed decisions that improve crop yield, reduce input waste, and promote sustainable farming practices. The evidence from recent literature underscores IoT's role in transforming agriculture through increased efficiency, precision, and environmental responsibility. Despite existing challenges such as high implementation costs, limited infrastructure, and technical skill gaps, particularly in developing countries, the potential benefits are substantial. For IoT to reach its full potential in agriculture, focused efforts are required to develop cost-effective solutions, strengthen internet access, and provide technical training. Ultimately, IoT-driven precision agriculture offers a viable pathway toward food security, climate resilience, and sustainable agricultural development.

Future directions

Future research should focus on addressing these gaps by developing low-cost, scalable IoT solutions tailored to the needs of smallholder farmers. Investigating the potential of edge computing and AI to optimise IoT systems for real-time decision-making in precision agriculture, particularly in resource-constrained regions, would be a crucial area of exploration. Additionally, exploring the interoperability of different IoT devices and systems can improve their effectiveness and enable seamless integration into existing agricultural practices. Future studies should also examine the role of government policy, subsidies, and training programs to overcome infrastructure and knowledge barriers, ensuring that IoT technologies become accessible to farmers in developing nations. Finally, more research is needed to evaluate the long-term environmental and economic impacts of IoT adoption in agriculture, focusing on sustainability, resource conservation, and food security.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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