A Multi-Method Approach to Assess the Adoption of Precision Agriculture Technology in Brazil

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Abstract

Precision Agriculture (PA) application aims to increase crop productivity while minimizing environmental impacts. We analyzed the topics most studied in the advancement of crop production in Brazil by applying the concepts of PA using the systematic literature review (SLR). A multi-method approach combined an SLR applying the PRISMA method and secondary data analysis. We found five clusters of technologies using the PA concept related to hardware development and four clusters related to applying technologies to software development in the PA concept. Most topics focused on using sensors to control water (soil and environment), soil electrical conductivity, and data communication. The focus on sustainability led researchers to reduce chemical products related to fertilizers and pesticides using Variable Rate Fertilizers (VRT) and reducing the environmental loading. According to the research results, it was evident that PA technology might help farmers make more accurate decisions about cultivation, production, harvest, and soil management. The availability of decision support systems powered by big data and artificial intelligence to select the best crop for a given season and soil might assist Brazil's sustainable growth of food production.

Keywords

Agricultural production, crop production, food production, hardware, software, sustainability.

Ivale, A. H., de Alencar Nããs, I. and de Camargo Jani, M. (2024) "A Multi-Method Approach to Assess the Adoptionof Precision Agriculture Technology in Brazil", *AGRIS on-line Papers in Economics and Informatics*, Vol. 16, No. 3, pp. 45-58. ISSN 1804-1930. DOI 10.7160/aol.2024.160304.

Introduction

Agriculture has undergone significant upgrades, starting thousands of years ago with the domestication of plants and animals, followed by the 'green revolution,' with systematic breeding and the widespread use of pesticides and fertilizers. Nowadays, precision agriculture, with advances in information and communication technology applied to all stages of the food production process, allowed increased productivity and minimization of environmental impacts (Walter et al., 2017).

With the increase of the world population in recent years and following the growth trend, there will be significant challenges concerning non-renewable energy sources, water, food, and the environment. Just as in the industrial segment, where the fourth industrial revolution arrived to increase productivity, quality, customization, and costs involved in production, we are already experiencing the use and application of these technologies in the Precision Agriculture (PA) segment. The application of this technology raises productivity and efficiency in using inputs, reduces labor costs, improves work quality and worker safety, and reduces environmental impacts (Massruhá et al., 2017).

Precision agriculture uses equipment with embedded technology, automated with a satellite steering system, autopilot, sensors, and seed and pesticide flow controls. Software aimed at obtaining, processing, and managing georeferenced data is also applied, as well as technology for soil fertility mapping for a straightforward application of fertilizers and pesticides, according to the variable rate, and remote sensing for crop monitoring. All technology is connected via IoT, and all data generated from its use is stored and processed via software to support decision-making, aiming to increase productivity (Bassoi et al., 2014).

The grain production area in Brazil is quite extensive, and in 2021, according to data from the National Food Supply Company (CONAB, 2022), the planted area was about 68.7 million hectares. The main grains grown are soy, corn, cotton, rice, and beans. In 2021, grain production in Brazil reached a record 271.7 million tons.

The record crop was driven by the increasing use of advanced agricultural technologies, including precision farming. As the Ministry of Agriculture, Livestock, and Food Supply (MAPA, 2019) states, Brazil ranks among the world's leading grain producers, boasting a projected harvest of 288.2 million tons during the 2020/2021 season. Regarding grain exports, Brazil is one of the world's largest exporters, emphasizing soy, corn, and coffee. Data from the Foreign Trade Secretariat (SECEX, 2022) in 2021 indicates that around 85.8 million tons of soybeans and 37.2 million tons of corn were exported.

Precision Agriculture (PA) aims to enhance food production efficiency while mitigating adverse environmental effects. PA helps sustainability in several ways: (1) By using precision agriculture, farmers can reduce the waste of resources such as water, fertilizers, and pesticides. Precision agriculture technologies like soil sensors, Global Positioning Systems (GPS), and drones help farmers apply these resources only where and when needed rather than uniformly across the entire field. Such initiatives reduce waste and ensure that resources are used more efficiently. (2) PA also reduces greenhouse gas emissions by improving crop production, and this optimization is achieved through decreased energy consumption in farming operations. Furthermore, precision agriculture technologies such as GPS and drones enable farmers to minimize fuel consumption by reducing the time and distance required to execute tasks like planting and harvesting. (3) PA can also enhance soil health, a crucial aspect of sustainable agriculture. Farmers can better understand soil nutrient levels and moisture content by utilizing PA technologies, enabling them to adapt their farming practices accordingly. Such improvement can help to reduce erosion, increase soil fertility, and promote the growth of beneficial microorganisms. Furthermore, (4) PA can also help protect biodiversity by reducing harmful pesticides and fertilizers.

Precision agriculture has gained space in Brazil lately, allowing better use of resources and increasing productivity. According to a study by EMBRAPA (2022), precision technologies can increase soybean productivity by up to 30% (Goldmeier, 2019). As information and communication technologies grew, PA became broadly used in Brazil in the last decade. The present study aims to evaluate the application of PA technologies in Brazilian crop production and the scientific and technological development of the knowledge field by using the Systematic Literature Review (SLR). The SLR makes it possible to analyze and map the scientific productions around the studied subject, seeking to understand the correlation between the keywords and the evolution of the theme in recent years (Gil et al., 2020; Kipper et al., 2020). The study aimed to determine the predominant areas of research focused on enhancing crop production in Brazil by utilizing Precision Agriculture principles.

Materials and methods

An SLR using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) protocol, with the support of the VOSViewer software (Van Eck and Waltman, 2020), was developed to reach the objective. Employing the PRISMA protocol (Harris et al., 2014) in this SLR on PA in Brazil provides a methodologically sound framework that enhances the study's transparency, comprehensiveness, and reliability.

The extent of our study led us to come across a significant number of pertinent citations that presented a noteworthy obstacle in adequately handling and assessing this information. In order to rise above these limitations and guarantee an accurate and open methodical review, we opted to implement the PRISMA framework. Utilizing PRISMA, our review was systematically organized to assess all pertinent citations and reduce publication bias. Moreover, the integration of PRISMA elevates the reproducibility and credibility of our findings by enabling fellow researchers to replicate our methodology and validate our outcomes. Although initial limitations arose from the high volume of citations, utilizing PRISMA facilitated efficient data management and upheld the integrity and quality of our systematic review.

Three research questions (RQ) were proposed to guide this review RQ1 - Which are the most strategic themes related to PA studied by Brazilian researchers? RQ2 - Which technologies are most applied in Brazilian agricultural production?; and RQ3 – What are the future challenges and trends?

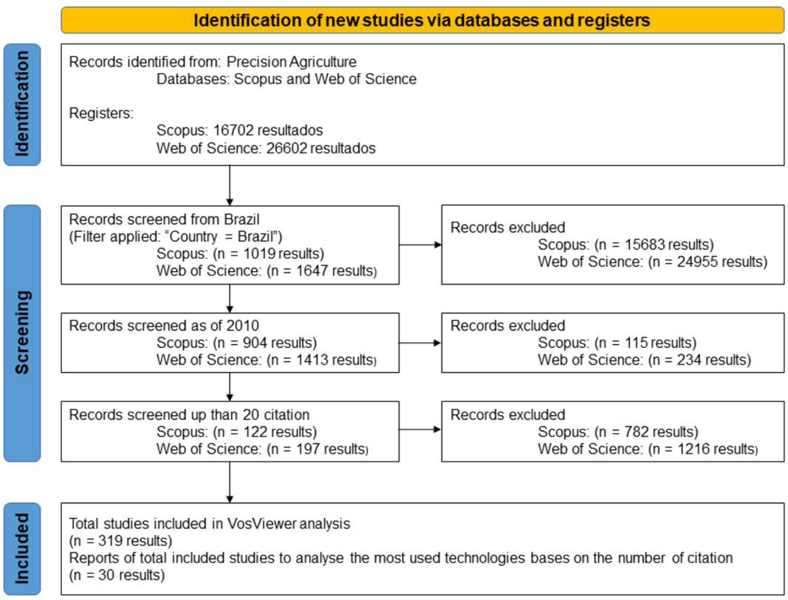
RQ1: PRISMA helps systematically identify and analyze the most strategic themes in PA research by Brazilian scholars, ensuring that the review covers a comprehensive range of studies without bias. RQ2: PRISMA's structured approach aids in the identification and synthesis of technologies applied in Brazilian agricultural production, providing a clear overview of technological adoption and innovation. RQ3: By facilitating a systematic and comprehensive literature search and analysis, PRISMA supports the identification of emerging challenges and future trends in PA, guiding stakeholders in strategic planning and research.

A multi-method approach was employed (Aitken et al., 2020; Lui et al., 2020; Broekhuizen et al., 2021), combining an SLR with secondary data analysis. We proceeded with literature research (Pereira et al., 2018) and analyzed the data and information collected through scientific publications across an inductive process. We used the integrative bibliometric review to summarize and categorize the articles (Botelho et al., 2011). We searched the Scopus and Web of Science databases for data recording and applied the PRISMA 2020 checklist and flowchart for justification. The search about PA in Brazil covered all the years that the search returned relevant results to the researched subject. In this first stage, we only performed exclusion by country.

We applied the word filter only related to Brazil, as the objective was to have a general perspective of the growth and evolution of the theme in the country. For the second and third filters, we applied the selection of articles published from 2010 with citations greater than 20 to select the most current and relevant works. This filter returned 319 articles that were later analyzed in VosViewer software (Van Eck and Waltman, 2020). In this phase, we also chose the 30 most current articles with the highest citations to survey the technologies and applications related to the topic. Figure 1 shows the schematic of SLR applying the PRISMA method (Harris et al., 2014). The flowchart shows the methodology applied and all the results obtained for each exclusion and selection criteria, which follows the PRISMA guidelines.

Figure 1 depicts a flow chart outlining the SLR process to identify Precision Agriculture (PA) studies from specific databases and registers. The process is segmented into three stages: Identification, Screening, and Inclusion, visually represented by separate rows with accompanying descriptive text and numerical data. The initial search was conducted in Scopus and Web of Science (WOS) databases, yielding 16,702 and 26,602 results, respectively. In the screening phase, the records were first filtered by country, with the term "Brazil" applied, resulting in 1,019 records from Scopus and 1,647 from WOS. A further temporal filter was applied to include only studies as of 2010, narrowing down the results to 904 from Scopus and 1,413 from WOS.

An additional citation-based filter was applied to include only records with more than 20 citations, resulting in 122 from Scopus and 197 from WOS. After each screening step, the number of records excluded from both databases is noted. In the inclusion phase, 319 studies were included for VosViewer analysis, a tool for constructing and visualizing bibliometric networks. Additionally, reports of included studies were generated for further analysis based on the number of citations, amounting to 30 results.



Source: The authors

Figure 1: Schematic of the SLR using the PRISMA method.

In the second stage of the SLR, we used the VOSViewer software (Van Eck and Waltman, 2020) to map keywords separated by cluster, aiming to verify and understand the correlation and the most explored technologies in Brazil's scenario of precision agriculture. The most researched subjects and their correlations were analyzed. The number of appearances by the sphere size categorizes the appearance of keywords in the searched studies. Related words are connected by a line, and the repetitions between them through their thickness. For the second step of the multi-method approach, the subjects of the published articles related to technology-based achievement with increased crop yield in the same period were analyzed.

The relevant keywords related to crop yield and technology-based approaches, including "precision farming," "remote sensing," "farming 4.0," and "smart farming," were examined. We searched the Scopus and Web of Science databases to locate articles examining the connection between the most commonly used technologies. The focus was on seeking some association between the most used technologies and the increase in agricultural production in Brazil, analyzing the potential benefits of adopting these technologies to sustainably improve global food security and agricultural productivity. The schematic view of the methods used to answer the research questions is presented in Figure 2.

Figure 2 presents a schematic diagram outlining the structure of a systematic literature review (SLR) based on the PRISMA framework applied to Precision Agriculture (PA) in the context of Brazilian agricultural research. It is divided into three main components: hardware, software, and systematic management, subdivided into thematic elements. The component hardware as a sensor icon symbolizes physical tools and equipment used in PA, such as sensors. Depicted by a management interface icon, this element emphasizes the software and decision-making tools used for data analysis and interpretation in PA. The systematic management section of the diagram indicates the management strategies in PA and shows no specific icons; it forms the base supporting the hardware and software components. In the central part of the diagram is the SLR process based on PRISMA, suggesting that the review is a methodical effort to compile and analyze literature on specific thematic areas in PA. The thematic areas of focus for the SLR are represented in the surrounding yellow ellipse, highlighting topics such as Agrochemical application, crop cultivation, productivity, harvest, and decision-making. The surrounding green area outlines broader, context-specific themes pertinent to PA in Brazil, including Environmental laws and land use, Communication and rural extension, and Climate change and its impacts. The diagram relates to the research questions guiding the thematic exploration of the SLR.

To address the bias that could be raised during the SLR process, we focused on the following

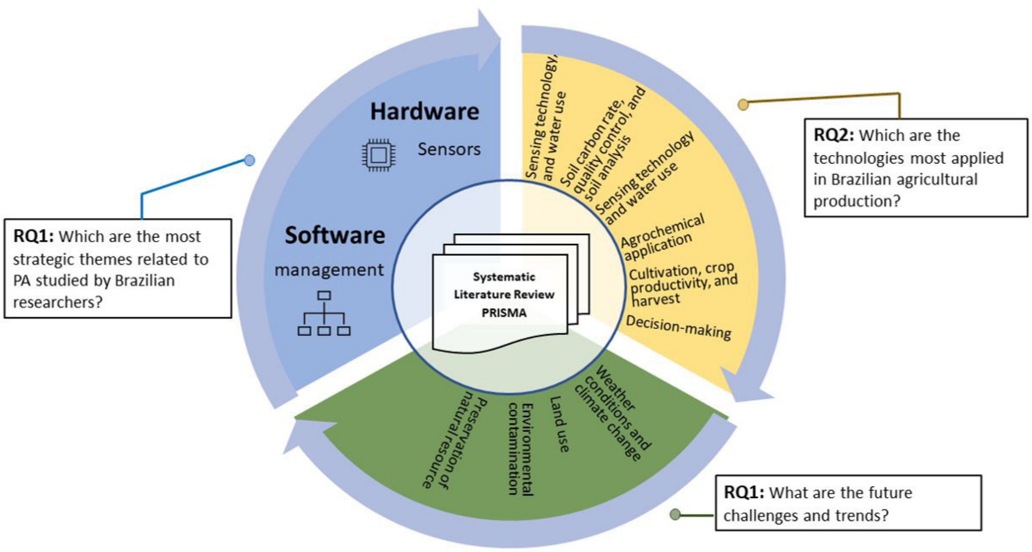


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Figure 2: Schematic view of the methods used to answer the research questions.

questions: (1) Were the databases and search terms used in the identification phase comprehensive enough to capture all relevant studies, or were they biased toward certain publications or disciplines? (2) Does including studies with more than 20 citations introduce a bias towards more popular or positive results, potentially overlooking significant negative or null findings? (3) Were the studies included in the analysis limited to those published in specific languages, which might exclude relevant research published in other languages? Moreover, by limiting the studies to those published as of 2010, there is a possibility of excluding relevant historical data or trends that could influence the interpretation of the evolution of PA technologies in Brazil.

Results and discussion

The Scopus base search returned a total of 16,557 published studies that were searched for as "Precision Agriculture" when applied to the filter of works only related to Brazil. We had 1009 published studies, as we see the division by year in Figure 1. The first study was published in 1997, followed by a relatively low number of publications until 2005. In the mid-2010s, the subject experienced a notable surge in growth, reflecting its increasing influence within the academic dominion.

The Web of Science (WOS) database search returned 26521 articles published and searched as "Precision Agriculture," with only 1645 articles of Brazilian origin. Figure 3 shows that the published articles have a similar profile to the results obtained from the Scopus database. The articles continued with minor presences until 2007 and assumed a high growth around 2012.

In addition to research related to PA in Brazil, the numbers in Figure 4 reflect a significant increase in grain production in Brazil. Despite a marginal rise in the cultivated land area post-2000, the surge in production was notably greater, signaling a substantial boost in productivity (EMBRAPA, 2022; CONAB, 2022).

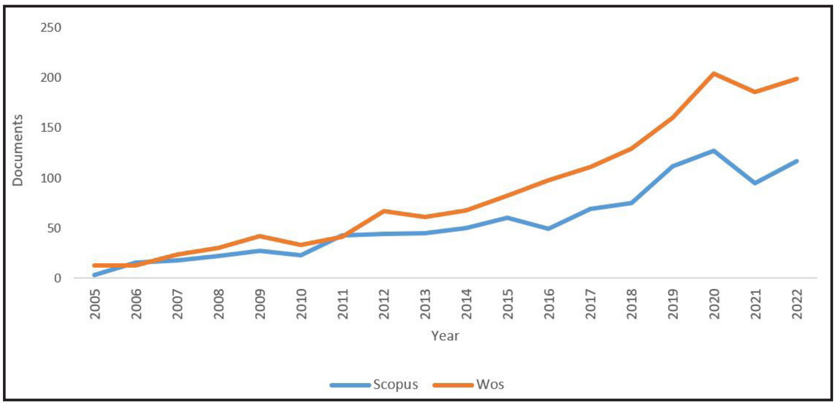

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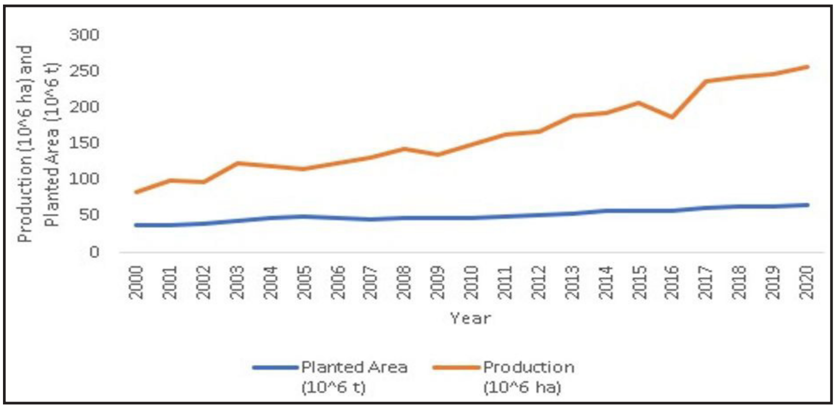
Figure 3: Curve of the studies published in the Scopus and Web of Science (WOS) websites each year from 2005 to 2023.



Source: EMBRAPA (2022), CONAB (2022)

Figure 4: Curve of Brazil's grain production and crop area from 2000 to 2020.

For the second analysis stage, a filter was performed on all selected articles, taking only the keywords related to technologies applied to Precision Agriculture (Table 1). From the data obtained, we performed a literature review to validate the correlation and application of the subject and understand which part of the process was applied. For instance, how each technology works and whether it is related to use as the equipment itself (hardware) or if it is more focused on supporting decision-making using software solutions.

The keywords were examined, and the scientific articles were selected and classified to analyze the clusters and their behavior. It was observed that the keywords were divided into four distinct fields correlated with the SLR presented in Table 1.

The technologies related to hardware are shown in Figure 5. The clusters are highlighted by colors, where we have colored the sensing technology and points related to water used to produce the dots in green. In yellow, the subjects are related to the soil, such as carbon rate, quality control, and soil analysis; in blue, we have chemical products related to fertilizers and pesticides with greater importance. The themes in red are related to cultivation, crop productivity, harvest, and electrical conductivity, which link next to the yellow field corresponding to the soil. In purple, we identified the topics related to land use, cover, and deforestation.

In the Figure 6, we present the processes of management-related keywords via software development. The figure represents a complex bibliometric network visualization mapping the interconnected research topics in soil science, agriculture, and environmental monitoring. The visualization illustrates how various concepts and themes are related within the literature. Central themes such as "soils," "remote sensing," "crops," "land use," and "water resources" are depicted as large nodes, indicating their prominence in the research. Each theme is connected to many related sub-themes, indicating interdisciplinary connections. For example, "remote sensing" is closely associated with "GIS," "drought," "hydrology," and "soil moisture," highlighting the role of remote sensing technologies in understanding and managing water-related aspects of agriculture.

The strong connection between "soils" and "fertility," "organic matter," and "crop yield" underscores the critical importance of soil in agricultural productivity. The link between "remote sensing" and "drought" or "hydrology" suggests a significant focus on using remote

Application	Description	References
	Hardware	
Soil, pest control, and harvest	Agricultural machines with integrated electronics (plows and seeders) and automated steering system. Remotely piloted aircraft (RPAs) or Unmanned Aerial Vehicles (UAVs) act in mapping using a global positioning system (GPS). Sensors to measure organic matter, soil characteristics, and contamination. Seal mapping using electrical conductivity measurements (ECa).	Bolfe et al. (2020); dos Santos et al. (2019); Iost Filho et al. (2020); Cardoso et al. (2022); Magalhães al. (2007); Souza et al. (2016); Lassalle et al. (2021).
	Sensing and mapping to measure productivity, fertility, and compaction attributes, based on topography, terraces, and soil type, for further dosing and localized application. Monitoring of temporal variability. Survey of diseases and illnesses through RPAs or UAVs. Optical sensors and sprayers for spot application. Use of multispectral images, together with GIS tools.	Tavares et al. (2019); Tavares et al. (2020); Molin et al. (2019); Molin et al. (2008); Morlin et al. (2020); Braunger et al. (2017); Demattê et al.(2015); Schepers et al. (2019).
	Harvesters equipped with GNSS (Global Navigation Satelite System) and productivity sensors. Harvesters with autopilot and harvest monitor.	Gavioli et al., 2016); (Valente et al., 2020).
	Software	
Management of production, processes, and inputs	Images are linked to data interpolation and transformation to generate index maps, crop health, soil conditions, management, and crop productivity estimates. The use of data for decision-making, climate forecasting, phytosanitary management, and financial market perspectives. Use Graphic Information Systems (GIS), geostatistics, and data mining in databases.	Schwalbert et al. (2018); Acorsi et al. (2019); Oldoni et al. (2016); Issad et al. (2019); Agostinho et al. (2008).
	Productivity sensors used in production. Use of Variable Rate Technology (VRT) as inputs at a variable rate. Modeling via geographic information system (SIG).	Bazame et al. (2021); Schepers et al. (2004); Kamienski et al. (2019); Keswani et al. (2019).
	Analytical methods and solutions to process data and build support systems for crop management decision-making. Use of the Internet of Things. IoT, sensors, and implements reduce operating costs, increase productivity, and create new business and service opportunities. Use computational tools based on artificial intelligence.	Patricio et al. (2018); Santos et al. (2020); Spekken et al. (2013); Kamienski et al. (2019); Camili et al. (2007); Faiçal et al. (2017); Franceschini et al. (2018).

Source: The authors

Table 1: Technologies used in Precision Agriculture in Brazil.

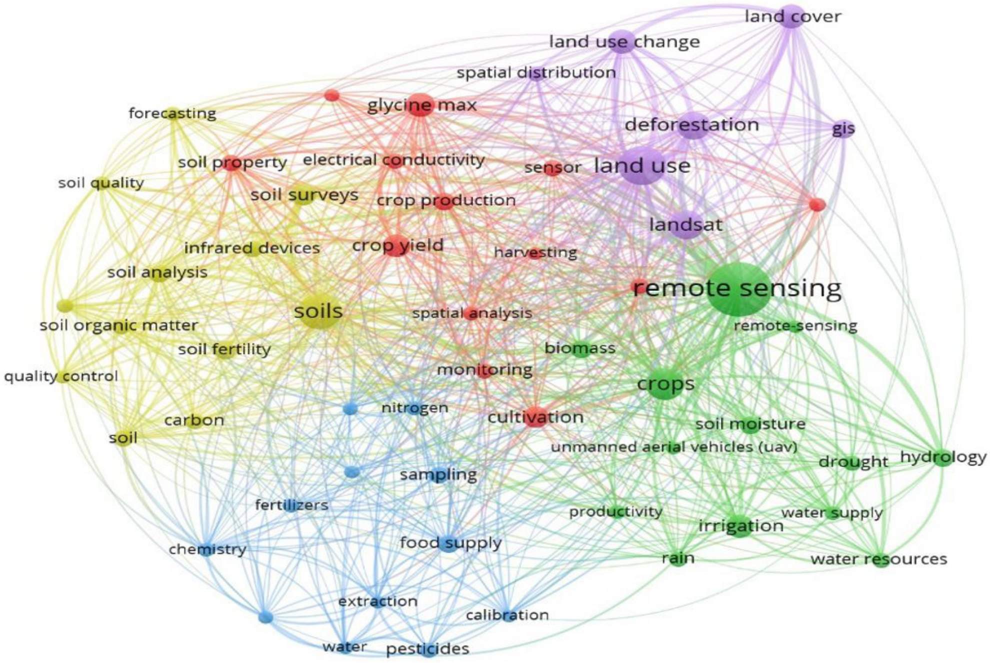


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Figure 5: Technologies related to hardware development in the Precision Agriculture concept.

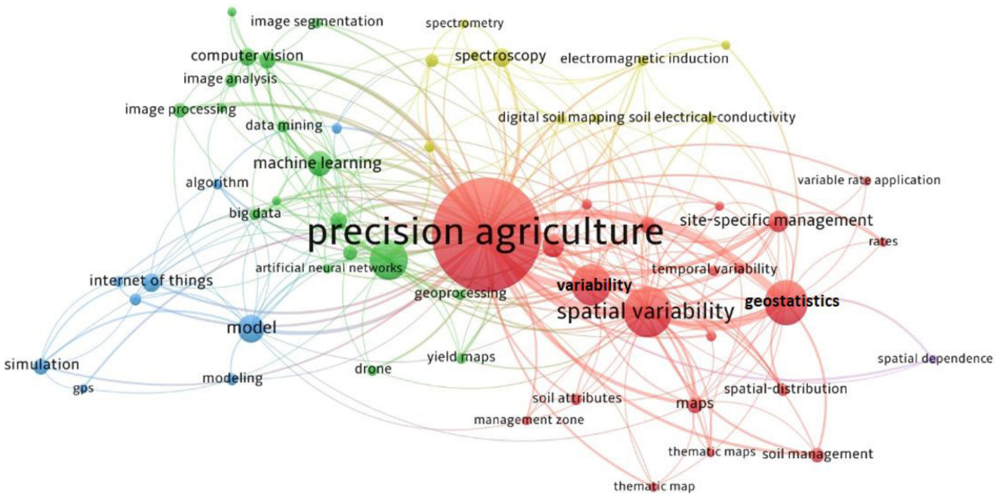

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Figure 6: Technologies applied to software development in the Precision Agriculture concept.

sensing for water management and assessment of environmental conditions affecting agriculture. The node "land use" connected to "land cover," "land use change," and "deforestation" indicates ongoing research on the impact of agricultural practices on land use patterns and environmental conservation. The network visualization provides insights into the current research landscape, identifying well-established research areas and emerging topics. It would also be essential to discuss how these themes contribute to understanding the complex interactions between agricultural practices, environmental management, and sustainable development.

Keywords such as modeling, IOT, image processing, soil analysis, simulations, variation rates, spatial variation, and geostatistics are highlighted. All words are linked to software development, processing, and supporting decision-making (Table 1).

The figure represents a bibliometric network visualization related to precision agriculture. The nodes (terms) are sized according to their occurrence frequency within the literature, and their proximity to one another indicates a strong co-occurrence or thematic linkage. The central and most prominent node is "precision agriculture," underscoring its role as the primary focus of the analyzed literature. Surrounding this central node are clusters of interconnected terms, each representing a sub-theme within precision agriculture. For example, a prominent cluster in red, centered around "variability" and "spatial variability," also includes "geostatistics," "site-specific management," and "temporal variability." This cluster suggests significant research interest in understanding and managing agricultural fields' spatial and temporal variation to optimize inputs and outputs. Another significant cluster in green includes terms like "computer vision," "image analysis," and "data mining," which are linked to "machine learning" and "artificial neural networks." This indicates a strong focus on using advanced analytical techniques and AI to process and interpret data in precision agriculture. The presence of "Internet of Things" (IoT) in the blue cluster suggests the relevance of interconnected devices and sensors in precision agriculture. This cluster also includes terms such as "model," "simulation," and "GPS," pointing towards the use of modeling and geospatial technologies for farm management. Precision agriculture topics interconnect and potentially create interdisciplinary approaches to solving complex problems in agriculture.

Most included studies were concentrated on a few key technologies within Brazilian Precision Agriculture, indicating a trend or a gap in the research. A consensus or strong correlation between certain agricultural practices and outcomes such as yield improvement, cost reduction, or environmental benefits might be identified. The VosViewer revealed that topics such as "sustainable farming practices" or "IoT in agriculture" are emerging as highly cited areas, suggesting increasing academic and practical interest. Many studies focus on specific crops or regions, highlighting a potential research bias or a regional priority.

Future research should cross-validate findings with additional databases or systematic reviews. Consider also including studies with fewer citations to provide a more comprehensive overview. We also suggest including studies across different languages and periods if relevant.

Conclusion

We analyzed the scientific development of PA in the academic scenario and identified the most researched technologies in Brazilian agricultural production that answered research question 1 (RQ1). The most strategic themes studied by the researchers can be grouped into five clusters, one related to sensors and hardware, which are also associated with soil and water use. Maia et al. (2017) describe an application of the Internet of Things (IoT) designed to monitor the water-soil balance, composed of temperature and humidity sensors (soil and environment), the soil electrical conductivity, Global Positioning System (GPS) and a ZigBee radio for data communication. The approach to the use of sensors in controlling water use with sensors is shared by other authors (Allen et al., 1998; Kim et al., 2008; Jabro et al., 2020). The sensing technology and points related to water produced the dots in green.

Various topics related to soil, such as the amount of carbon present, the methods used to maintain quality, and the analysis of soil composition, have come together to form another cluster. These topics focus on the techniques and technologies that can aid farmers in managing unique aspects of their production, such as soil properties, fertilization methods, and harvest strategies, aiming to increase efficiency, productivity, and overall quality of the crops. Farmers can better understand their soil by utilizing this data, including its characteristics, nutrient requirements, climate patterns, weed growth, and manual practices. Other studies have employed sensors and geostatistics to identify the soil type, measure micronutrients and plant nutrition levels, and analyze the contents of soil fertilizers. These methods allow for a spatial analysis that is both cost-effective and less prone to uncertainty, ultimately leading to improvements in productivity (Bottega et al., 2013; Valente et al., 2014; Silva et al., 2015; Sott et al., 2020).

The cluster involving chemical products related to fertilizers and pesticides is called Variable Rate Technology (VRT). Pesticides are chemical products that aim to reduce the environmental impact by using them only when and where they are needed. This approach helps farmers to decrease the overall amount of inputs used and, as a result, reduce the environmental loading. Avoiding overuse provides several environmental benefits, such as more targeted use of information that decreases losses caused by excess applications and nutrient imbalances, weed escapes, insect damage, and more. Additionally, a precision application can help reduce the development of pesticide resistance. Through the precise provision of nutrients and effective pest management, farmers can enhance their crop yields. VRT aids in reducing the application of fertilizers and pesticides, thus mitigating the risks of water contamination and lessening the environmental impact on local ecosystems (Bongiovanni et al., 2004; Pathak et al., 2019; Raj et al., 2022). PA technology can help farmers make informed decisions about cultivation, production, harvest, and soil management. Farmers can use decision support systems powered by big data and artificial intelligence to select the best crop for a given season and soil type by collecting and analyzing data related to factors like soil type and electrical conductivity. These systems consider multiple input factors to determine the best crop, such as the fertilizers required, irrigation methods and schedules, weed control measures, insecticides, and harvest periods. Using technology to optimize these factors, farmers can increase crop yields and obtain a higher-quality harvest. The decision-making process is facilitated by software that helps analyze the data and provide recommendations based on the input parameters. Ultimately, these tools can help farmers make more informed decisions, improving crop and business outcomes (Venkatalakshmi et al., 2014; Tantalaki et al., 2019).

Finally, we identified study fields of land use, land cover, and deforestation. To plan sustainable land cover, we can use spatial land-cover models. The adverse effects of the population's constant desire for more land lead to deforestation, the loss of agricultural land, and the conversion of grasslands to urban and industrial zones. It is possible to reduce or prevent these consequences using technologies such as multitemporal remote sensing data, spatial criteria, and predictive models, which can efficiently monitor these changes and assist in developing sustainable land use strategies (Tariq et al., 2023). We believe Brazilian farmers mostly use the above-listed technologies, at least the large ones who produce crops for export, answering research question 2 (RQ2).

Our findings agree with previous results of a survey by EMBRAPA (2022). Precision Agriculture in Brazil application, in general, focuses mainly on the soil. This encompasses the application of soil correctives, care for the soil quality, application of fertilizers and pesticides, and harvest output, with equipment with embedded technology, guided via GPS, autopilot, and applying inputs at varying rates (Bernardi et al., 2014).

The current crop production scenario demands productivity, cost reduction, and product requirements with ever-better quality, which are economic factors that support the need for precision agriculture. Environmental factors such as weather conditions, scarce natural resources, and environmental contamination lead us to answer research question 3 (RQ3). This technological scenario increasingly demands multidisciplinary training, where automation and precision agriculture are essential. However, government support is needed to access technologies and investment in education and practice for technicians and products, items that did not stand out in our analysis. Nowadays, the absence of human development factors is visible in public policies and investment in education (Bassoi et al., 2019), decreasing farm labor opportunities.

Future studies should focus on the development of human resources and governmental actions applied to precision agriculture in Brazil. To mitigate the lack of education and governmental policies related to the training of the farmers to use and apply the technologies and to help them with financial programs.

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