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Prospective Study on Precision Agriculture with Fiber Optic-Based Humidity and Salinity Sensors

Estudo Prospectivo sobre a Agricultura de Precisão com Sensores de Umidade e Salinidade à Base de Fibra Óptica

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Abstract

Precision Agriculture (PA) has emerged as a key approach to promoting sustainability in the agricultural sector by enhancing productivity and enabling the efficient use of natural resources. Among the technologies employed, optical sensors particularly fiber-based systems-have shown significant potential for monitoring soil parameters such as moisture and salinity, especially in regions like the Brazilian Semiarid and the São Francisco Valley. This exploratory study analyzes scientific articles and patent documents published between 2013 and 2023, using specific keywords and searches conducted in the CAPES Portal and Questel Orbit® software. The results indicate a growing interest in sensor technologies and data-driven approaches, although emerging technologies such as microwave photonics remain underexplored. The low number of patent filings in this field highlights important opportunities for technological innovation. Strengthening collaboration among academia, industry, and government is essential to foster the adoption of these technologies and to support sustainable agricultural development in Brazil.

Keywords: Telemetry; Microwave Photonics; Electronic Instrumentation.

Resumo

A Agricultura de Precisão (AP) tem se destacado no desenvolvimento sustentável do setor agrícola, promovendo maior eficiência produtiva e uso racional dos recursos naturais. Entre suas tecnologias, os sensores ópticos, especialmente os baseados em fibras, mostram-se promissores no monitoramento de variáveis como umidade e salinidade do solo, com potencial de aplicação em regiões como o Semiárido e o Vale do São Francisco (VaSF). Este estudo exploratório analisou artigos científicos e documentos de patentes publicados entre 2013 e 2023, utilizando palavras-chave específicas e realizando buscas nos portais da Capes e no software Questel Orbit®. Os resultados apontam crescimento no interesse por sensores e dados, embora tecnologias como fotônica de micro-ondas ainda sejam pouco exploradas. A baixa incidência de patentes nessa área indica oportunidades de inovação. A colaboração entre academia, indústria e Estado é essencial para ampliar a adoção dessas tecnologias e garantir a sustentabilidade agrícola no Brasil.

Palavras-chave: Telemetria; Fotônica em Micro-Ondas; Instrumentação Eletrônica.

Technological Area: Photonics, Optical Sensing, and Data Science Applied to Agriculture.

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1 Introduction

Precision Agriculture (PA) was introduced in Brazil in the early 1990s with the aim of optimizing agricultural production and increasing the profitability of rural properties, resulting in greater investments in the sector (Vidal et al., 2016). PA is not limited to the simple application of treatments across different areas; rather, it encompasses a set of technologies designed for the precise management of agricultural crops, taking into account the local characteristics of each farming region (Mantovani; Queiroz; Dias, 1998; Leite et al., 2021).

Among the technologies that comprise PA, sensors play a fundamental role. They provide valuable data on climate conditions, soil properties, and plant status, enabling the monitoring of factors such as moisture, salinity, and soil composition. Soil moisture, for instance, is one of the primary factors directly affecting plant health. Its efficient management is essential to ensure adequate water distribution, preventing both water deficit and excess moisture, which can negatively affect crop development (Li et al., 2021).

The diversity of sensors employed in PA is remarkable. These devices convert physical parameters into electrical signals that are transmitted to a microcontroller, enabling detailed analyses of soil conditions and crop performance (Dias et al., 2010). This transformation of physical measurements into processable information supports more efficient agricultural management, resulting in more accurate and profitable operations while minimizing waste and preventing soil degradation (Silveira, 2011).

Another growing challenge in agriculture is soil salinization, particularly in arid and semi-arid regions. This process affects soil fertility, water retention capacity, and, consequently, agricultural productivity. Furthermore, it has a direct impact on local economies and the well-being of rural communities. Early salinity detection is of paramount importance because it allows corrective practices, such as liming, to be implemented before the damage becomes irreversible or exceedingly difficult to mitigate and correct (Zhao et al., 2017; Azevedo et al., 2018; Rengasamy, 2006).

In recent years, the use of sensors in PA has expanded considerably, including optical fiber sensors, which have gained prominence in soil moisture and salinity monitoring. These innovative technologies convert physical variables, such as moisture and salinity, into electrical signals that are interpreted by microcontrollers, enabling more detailed analyses of soil conditions and crop performance (Dias et al., 2010). This technological advancement facilitates agricultural management by supporting more precise decision-making, reducing waste, and optimizing resource use, particularly water resources (Silveira, 2011).

Investing in technological innovations such as these not only enhances agricultural production but also promotes the sustainability of the sector. More efficient resource utilization helps ensure the long-term viability of agricultural activities while protecting the environment. Furthermore, by strengthening partnerships among the public sector, industry, and universities, Brazil has the opportunity to establish itself as a global leader, expanding its exports and contributing to worldwide food security.

This exploratory study, based on the analysis of scientific articles and patents, seeks to highlight the growing interest in PA technologies and the importance of collaboration among academia, industry, and government in fostering innovation within the sector. The objective is to understand how these joint efforts can drive significant advances in Precision Agriculture, ensuring a more sustainable and competitive future for Brazilian agriculture.

2 Methodology

For the development of this technological prospecting study, a preliminary exploratory investigation was conducted to gather information on intellectual property, patents, precision agriculture, moisture and salinity sensors, and optical fiber-based sensing technologies. The analysis of scientific articles provided a comprehensive understanding of the general aspects of the topic, while also enabling the identification of keywords for prior art searches and the analysis of technological prospecting data. The literature review was carried out between May and June 2023 using the CAPES Journal Portal, employing keywords such as “precision agriculture,” “telemetry,” “microwave photonics,” “electronic instrumentation,” and “optics,” as detailed in Box 1.

Open-access articles published in Portuguese and English between 2013 and 2023 were selected, focusing on precision agriculture applications involving optical fiber-based moisture and salinity sensors. Articles published in Spanish, as well as those that did not address the research problem or were incomplete, were excluded. Patent prospecting was conducted through an exploratory search using the Questel Orbit software platform (Orbit Intelligence, 2023), applying the same combination of keywords. The search focused on intellectual property records filed within the last ten years (2013–2023), with thematic alignment identified through the titles or abstracts of patent documents. All searches were performed on June 29, 2023.

Box 1 – Search combinations used for article identification in the CAPES Journal Portal

Combinations	Keywords	Results
Combination1	*precision agriculture*	18,437 documents
Combination 2	*precision agriculture* NOT *vehicle robot*	17,640 documents
Combination 3	*precision agriculture* AND *telemetry* NOT *vehicle robot*	76 documents
Combination 4	*precision agriculture* AND *telemetry* AND *microwave photonics* NOT *vehicle robot*	0 documents
Combination 5	*precision agriculture* AND *telemetry* AND *electronic instrumentation* NOT *vehicle robot*	4 documents
Combination 6	*precision agriculture* AND *telemetry* AND *optics* NOT *vehicle robot*	2 documents
Combination 7	*precision agriculture* AND *optics* NOT *vehicle robot*	189 documents

Source: Prepared by the authors (2023)

3 Results and Discussion

The analysis of the keyword combinations shows that the search for "precision agriculture" generated a substantial volume of documents (18,437), while excluding "vehicle robot" slightly reduced the number of results (17,640). When the search was refined by including the term "telemetry," the number of results decreased to 76, indicating a more specialized and niche research field. Combinations incorporating "microwave photonics" and "electronic instrumentation" yielded even fewer results, with 0 and 4 documents, respectively, suggesting limited exploration of these technologies within the context of precision agriculture. Finally, the combination "precision agriculture AND optics" returned only two documents, reflecting another emerging area with a relatively limited research base.

When the search was adjusted to exclude the term "vehicle robot," a slight reduction in the number of results was observed (17,640), compared with the 18,437 documents initially retrieved using the term "precision agriculture." This finding indicates that, although autonomous vehicles represent an important component of precision agriculture, they are not the primary focus of most studies. This reinforces the notion that the field extends far beyond robotic vehicles, encompassing a broad range of technologies, including drones, remote sensing systems, monitoring platforms, and real-time data analytics.

Furthermore, when the search was refined using more specific terms such as "telemetry," the number of documents decreased dramatically to only 76, revealing a narrower and still developing research segment. Other terms, such as "microwave photonics" and "electronic instrumentation," returned zero and only four documents, respectively, suggesting that these technologies have thus far been only minimally incorporated into precision agriculture research. Similarly, the combination "precision agriculture AND optics" produced only two results, highlighting an emerging field with considerable potential but still a limited scientific foundation.

Overall, these findings reveal not only the diversity of approaches within precision agriculture but also important research gaps that may be explored in future studies, particularly regarding the application of advanced technologies that remain underutilized within the sector.

The addition of the term "telemetry" generated only 76 documents, suggesting that, although telemetry is a promising technology, it remains less explored than other technologies, such as soil sensors. The relatively low number of publications may reflect challenges related to adaptation, scalability, or implementation costs, which may limit its broader adoption in precision agriculture.

The search for "microwave photonics" yielded no results, indicating that this technology, despite its considerable potential for high-precision sensing applications, has not yet been significantly explored in precision agriculture. Its absence from the literature suggests a research gap, possibly associated with limited funding opportunities or insufficient infrastructure for implementation.

When "microwave photonics" was replaced with "electronic instrumentation," the search returned only four documents, indicating a scarcity of research on advanced electronic instrumentation in precision agriculture. This suggests that, although essential, the development and implementation of more sophisticated electronic technologies are still at an early stage.

The final search, which replaced "electronic instrumentation" with "optics," resulted in only two documents, indicating that optics, while important for measuring environmental variables, remains a highly specialized field within precision agriculture. The small number of publications suggests that, despite its potential, optical technology is still in an emerging phase and faces technical and implementation challenges.

However, the combination "precision agriculture AND optics NOT vehicle robot" generated 189 documents, demonstrating growing research interest in the application of optical technologies. Although still limited, optical technologies, including hyperspectral imaging systems and Light Detection and Ranging (LiDAR), have considerable potential to transform precision agriculture by improving crop management and enabling the detection of issues such as plant diseases and water stress.

In summary, the searches conducted highlight the advancement of precision agriculture, particularly regarding sensor technologies and data-driven management approaches. At the same time, they reveal significant gaps in advanced technologies such as microwave photonics and electronic instrumentation. Optical technologies, although promising, remain in the early stages of development. These findings indicate that, despite substantial progress, considerable efforts are still required to effectively and affordably integrate these innovations into agricultural systems through coordinated initiatives in research, technological development, and adaptation to the global agricultural context.

Regarding the patent prospecting analysis, searches were conducted in the Questel Orbit® patent database (Orbit Intelligence, 2023) using advanced search filters. Patent families were grouped regardless of language, and searches were performed within patent titles and abstracts. The analysis considered documents published between 2013 and 2023, corresponding to the most recent ten-year period, as illustrated in Box 2.

The analysis of searches conducted in the Questel Orbit® patent database provides an overview of technological innovation in precision agriculture, with particular emphasis on telemetry and other emerging technologies. The initial search using the term "precision agriculture" resulted in 514 patent documents, indicating the well-established development of this field. However, when the term "telemetry" was added, the number decreased to only three patent documents, suggesting that, despite its importance in agricultural monitoring, telemetry remains a relatively underexplored or underpatented area. The subsequent exclusion of the term "vehicle robot" did not alter this number, indicating that the patented innovations identified are not directly associated with autonomous vehicles, which may reflect a gap in the development of advanced agricultural robotics.

The absence of results for searches involving terms such as "microwave photonic," "electronic instrumentation," and "optic" suggests that these technologies do not yet have a significant patent presence within the precision agriculture sector. This finding points to a promising area for future innovation, as the integration of these technologies with telemetry could enable substantial advances in remote monitoring and agricultural automation. In contrast, the search for "precision agriculture AND optic" resulted in a single patent document, indicating an emerging interest in optical technologies within the sector, particularly those related to remote sensing and computer vision systems.

These results highlight a disparity in the volume of patented innovations between broad and highly specialized concepts. The low technological maturity of areas such as microwave photonics and advanced electronic instrumentation may indicate that these innovations remain in the early stages of research and development. Furthermore, implementation challenges, including infrastructure limitations and connectivity constraints in rural areas, may hinder the adoption of these technologies.

Box 2 – Searches conducted in the Questel Orbit® Patent Database

Combinations	Keywords	Results	Search Date
Combination 1	*precision agriculture*	514 patent documents	June 29, 2023
Combination 2	*precision agriculture* AND *telemetry*	3 patent documents	June 29, 2023
Combination 3	*precision agriculture* AND *telemetry* NOT *vehicle robot*	3 patent documents	June 29, 2023
Combination 4	*precision agriculture* AND *telemetry* AND *microwave photonic*	0 patent documents	June 29, 2023
Combination 5	*precision agriculture* AND *telemetry* AND *electronic instrumentation*	0 patent documents	June 29, 2023
Combination 6	*precision agriculture* AND *telemetry* AND *optic*	0 patent documents	June 29, 2023
Combination 7	*precision agriculture* AND *optic*	1 patent document	June 29, 2023

Source: Prepared by the authors (2023)

The lack of commercial incentives and the protection of innovations through trade secrets by large corporations may also contribute to the limited number of patent filings.

This scarcity of patents at the intersection of precision agriculture, telemetry, and advanced technologies reveals significant opportunities for startups, researchers, and companies seeking to develop new applications. The convergence of these technological domains may play a critical role in the future of agricultural automation, promoting improvements in efficiency, sustainability, and productivity across the sector.

Graph 1 presents the patent landscape in precision agriculture organized by applicant country, highlighting the ten countries with the highest number of patent filings. This analysis identifies the leading nations in technological innovation within the sector, providing a global perspective on the distribution of knowledge and emerging trends, which is essential for recognizing centers of excellence and the development of new technologies.

An analysis of the top five countries presented in Graph 1 reveals China's leadership with 141 patent documents, of which 90 have been granted and 51 remain pending. India ranks second with 115 patent documents, including 9 granted and 106 pending patents. The United States occupies third place with 66 patent documents, comprising 52 granted and 14 pending patents. The European Patent Office (EPO) ranks fourth with 26 patent documents, including 16 granted and 10 pending patents. Brazil appears in fifth place, with 18 active patent documents, of which 8 have been granted and 10 remain pending (WIPO, 2023).

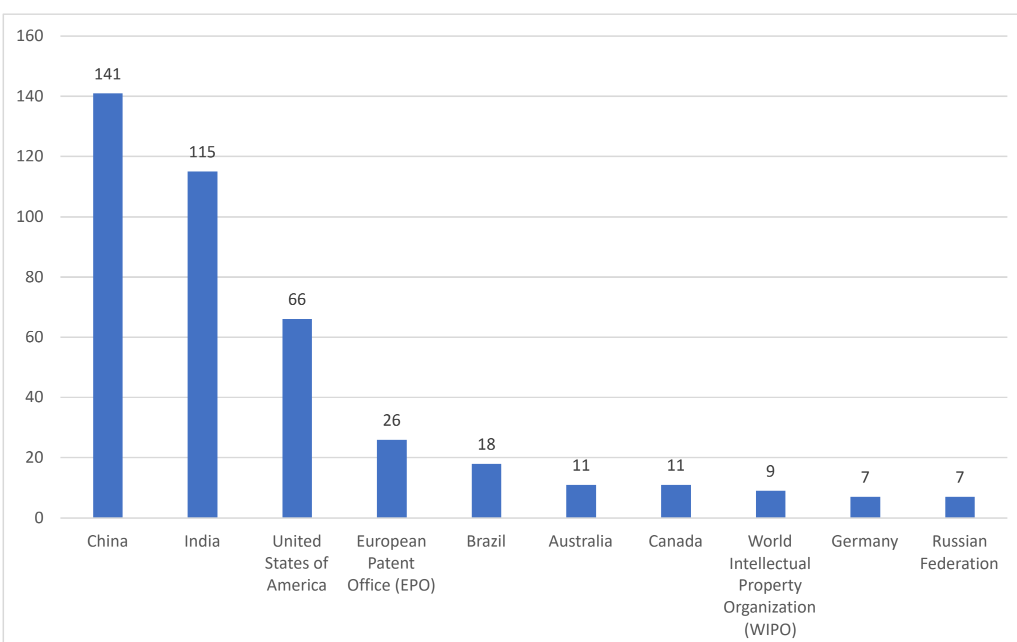
The analysis of patents related to precision agriculture highlights China's significant position in this field. According to a report by the World Intellectual Property Organization (WIPO), China is a leading contributor to international patent filings in the area of autonomous devices for precision agriculture, with 1,379 international patent families. This Graph is surpassed only by filings associated with the United States (1,923), WIPO (1,789), and Europe (1,768) (WIPO, 2023).

Furthermore, a study published in *Cadernos de Prospecção* indicates that China holds the largest number of patent protections related to Machine-to-Machine (M2M) technologies, a fundamental component of Agriculture 4.0 (Santos et al., 2021).

These findings underscore China's prominent role in the development and protection of innovations aimed at precision agriculture, reflecting its strong commitment to modernization and sustainability within the agricultural sector.

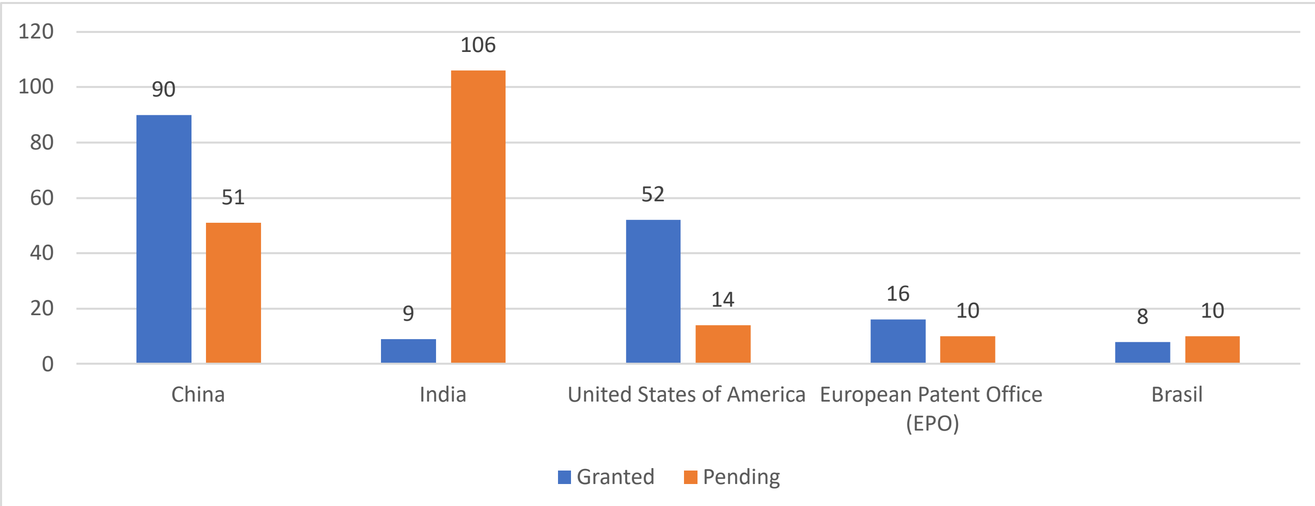
Graph 2 presents a comparative analysis of the number of granted and pending patents among the five leading countries in patent filings. The visualization illustrates the innovation dynamics within each nation, highlighting countries with the highest numbers of granted patents as well as those with substantial numbers of pending applications. These patterns reflect the pace of innovation, the level of technological competitiveness, and the influence of patent systems in fostering research, development, and technological advancement.

Graph 1 – Number of patents by country considering the keyword combination "precision agriculture"



Source: Prepared by the authors (2023)

Graph 2 – Comparison of the number of granted and pending patents by country



Source: Prepared by the authors (2023)

India ranks second in the precision agriculture patent landscape; however, it has a relatively low number of granted patents, with only nine patents approved. In contrast, it has 106 pending patent applications, indicating challenges within the patent granting process, including bureaucratic procedures, lengthy examination periods, and complex regulatory requirements. This scenario reflects a patent system burdened by a substantial backlog of applications, possibly due to limited resources and the complexities associated with evaluating highly specialized technologies.

Despite these challenges, the large number of pending patent applications may indicate a vibrant innovation environment, where researchers and companies are actively seeking to protect their inventions. However, inefficiencies within the patent system may discourage investment and negatively affect the country's competitiveness, particularly in an increasingly globalized market.

The high volume of pending patent applications also suggests that India is undergoing a process of adaptation and modernization of its patent system to address growing demand. To strengthen its competitiveness in the global agricultural innovation landscape, it is essential to improve the efficiency of the patent examination process and enhance the technical expertise of patent examiners in emerging technologies. Such measures could accelerate innovation in precision agriculture and reinforce India's position in the international market.

Regarding Brazil, agribusiness plays a fundamental role in the national economy, contributing substantially to gross domestic product (GDP), exports, and employment generation. Nevertheless, the number of patents in the agricultural sector remains relatively low. This situation is paradoxical, considering that Brazil is among the world's leading producers of food, fiber, and biofuels, yet it has not developed a strong culture of intellectual property protection in the agricultural sector (Revista Cultivar, 2016).

Several factors contribute to this scenario. The patenting process is often perceived as bureaucratic, costly, and time-consuming, discouraging many innovators, particularly small-scale producers, from seeking patent protection. In addition, financial constraints, limited technical knowledge, and insufficient awareness of the intellectual property system further complicate the patent application process (Revista Cultivar, 2016).

Another challenge is the limited integration among universities, research institutions, private companies, and the productive sector. This lack of interaction hinders the development of a robust innovation ecosystem and restricts the transfer of new technologies from academia to agricultural production systems. Insufficient governmental support and relatively low levels of investment in research and development by private companies also contribute to this situation (Castro e Silva et al., 2005).

As a result, the number of patents filed by Brazilian institutions remains low, while companies from other countries continue to dominate the technological landscape. This dependence on foreign technologies may compromise the competitiveness and technological autonomy of the sector. Studies conducted by the National Institute of Industrial Property (INPI) and the Technology and Biotechnology Study Group (GTEB) indicate the urgent need for public policies aimed at fostering innovation in rural areas and improving access to intellectual property protection mechanisms (INPI; GTEB, 2007).

Finally, many rural producers successfully transform their ideas into practical solutions for agricultural applications. However, for an invention to be patented, it must meet the legal requirements of novelty, industrial applicability, and inventive step, as established by the Brazilian Industrial Property Law (Law No. 9,279/1996). Ideas or methods that cannot be industrially applied are not eligible for patent protection. Certain creations may instead be protected through copyright mechanisms, although these do not fall under the jurisdiction of the INPI. Therefore, it is essential for agricultural innovators to understand the available intellectual property protection mechanisms in order to prevent their innovations from being copied or patented by third parties (Revista Cultivar, 2016).

Graph 3 illustrates the distribution of patents by year of first priority, highlighting the temporal evolution of technological innovations. This analysis enables the identification of innovation trends, patenting activity peaks, and the pace of technological development, providing insights into advances in specific technological domains over time.

Graph 3 highlights peaks in patenting activity, which may correspond to significant technological advances, including disruptive innovations or substantial improvements to existing technologies. A sharp increase in patent filings during a particular year may indicate a technological breakthrough or the emergence of new market demands, whereas a decline may suggest technological maturation or a slowdown resulting from external factors such as economic crises or regulatory changes.

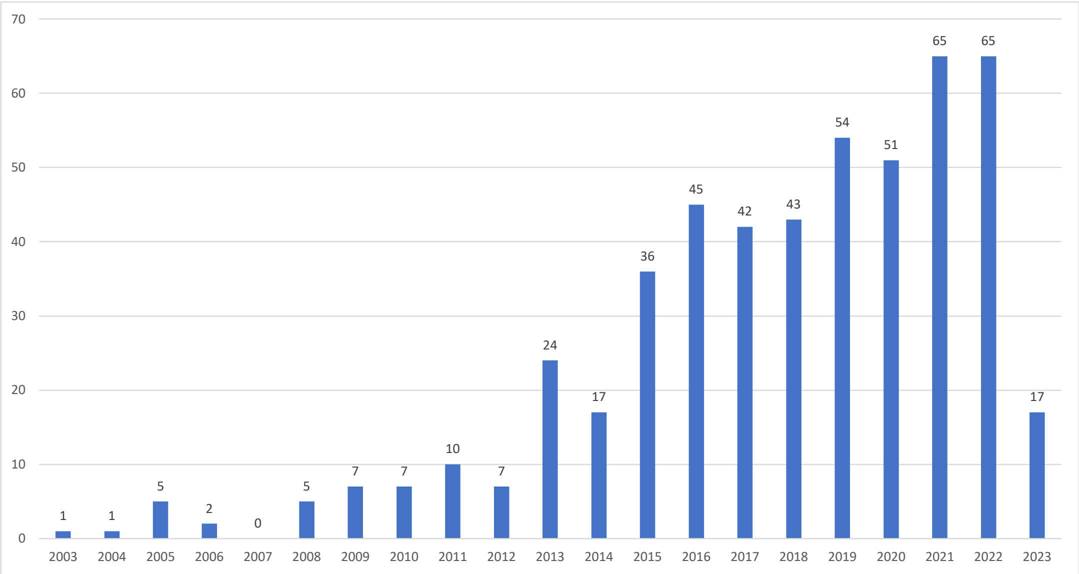
The temporal distribution of patents also reflects the evolution of technological fields over time. Growth in areas such as biotechnology and artificial intelligence may serve as an indicator of global trends as well as broader economic and social influences. Conversely, a reduction in patent activity within a specific field may suggest technological saturation or a shift toward more incremental forms of innovation.

Changes in patent systems, including faster examination procedures or modifications to intellectual property legislation, may also directly affect the number of patents filed and granted, thereby influencing the pace of innovation. Economic and geopolitical factors, such as financial crises or government policies designed to encourage innovation, can either stimulate or constrain patenting activity.

Furthermore, Graph 3 may help identify emerging technological trends, such as increasing patent activity in fields related to artificial intelligence and automation, both of which have the potential to transform entire sectors of the economy. Nevertheless, it is important to recognize that the number of patents does not necessarily reflect the true extent of innovation, as patenting strategies adopted by companies and research institutions may influence filing volumes. Patent activity may also be concentrated among large corporations or technologically dominant countries.

In summary, Graph 3 provides a detailed overview of fluctuations in technological innovation over time. However, its interpretation should be approached with caution, taking into account not only the quantity of patents but also their technological relevance, practical impact, and overall quality.

Graph 3 – Distribution of patents by year of first priority



Source: Prepared by the authors (2023)

Graph 4 presents quantitative data on the technologies represented in the patent documents, using a color scale to indicate the volume of patent filings within each technological domain. Areas displayed in darker red tones correspond to a higher number of patents, reflecting greater innovative activity and technological concentration. In contrast, areas represented by gray tones indicate lower patent volumes, suggesting more limited technological development or participation. This visualization facilitates the identification of technological trends, innovation hotspots, and concentrations of patent activity across different technological fields.

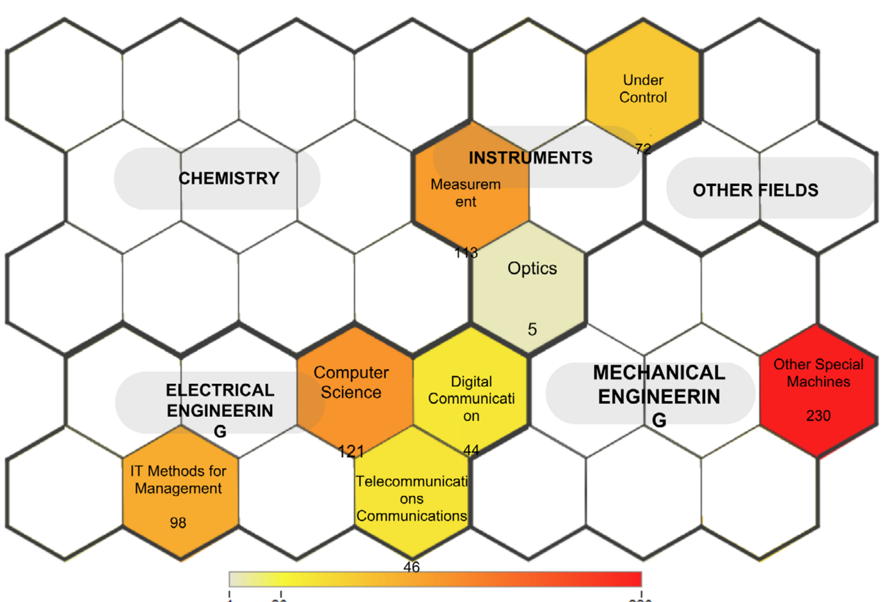
The technological fields with the highest concentration of patents, represented by the most intense colors, indicate highly innovative and competitive environments characterized by emerging technologies with substantial potential, such as artificial intelligence and biotechnology. The large volume of patent filings in these areas also suggests a strong emphasis on intellectual property protection, which is essential for ensuring exclusivity and maintaining competitiveness in the global marketplace. However, a high number of patents does not necessarily imply disruptive innovation, as it may also reflect technological saturation or strategic patenting practices aimed primarily at protecting existing market positions rather than introducing groundbreaking advances.

Conversely, technological fields with lower patent volumes, represented by gray tones, may indicate areas that remain underexplored or are still in the early stages of research and development, thereby presenting opportunities for novel solutions and future innovation. Nevertheless, a limited number of patents may also result from regulatory barriers or from the nature of certain technologies that are difficult to patent, such as software-based solutions or innovative business models. Therefore, the absence of patent activity should not automatically be interpreted as a lack of innovation but rather as a characteristic of the technological domain under consideration.

Furthermore, Graph 4 may reveal geopolitical and economic patterns, reflecting priority investment areas, regional technological expertise, and the availability of supporting infrastructure in different parts of the world. Such insights can contribute to the formulation of public policies aimed at stimulating or redirecting research and development (R&D) efforts. The analysis may also highlight emerging trends, such as the growing demand for technologies that optimize the use of natural resources, particularly within precision agriculture, thereby supporting strategic decision-making by both governments and private organizations.

However, Graph 4 should be interpreted within a broader context that considers additional factors, including market dynamics, the presence of major industrial stakeholders, and economic cycles, all of which can influence patenting activity. In summary, Graph 4 provides valuable information regarding the concentration of technological innovations, but its interpretation requires careful consideration of the economic, political, and social factors that shape the innovation ecosystem.

Graph 4 – Distribution of technologies across patent documents by technological field



Source: Prepared by the authors (2023)

With regard to optical patents in Precision Agriculture (PA), it is important to examine how optical technologies, although still relatively underexplored, may provide innovative solutions for the agricultural sector. These technologies have the potential to enhance resource monitoring and management, thereby improving efficiency and sustainability in precision agriculture systems.

One example is patent IN201811043318, filed in India in 2018, which describes a wireless sensor platform for agricultural applications based on the Internet of Things (IoT). Another relevant patent is US10567678, granted in the United States in 2020, which relates to a multispectral camera incorporating a replaceable filter array.

The integration of the Internet of Things (IoT), Big Data analytics, and machine learning is driving digital transformation within the agricultural sector by enabling real-time data acquisition, large-scale information storage and processing, and the application of predictive models to optimize agricultural management practices (Khanna & Kaur, 2019). This technological convergence contributes to more efficient and sustainable resource management while reducing operational waste (Wolfert et al., 2017).

In addition, international patents such as WO2017/099570 describe systems and methods for precision agriculture based on multispectral and hyperspectral image analysis using unmanned aerial vehicles (UAVs), published in 2017. Another patent, WO2017/099568, describes a method for planning flight paths over irregular polygons using two or more drones for multispectral and hyperspectral image acquisition and analysis, also published in 2017.

Another example is patent IN201721005046, filed in India in 2017, which describes the use of an airship for precision agriculture and the monitoring of specific agricultural areas. These patents illustrate the advancement of technologies applied to precision agriculture, particularly those involving sensors and aerial imaging systems designed to optimize agricultural production. Studies indicate that the integration of IoT and machine learning technologies can reduce operational costs by up to 25% while increasing production efficiency by approximately 15% (Jha et al., 2019).

The patent analysis reveals a significant gap in the application of precision agriculture technologies involving optical fiber sensors, with no patent documents identified within the scope of the search. This finding suggests that technologies capable of optimizing agricultural production while reducing environmental impacts remain underexplored. The absence of patent filings may reflect challenges associated with large-scale implementation and highlights the need to encourage further research into these innovations, particularly within the Brazilian agricultural sector. Collaborative efforts among researchers, private companies, and governmental institutions will be essential to advance these technologies and promote greater sustainability in agricultural production systems.

4 Final Considerations

The findings reveal a substantial volume of academic publications and patent documents related to Precision Agriculture (PA), although patented technological developments, particularly in areas such as telemetry and advanced sensing technologies, remain limited. Precision Agriculture, which relies on technologies including sensors, georeferencing systems, and data-driven management approaches, demonstrates significant potential for optimizing resource utilization and enhancing agricultural sustainability. Technologies such as telemetry and optical fiber sensors have contributed to improving the efficiency of agricultural management practices while reducing environmental impacts.

The patent analysis indicates that, despite the extensive academic output in the field of Precision Agriculture, technological innovation remains under development, with relatively few patent contributions identified. China emerges as the leading country in the protection of technological innovations, followed by the United States, India, and Brazil. Although Brazil currently occupies a less prominent position, it possesses considerable potential for growth in Precision Agriculture innovation.

The study highlights the need for continued investment in research, development, and technological innovation to further explore the opportunities offered by Precision Agriculture. Expanding the application of advanced technologies, particularly in areas such as telemetry, optical sensing, and intelligent monitoring systems, may contribute significantly to increasing agricultural productivity, improving resource efficiency, and promoting greater environmental sustainability.

5 Future Perspectives

Research on innovations in Precision Agriculture (PA) reveals a rapidly expanding field focused on improving agricultural productivity while enhancing environmental sustainability. The initial literature search identified 18,437 documents, which were subsequently refined through the exclusion of terms related to autonomous vehicles and the inclusion of keywords such as telemetry and optical instrumentation. The results indicate that, although Precision Agriculture has been widely studied, the application of advanced monitoring technologies remains relatively limited and underexplored. PA integrates traditional agricultural practices with innovative technologies, including sensors, georeferencing systems, and data-driven management tools, to optimize production processes and reduce environmental impacts. Within this context, telemetry plays a crucial role by enabling real-time monitoring and decision-making.

Regarding patent activity, China leads the number of patent filings, followed by India and the United States, reflecting substantial investments in technological innovation within the agricultural sector. Although academic research on Precision Agriculture is extensive, patent activity remains concentrated in broader technological domains, with noticeable gaps in specialized areas such as advanced sensing technologies, optical instrumentation, and optical fiber-based monitoring systems.

According to the authors, Precision Agriculture is expected to expand significantly in the coming years, driven by the integration of real-time monitoring technologies and the development of increasingly sophisticated sensors designed to improve agricultural efficiency and sustainability. The advancement of high-precision sensing technologies, combined with telemetry systems, optical instrumentation, artificial intelligence, and data analytics platforms, is expected to play a fundamental role in addressing the challenges associated with modern agricultural production.

Future developments may include the widespread adoption of optical fiber sensors for monitoring soil moisture, salinity, nutrient availability, and crop health with greater accuracy and reliability. The integration of these technologies into Internet of Things (IoT) ecosystems and smart farming platforms may enable continuous data acquisition, predictive analytics, and automated decision-making processes. Such advances have the potential to improve resource management, reduce water and fertilizer consumption, minimize environmental impacts, and increase crop yields.

In addition, stronger collaboration among universities, research institutions, industry stakeholders, and governmental agencies will be essential for accelerating technological development and facilitating the transfer of innovations from research laboratories to commercial agricultural applications. Investments in research and development, intellectual property protection, and innovation-friendly public policies will be critical to fostering the next generation of Precision Agriculture technologies.

Overall, the future of Precision Agriculture points toward increasingly intelligent, connected, and sustainable production systems. The convergence of advanced sensing technologies, telemetry, optical instrumentation, artificial intelligence, and digital agriculture platforms may provide robust solutions for enhancing productivity while promoting environmentally responsible agricultural practices on a global scale.

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