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Precision agriculture techniques for optimizing chemical fertilizer use and environmental sustainability: a systematic review

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Precision agriculture (PA) techniques are critical for optimizing chemical fertilizer use in modern farming. However, a comprehensive synthesis of their effectiveness in enhancing nutrient management and reducing environmental impacts is lacking. This systematic review, following Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines, analyzes global evidence to evaluate PA's role in improving fertilizer application practices. Our analysis of 51 peer-reviewed studies reveals that PA significantly enhances nutrient use efficiency and crop yields. Specifically, 37.25% of studies highlight PA-driven technological innovations, while 29.41% document major improvements in nutrient management. These findings confirm that PA promotes sustainable fertilizer utilization and reduces environmental footprints. To realize its full benefits, policymakers must address key challenges to widespread adoption, such as cost barriers, lack of technical expertise, and infrastructure limitations.

KEYWORDS

precision agriculture (PA), chemical fertilizer, nutrient management, nutrient use efficiency, agricultural technology

1 Introduction

Precision agriculture (PA) represents a revolutionary paradigm in modern farming that harnesses advanced technologies to optimize agricultural practices at a highly localized level (Zaman, 2023). Central to this approach are the principles of site-specific management (Abioye et al., 2022; Plant, 2001) and data-driven decision-making (Cheng et al., 2023; Raj et al., 2021; Mehrabi et al., 2020). PA systematically collects and analyzes spatial data on variables like soil composition, crop vitality, and environmental factors (Pedersen and Lind, 2017). This data-driven approach enables farmers to customize resources such as water, fertilizers, and pesticides to meet the specific needs of individual areas within a field (Pedersen and Lind, 2017). The use of targeted management strategy promotes resource efficiency, enhances crop yields, and minimizes adverse environmental impacts (Bijay-Singh and Craswell, 2021; Tyagi et al., 2022). Hence, it is urgent to provide a comprehensive understanding about the mechanism how PA translates data into actionable management strategies for environmental protection and food security (Cowan et al., 2022).

PA integrates advanced technologies like GPS, drones, and sensors to improve farming accuracy and efficiency (Ahmad and Mahdi, 2018a). There is now a strong focus on optimizing farm inputs to balance food production, environmental health, and economic benefits (Ahvo et al., 2023; Guo et al., 2021; Wang et al., 2017; Li et al., 2022). Through precise management of nutrients, water, and chemicals, PA increases farm profitability and resource efficiency (Zhao et al., 2022; Puppala et al., 2023; Rose et al., 2023). Farms using PA show higher technical efficiency than those using conventional methods (DeLay et al., 2022). This strategy helps reduce yield losses (Velusamy et al., 2021) and lessen environmental harm. PA lowers greenhouse gas emissions (Balafoutis et al., 2017) and decreases nutrient leaching (Hedley, 2014). It also supports sustainability by boosting carbon sequestration (Qureshi et al., 2018) and increasing soil organic matter (Zhou et al., 2023). A deeper understanding of PA is essential for advancing sustainable agriculture (Juncal et al., 2023).

Various nations now face major challenges in ensuring food security and combating climate change through sustainable farming (Feliciano et al., 2022; Wiebe et al., 2019; Chataut et al., 2023). Understanding the global use of PA is therefore increasingly vital. PA is recognized as a transformative solution for making farming more efficient and sustainable worldwide (Nath, 2023). This is especially critical as the global population is projected to reach 9 billion by 2050. This growth creates an urgent need to increase agricultural productivity without worsening environmental harm (Mwesigyea & Matsumoto, 2016; Liu et al., 2021). The worldwide shift toward digitalization and smart farming has further accelerated the adoption of PA across diverse agricultural systems (Karunathilake et al., 2023).

The global adoption of PA reflects a collective effort to address food security, environmental preservation, and economic sustainability in agriculture (Lee et al., 2021). PA offers a strategic pathway for nations to increase food production while reducing environmental impacts, especially under growing pressures from climate change, economic shifts, and population growth. The development and implementation of PA practices vary considerably across different countries, including China, Brazil, the United States, India, Europe, and Russia. China, for example, has made notable advances through large-scale mechanization, digital agriculture platforms, and strong government support (Kritikos, 2017; Savelieva et al., 2022; Shaheen et al., 2020; Kendall et al., 2022). Brazil has also rapidly adopted PA technologies, especially in soybean and corn farming, aided by major investments in satellite technology and precision equipment (Hörbe et al., 2013). These global examples highlight both successful models and the need for continued dialogue on sustainable agriculture.

PA significantly advances several United Nations Sustainable Development Goals (SDGs) (Bhat and Huang, 2021). It contributes directly to SDG 2 (Zero Hunger) by improving food security and enabling sustainable farming. This is achieved through more efficient resource use, higher crop yields, and lower environmental impact. PA also supports SDG 9 (Industry, Innovation, and Infrastructure) by spurring technological innovation in agriculture. Furthermore, it promotes SDG 12 (Responsible Consumption and Production) by reducing waste and encouraging sustainable resource management (Bengtsson et al., 2018). PA also aids SDG 13 (Climate Action) through climate-smart practices that reduce emissions and improve resilience. However, a systematic synthesis of evidence specifically linking PA to optimized fertilizer use and its consequent environmental co-benefits remains lacking.

This systematic review addresses this gap by employing the PRISMA methodology. We analyze global evidence to establish clear connections between PA adoption and sustainable agricultural outcomes. Specifically, we examine how PA techniques optimize chemical fertilizer application. Our synthesis assesses improvements in fertilizer use efficiency, crop yield enhancement, and environmental risk reduction. Traditional farming often creates economic strain through excessive fertilizer use, raising costs without boosting productivity (Chai et al., 2023). This review provides a comprehensive evaluation of PA's role in achieving both environmental sustainability and economic efficiency. Ultimately, PA enables farmers to reduce agriculture's environmental footprint while increasing productivity and lowering production costs.

Theoretically, this review addresses a critical gap by specifically analyzing PA's role in optimizing chemical fertilizer use, enhancing nutrient use efficiency, and driving agricultural technology innovation—areas often overlooked in existing literature (Kendall et al., 2022; Qureshi et al., 2018; Rodrigues, 2022; Obaideen et al., 2022; Tey and Brindal, 2012). Practically, it offers evidence-based guidance for policymakers, researchers, and farmers by identifying barriers, enablers, and best practices for scalable PA implementation. This synthesis bridges theoretical frameworks and on-ground application, supporting more informed and sustainable agricultural decision-making.

2 Methodology

2.1 PRISMA approach

This systematic review was conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) approach to systematically evaluate the impact of PA techniques on optimization of chemical fertilizer application (Moher et al., 2009). The PRISMA framework is a widely regarded as a benchmark for conducting systematic reviews, providing a structured and transparent protocol that enhances the reproducibility and credibility of literature syntheses (Page et al., 2021). This approach encompasses a systematic sequence for identifying, screening, and synthesizing peer-reviewed studies, thereby ensuring rigorous methodological standards throughout the review (see Figure 1). The utility of the PRISMA method lies in its ability to reduce bias, enhance clarity of reporting, and highlight gaps or inconsistencies in existing research. By adhering to PRISMA protocols, we aimed to enhance the validity and reliability of our findings, ultimately generating robust evidence to inform policy-making and best practice in agriculture.

2.2 Literature search strategy

A comprehensive search strategy was meticulously implemented to identify and include relevant literature in this review. The systematic search was conducted across established electronic databases, specifically Web of Science and Scopus. An effective combination of keywords and controlled vocabulary was employed, focusing on the themes such as the role of PA in optimizing chemical fertilizer application, enhancing nutrient management, fostering agricultural technology innovation, and improving nutrient use efficiency. Complementing the database searches, manual searches of leading journals and the reference lists of key articles were conducted, ensuring that all essential literature pertinent to the review was captured.

2.3 Inclusion and exclusion criteria for article selection

The selection of articles for inclusion in this systematic review was guided by explicit inclusion criteria. Only empirical studies that investigated the effect of PA techniques on optimization of chemical fertilizers, nutrient use efficiency, nutrient management, and agricultural technology innovation were eligible. To uphold the quality and credibility of the review, only articles published in peer-reviewed journals were considered. Additionally, articles had to be available in English to facilitate comprehensive analysis. The review focused on publications from 2009 to 2024, ensuring relevance to ongoing development in global agricultural practices.

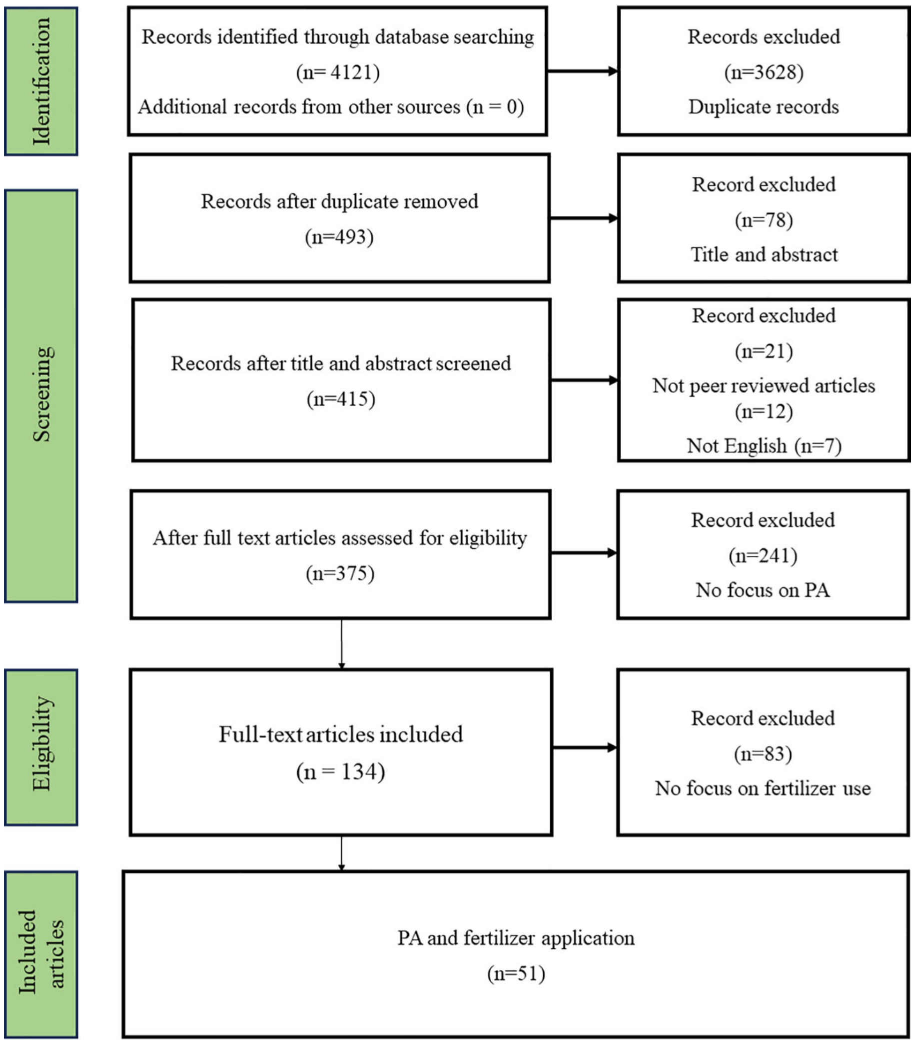

FIGURE 1
PRISMA flow diagram.

Exclusion criteria were rigorously applied to eliminate studies outside the scope of this review. Non-empirical works, including review articles, editorials, and opinion pieces, were excluded due to their lack of original data. Furthermore, articles that were not available in full-text format were omitted to allow for a thorough evaluation of their research findings and methodologies.

2.4 Data extraction, synthesis methods and quality assessment

Data extraction comprised a systematic process of collecting relevant information from the selected articles, including study characteristics, methodological specifics, key findings, and outcomes related to the impact of PA techniques on chemical fertilizer optimization. A predefined data extraction form was employed to ensure uniformity and consistency throughout the extraction process. The collected data underwent thematic analysis to identify patterns, trends, and critical insights pertinent to the research question (see Figure 2).

The quality of the included studies was evaluated utilizing established criteria appropriate for their respective study designs, allowing for an evaluation of methodological rigor and potential sources of bias. This quality assessment ensured that the synthesis of evidence was grounded in high-quality research. Studies with exhibiting substantial methodological limitations were subjective to careful review and, if necessary, excluded from the final analysis to maintain the integrity of the review.

2.5 Risk of bias assessment for the studies

To further fortify the robustness of the review findings, we employed the revised Cochrane Risk of Bias tool for randomized trials (RoB 2.0) (Higgins et al., 2011). This tool was instrumental in mitigating bias in the selection of studies included in the review. Additionally, to minimize the risk of bias during the inclusion and exclusion process, each author independently conducted searches using specified keywords across the two primary data sources This dual-search methodology enhanced the rigor and reliability of the literature selection process.

3 Results and discussion

3.1 Literature search result

In conducting this systematic review, an exhaustive search of various scientific databases yielded an initial collection 4,121 records. After removal of duplicates and a meticulous screening of titles and abstracts, 415 records remained for further consideration. The application of specific exclusion led to the elimination of articles that were not peer-reviewed, were published in languages other than English, or that did not pertain to PA or fertilizer use. Ultimately, 134 full-text articles were assessed for eligibility, of which 84 articles were excluded for failing to address the use of fertilizers. The final selection consisted of 51 articles that were deemed suitable for extraction and further analysis (refer to Figure 1 for detailed flow).

3.2 Temporal distribution

The temporal distribution of studies focused on the impact of PA on optimizing fertilizer use reveals a significant upward trend over time. Initial investigations were sparse during the early 2000s; however, attention to this area of research notably began to increase from 2017 onwards. This trend is particularly pronounced in the years 2021, 2022, and 2023, which collectively accounted for 70% of the articles included in this systematic review (see Figure 3). This trend is particularly pronounced in the years 2021, 2022, and 2023, which collectively accounted for 70% of the articles PA's potential in

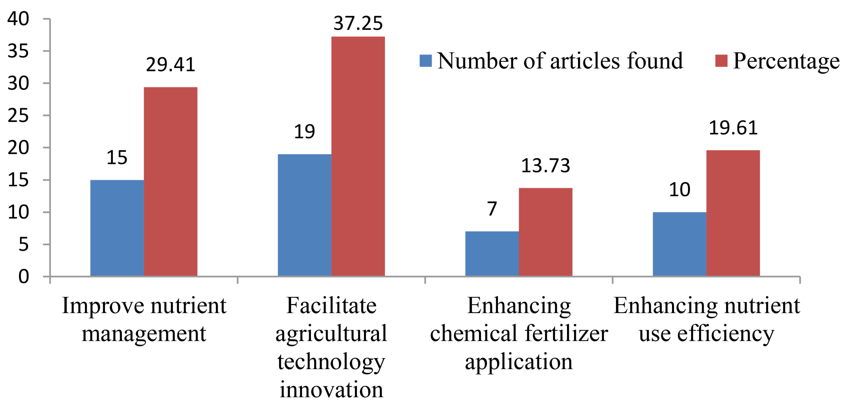

FIGURE 2
Thematic distribution of review articles.

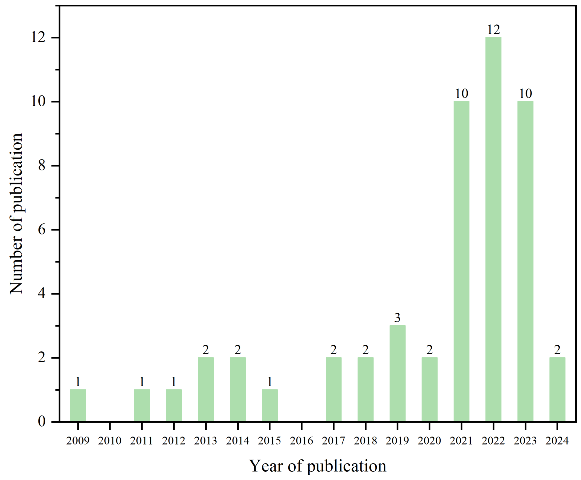

FIGURE 3
Temporal distribution of studies.

fertilizer management practices, improving nutrient efficiency, and reducing environmental impacts. The data suggest an evolving research landscape underscored by a heightened emphasis on sustainable agricultural practices underscored by a heightened emphasis PA technologies.

3.3 Geographic distribution of selected articles

The selected articles for this review span four geographic regions, with experts contributing insights on PA's influence on chemical fertilizer application (see Figure 4). Notably, the majority of studies originating from Asia (52.94%) and Europe (23.53%). A smaller proportion of the studies emerged from Australia (1.96%) and Africa (3.92%), indicating a regional disparity in the research focus and contribution to the field of PA and fertilizer use (Figure 4).

3.4 Thematic distribution of review articles

The 51 articles included in this review cover four primary thematic research areas, as illustrated in Figure 2. Among these, the examination of PA's role in facilitating agricultural technology innovation emerged as the most prominent theme, representing 37.25% of the total articles reviewed. Additionally, 29.41% of the articles focused on the enhancement of nutrient management as influenced by PA, while 19.61% addressed PA's role in enhancing nutrient use efficiency. This thematic categorization highlights the multifaceted contributions of precision agriculture to contemporary agricultural practices.

3.5 Study type classification

An analysis of the study types within the selected articles revealed that 66.64% were classified as original research articles underscoring a robust foundation of empirical findings within the literature. Moreover, 27.45% of the articles were categorized as review articles, indicating a significant effort to synthesize existing knowledge in this field. A smaller yet essential component, accounting for 5.88%, consisted of technical reports, which provide practical insights and applications related to PA and fertilizer use (see Figure 5). This classification reinforces the predominance of original research in advancing our understanding of PA applications in agriculture.

3.6 Impact of PA techniques on optimizing chemical fertilizer application

PA techniques play a crucial role in optimizing chemical fertilizer applications through several advanced methods that enhance nutrient management efficiency. Table 1 summarizes the various PA technologies and their specific functions in effective fertilizer management. One of the primary methods employed in PA is the utilization of remote sensing and

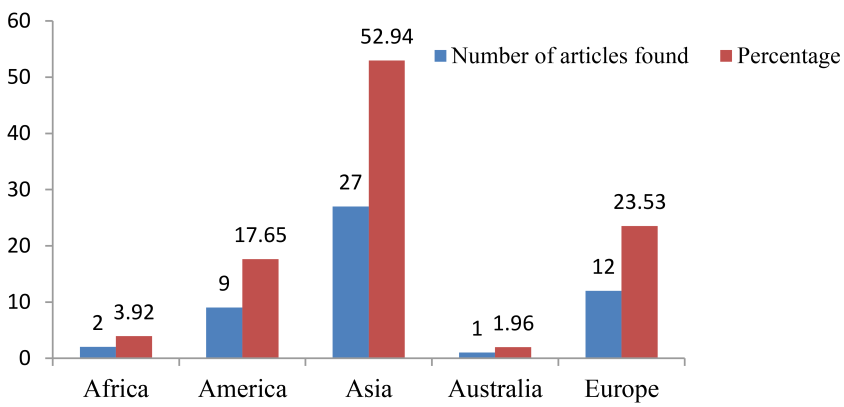

FIGURE 4
Geographic distribution of reviewed articles.

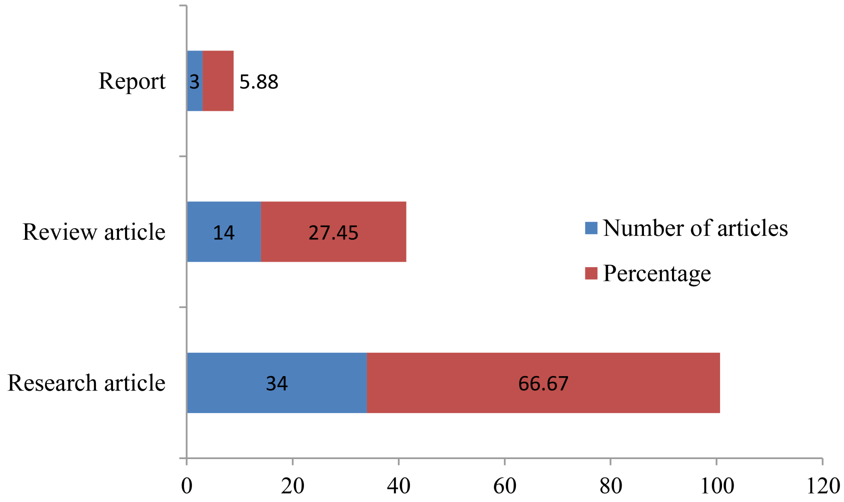

FIGURE 5
Classification of articles included in the study.

imagery analysis, which facilitate the identification of spatial variations in nutrient deficiency and excess within agricultural fields. By leveraging satellite imagery and drone technologies, farmers can precisely target areas that require fertilization. This targeted application not only ensures that fertilizers are applied only where deficiencies exist but also minimizes the uniform distribution across entire fields. Consequently, this strategy reduces fertilizer overuse, decreases waste, and significantly improves nutrient use efficiency.

Another integral component of PA is the implementation of Geographic Information Systems (GIS) and mapping technologies, which enable the creation of detailed maps illustrating soil nutrient distribution and variability (Qiu et al., 2011; Xie et al., 2012). When combined with variable rate technology (VRT), farmers can develop tailored fertilizer prescriptions that respond to spatial nutrient variations within their fields (Griffin and Traywick, 2021). VRT allows for dynamic adjustments to fertilizer application rates and patterns based on specific field conditions. By precisely calibrating fertilizer delivery, this technology prevents over-application in nutrient-rich areas while simultaneously addressing deficiencies in less fertile zones, thereby optimizing fertilizer usage and minimizing nutrient losses (see Table 2).

Additionally, soil and plant sensors provide real-time monitoring of soil nutrient levels and plant nutrient uptake, enabling farmers to continuously track these parameters and make informed fertilizer application decisions (Ashraf et al., 2014; Yin et al., 2021). By adjusting fertilizer application timing and rates with actual plant nutrient requirements, this precision approach mitigates the risk of over-fertilization. Furthermore, by delivering nutrients precisely when crops need them, farmers can foster optimal growth conditions. Utilizing real-time data to adjust fertilizer applications not only enhances nutrient use efficiency, but also reduces costs and minimizes the environmental impact associated with excessive fertilizer use (see Table 2).

3.7 The impact of PA techniques on nutrient use efficiency

PA techniques have fundamentally transformed fertilizer management in modern agriculture, significantly improving efficiency and sustainability across farming practices. These techniques integrate a range of advanced technologies and strategic approaches that enable farmers to optimize nutrient application,

TABLE 1 Sample studies that show impact of PA techniques on improving nutrient management.

Studies	Method of data collection	PA technologies	Function
Parihar et al., 2022	Quantitative method	Conservation agriculture	Improves soil nutrient management
Sapkota et al., 2021	Quantitative method	Nutrient Expert	Reduce excess nutrient application and balanced fertilizer use which allow high crop production with small input
Vullaganti et al., 2025	Quantitative method	Site-specific nutrient management	Site-specific nutrient management promotes sustainable agriculture by addressing soil variability and improving crop yields
Tovihoudji et al., 2019	Quantitative method	DSSAT model	show the exact time N stress to dose N for efficient nutrient management and crop yield

TABLE 2 Role of PA technologies on optimizing chemical fertilizer application.

Studies	Method of data collection	PA technologies	Function
Agrahari et al., 2021; Feng et al., 2020; Jaberi-Aghdam et al., 2023; Kasuga et al., 2023; Karthika, 2024	Both qualitative and quantitative method	Remote Sensing and Imagery Analysis	Identify areas of nutrient deficiencies, excesses in the field, targeted application of fertilizers and monitor crop health and growth to.
Bhanumathi and Kalaivanan, 2019, 2019; Xie et al., 2012	Both qualitative and quantitative method	Geographic Information Systems (GIS) and Mapping.	Create precision application maps, enabling farmers to apply fertilizers at variable rates and minimize over-application.
Ahmad and Mahdi, 2018b; Blasch et al., 2021; Mirzakhaninafchi et al., 2021, 2022; Sawyer, 1994	Both qualitative and quantitative method	Variable Rate Technology (VRT)	Implement customized fertilizer prescriptions, adjusting application rates and reduce fertilizer wastage
Arivalagan et al., 2020; Cruz Ulloa et al., 2022; Yuan et al., 2023	Both qualitative and quantitative method	Automated Machinery and Robotics	Ensure accurate, consistent application of fertilizers and reduce human error and variability in fertilizer application,

minimize waste, and ultimately boost crop productivity. The effects of PA on fertilizer use efficiency are notable, particularly through its mechanisms of targeted application, data-driven decision-making, and enhanced nutrient management (Sanghera, 2021).

A pivotal advancement in fertilizer use efficiency is the implementation of targeted application strategies (Chang et al., 2017; Chattha et al., 2014). Rather than applying fertilizers uniformly across an entire fields, PA promotes site-specific nutrient management (Tee et al., 2023). Employing cutting-edge tools such as remote sensing, soil sampling, and GPS-guided machinery, farmers can identify spatial variability in soil fertility and adjust fertilizer applications accordingly (see Table 3). This precision in nutrient delivery ensures that inputs are applied only where they are most needed, which not only enhances crop nutrient uptake but also mitigates the risks associated with excessive fertilizer use. By preventing over-application and addressing localized nutrient deficiencies, farmers can significantly improve fertilizer use efficiency while simultaneously reducing environmental consequences such as nutrient runoff and leaching (Table 3).

Data-driven decision-making is another significant aspect contributing to improved fertilizer use efficiency through PA (Rozenstein et al., 2024; Saliu and Deari, 2023; Tantalaki et al., 2019; Thilakarathne et al., 2022; Villalobos et al., 2020). Employing sensors, drones, and other monitoring technologies allows farmers to gather real-time data on soil conditions, crop health, and nutrient concentrations (Singh et al., 2022). Such information offers valuable insights into crops nutritional needs, enabling farmers to make informed decisions regarding fertilizer application rates and timing. When this data is integrated with advanced analytics and decision support systems, it facilitates the optimization of fertilizer management strategies tailored to specific crop requirements. This responsiveness not only enhances nutrient availability, but also reduces waste and minimizes costs associated with over-application (see Table 3).

Reducing fertilizer waste is a crucial component of sustainable agriculture (Koul et al., 2022; Rehman et al., 2022). PA techniques provide effective mechanisms to achieve significant reduction in fertilizer waste (Cayuela et al., 2022). A prominent strategy is the use of Variable Rate Technology (VRT) (Bullock et al., 2008; Masi et al., 2023; Späti et al., 2021), which enables the application of fertilizers at variable rates based on site-specific conditions (He, 2022). By leveraging soil maps, remote sensing data, and real-time monitoring tools, farmers can develop prescription maps that specify precise fertilizer application rates for different zones within a field (Pei et al., 2021). This targeted approach ensures that nutrients are applied only

TABLE 3 Studies that show impact of PA techniques on nutrient use efficiency.

Studies	Method of data collection	PA technologies	Function
Qiu et al., 2011	Quantitative method	GIS tool for fertilizer application	Using GIS as a tool for nitrogen fertilizer application and minimizing denitrification and leaching of nitrogen
Reyes et al., 2015	Quantitative method	Automatic control system	The control software used as fertilizer rate prescription determine the amount of fertilizer used and allow crops get optimum amount of nutrient
Xing and Wang, 2024	Qualitative method	Various precision techniques	Machine learning and remote sensing integration enables real-time monitoring and adaptive management, enhancing resource efficiency and reducing pollution.
Wang et al., 2017	Qualitative method	Data Envelopment Analysis method	Optimize agricultural input utilization efficiency and increase crop productivity
Yang et al., 2022	Quantitative method	Improved NFOA Model	Provide accurate information for crop N fertilizer variable tracking
Chore and Thankachan, 2023	Quantitative method	Incremental Learning Approach	Helps to apply optimum amount of nutrient for crop to sustain yield.

where they are essential—thereby preventing over-application in nutrient-rich areas while addressing deficiencies in regions where nutrient-poor zones where sol fertility is lacking.

Another effective method for reducing fertilizer waste within in PA framework is the integration of advanced sensors and monitoring technologies (Agrahari et al., 2021). These sensors provide real-time data concerning soil moisture, nutrient levels, and overall crop health, enabling farmers to make timely and well-informed adjustments to their fertilizer management practices (Senapaty et al., 2023). Proactive monitoring these parameters aids in the early detection of nutrient deficiencies, enabling farmers to fine-tune fertilizer application rates and avoid over-fertilization (Wang et al., 2023). This anticipated strategy not only maximizes nutrient uptake, but also minimizes losses due to leaching or runoff, consequently reducing overall fertilizer waste. The adoption of sensor technologies facilitates greater precision in fertilizer application, improving efficiency while concurrently mitigating environmental impacts.

The integration of remote sensing and image analysis also plays a vital role in reducing fertilizer waste in realm of PA (Jung et al., 2021). These advanced technologies empower farmers to assess precise assessments of crop health, detect nutrient deficiencies, and identify areas of stress or underperformance within their fields. By analyzing satellite imagery, aerial photos, or drone data, farmers can accurately delineate specific zones that require targeted fertilizer applications. This targeted approach significantly avoids unnecessary fertilizer use in areas where crops are thriving while ensuring that nutrients are delivered where they are most needed.

Leveraging remote sensing not only aids in refining fertilizer management decisions but also optimize nutrient utilization efficiency and overall productivity (Steeneken et al., 2023). When combined with Variable Rate Technology (VRT) and sensor technologies, remote sensing becomes a comprehensive component of a holistic PA strategy. Together, these technologies synergistically work to reduces fertilizer wastage, improves nutrient use efficiency, and promote sustainable agricultural practices (see Table 3).

In addition to optimizing resource application, the combination of remote sensing and VRT facilitates real-time monitoring and adaptive management practices (Talbot and Monfet, 2021). This ensures that farmers can respond promptly to changing field conditions and evolving crop needs, ultimately leading to enhanced yield and reduced environmental impact. By harnessing these innovative technologies, the agricultural sector can move towards a more sustainable and productive future, where resource efficiency aligns with ecological stewardship.

3.8 Impact of PA techniques on improving nutrient management

PA techniques have revolutionized nutrient management practices in agriculture, leading to significant improvements in efficiency and sustainability (Chen et al., 2009; Hedley, 2014). By leveraging advanced technologies and data-driven approaches, farmers can effectively optimize nutrient applications, monitor soil conditions, and make informed decisions to ensure that crops receive the appropriate nutrients at the right time (see Table 1). The improvement of nutrient management through PA is particularly evident in strategies such as site-specific nutrient application, real-time monitoring, and precise fertilizer timing (Sapkota et al., 2021).

A fundamental component of improved nutrient management in PA is the implementation of site-specific nutrient application (Pooniya et al., 2021). Through the utilization of technologies such as GPS-guided machinery and remote sensing, farmers can generate detailed soil maps that reveal variability within their fields (Wu and Ma, 2015). This information informs the application of fertilizers at variable rates that cater to the specific nutrient needs of each zone. By tailoring nutrient inputs to align with localized requirements, farmers can reduce the risk of over-fertilization in nutrient-rich areas while effectively addressing deficiencies in nutrient-poor zones. This targeted approach not only enhances nutrient utilization and reduces waste, but also ensures that crops receive optimal nutrients for growth and productivity.

Real-time monitoring of soil conditions and plant nutrient levels represents another crucial element of enhancing nutrient management through PA (Yin et al., 2021). The advent of advanced sensors and monitoring technologies allows for continuous data collection on essential parameters such as soil moisture, nutrient concentrations, and crop nutrient uptake dynamic (Kamienski et al., 2019). By meticulously tracking these parameters, farmers can promptly refine their nutrient management strategies. For instance, if sensor data indicate a nutrient deficiency or excess in particular area, farmers can adjust fertilizer application rates accordingly (Chore and Thankachan, 2023). This proactive approach not only helps to prevent nutrient imbalances, but also minimizes waste, ensuring that crop receive he right nutrients exactly when they are needed.

The precise timing of fertilizer applications is essential in optimizing nutrient management within PA frameworks. By analyzing key factors such as crop growth stages, prevailing weather conditions, and soil moisture levels, farmers can determine the optimal timing for fertilizer applications. Synchronizing fertilizer use with crop nutrient demands and environmental conditions enables maximum nutrient uptake while minimizing nutrient losses. PA practices facilitate this synchronization, aligning nutrient applications with critical growth stages of crops, thereby ensuring efficient nutrient utilization and ultimately enhancing crop productivity (see Table 1).

3.9 Role of PA techniques on facilitating agricultural technology innovation

PA serves as a catalyst for technological innovation by increasing farmers' ability to maximize yields and incomes from their land (Blasch et al., 2021). In recent years, PA has facilitated the development of advanced sensor technologies and robotic, coinciding with the increasing demand for organic produce. This synergy has encouraged researchers and experts to foster new technologies aimed at boosting agricultural productivity and addressing the challenges of supply and demand (Cruz Ulloa et al., 2022).

PA leverages the inherent inter- and intra-field variations in soil characteristics, topography, and climate conditions to optimize the application of agricultural technologies and enhance overall profitability (see Table 4). By spatially targeting these technologies to areas where they can achieve maximum effectiveness, PA maximizes agricultural output relative to the available resources. Since the introduction of precision technologies in the 1990s, tools such as automated guidance systems, variable rate technology (VRT), and yield mapping have seen widespread adoption. More recently, innovative technologies including unmanned aerial vehicles (UAVs) and multispectral sensors have gained traction, further transforming agricultural practices (DeLay et al., 2022).

Moreover, PA facilitates the implementation of advanced irrigation systems that utilize cutting-edge technologies as a primary mean of improving water use efficiency. Data collected from the field through PA techniques such as remote sensors is processed using information and communication technologies (ICTs) to accurately determine crop water requirements and to dispense the optimal amount of water at precise intervals (Cayuela et al., 2022). These technological advancements in PA have the potential to substantially transform rural agricultural landscapes by increasing productivity and operational efficiency while alleviating labor-intensive practices. For example, the UAVs provide significant flexibility in collecting real-time crop data, allowing farmers to make timely and informed decisions about agricultural management (Puppala et al., 2023).

4 Conclusion

This review confirms the significant role of PA in optimizing chemical fertilizer use and supporting environmental sustainability. Analysis of 51 peer-reviewed studies shows that PA technologies—such as GPS guidance, remote sensing, and variable rate application—improve nutrient use efficiency, spur innovation, and refine nutrient management. Although most evidence comes from developed countries, PA holds transformative potential for developing regions where sustainable agricultural intensification is urgently needed. To unlock these benefits, policymakers should address adoption barriers through targeted investments in R&D, infrastructure, and capacity-building. Promoting accessible and affordable PA technologies will be essential for enabling broader implementation and advancing global sustainability goals.

Collaboration among government agencies, research institutions, and the private sector is essential to drive innovation and provide farmers with practical technical support. Developing data-sharing platforms can further facilitate knowledge exchange and improve the effectiveness of PA initiatives. Nutrient management strategies must be tailored to local conditions, incorporating variables like soil type and climate. Regional or crop-specific guidelines will help optimize the implementation of PA practices. Additionally, enhancing farmer education through training, demonstrations, and extension services is critical for widespread adoption.

This review highlights the promising role of PA in optimizing fertilizer use. With supportive policies, education, infrastructure, and stakeholder collaboration, PA can significantly advance sustainable agriculture, improve nutrient management, and strengthen both environmental and economic resilience in farming systems.

This systematic review has several important limitations. Publication bias may be present, as the analysis relied exclusively on studies from Web of Science and Scopus, potentially omitting relevant work in other databases or non-indexed sources. The temporal scope, studies from 2009 to 2024, might also exclude earlier foundational research or very recent advances. Although a comprehensive search strategy was applied, variability in indexing and terminology across databases could have led to the omission of important studies. Furthermore, the review focuses specifically on PA's role in chemical fertilizer optimization and does not extensively cover broader nutrient management strategies or non-PA approaches. Finally, the generalizability of the findings is constrained by the diversity of agricultural systems, regional climates, and varying levels of technology adoption. These limitations should be considered when interpreting the results and their applicability.

TABLE 4 Studies that show the role of PA techniques on facilitating agricultural technology innovation.

Studies	Method of data collection	PA technologies	Function
Griffin and Traywick, 2021	Qualitative method	Variable Rate Technology	Provide detail information for farmers and allow farmers to adopt PA technologies and help experts to innovate new agricultural technologies
Ishola et al., 2013	Quantitative method	Long-range Radio Frequency Identification	Serve as alternative solution for geo-location determinations for the fertilizer applicator in the plantations which help further innovation of agricultural technology
Avola et al., 2024	Quantitative method	Patents analyses	The growing importance of environmental sensors and imaging devices, the rise of unmanned agricultural vehicles, and fertilization's dominance in farming patents are notable.
Kurkute, 2018	Qualitative method	Agricultural drones	Using agricultural drones provide detail soil and crop information for further innovation of new pesticide and fertilizer management technologies
Mohan, 2021	Quantitative method	GPS and Sensor-Based Technologies	GPS and Sensor Based Technologies provide site specific crop and soil information which help experts develop new site-specific fertilizer and crop management technology

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material. Further inquiries can be directed to the corresponding author.

Author contributions

BC: Conceptualization, Funding acquisition, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing. FS: Formal Analysis, Investigation, Supervision, Validation, Visualization, Writing – review & editing. BG: Formal Analysis, Investigation, Supervision, Validation, Visualization, Writing – review & editing. AKA: Data curation, Formal Analysis, Investigation, Supervision, Validation, Visualization, Writing – review & editing. MA: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. WD: Formal Analysis, Validation, Visualization, Writing – review & editing. TB: Formal Analysis, Validation, Visualization, Writing – review & editing.

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Conflict of interest

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