Innovation in precision agriculture:

patent landscape

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Abstract

The aim of this study was to characterize, through patentometrics, the technological dynamics associated with precision agriculture based on international filings, identifying temporal trends, protection jurisdictions, leading applicants, and dominant technical areas. An observational cross-sectional study (2025) was conducted following WIPO guidelines for patent landscape reports. Espacenet was queried using a deliberately broad strategy combining IPC/CPC codes with title or abstract text filters, restricted to PCT applications and the 2005–2025 window. Data cleaning reduced 39 996 initial records to 1 497 PCT documents and to 1 367 documents published after 2005, suggesting that much prior art follows national routes and that the PCT subset concentrates inventions with global market ambition. The time series showed acceleration from 2013, and an inflection point in 2017; trend growth was supported by a 7.29% CAGR (2014–2024), although forecasting models were sensitive to the most recent years due to publication lag. The protection is concentrated in the United States, China, and the European route, with fragmented leadership and the coexistence of universities and firms and with a technological core focused on farm management and decision support, remote sensing and AI, and in-field execution. It is concluded that the field remains in expansion and offers differentiation opportunities through integration, interoperability, and operational validation.

Keywords:
knowledge management, intellectual property, interoperability, Internet of Things, remote sensing.

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Introduction

Throughout history, agriculture has been a central pillar of human development. Traditional agriculture, based on manual practices and the domestication of plants and animals, is known as Agriculture 1.0. With the Industrial Revolution, machinery was incorporated into farming, and with the Green Revolution, the use of chemical fertilizers, pesticides, and improved seeds increased, leading to Agriculture 2.0. In the mid-1990s, the first information technologies began to be widely introduced through the use of basic sensors and satellite monitoring; in addition, significant advances were made in agricultural biotechnology, giving rise to Agriculture 3.0 (Herrera & García-Bertrand, 2018; Viola & Mendes, 2022).

At present, the integration of the technological sector and data analysis continues, but on a much broader scale, with cutting-edge technologies and advanced systems. This has given rise to Agriculture 4.0, or precision agriculture, characterized by the integration of robotics, artificial intelligence, the Internet of Things, and automation with the aim of achieving more efficient and sustainable production (Santos Valle & Kienzle, 2020). At the same time, these advances present unprecedented challenges for agriculture.

Agriculture is currently facing a global crisis driven by several interrelated factors, including population growth, the depletion of natural resources, and the effects of climate change. According to the Food and Agriculture Organization of the United Nations (FAO), the world population is projected to reach 9.7 billion people by 2050 and 10.8 billion by 2080. This demographic growth will place considerable pressure on agricultural production systems (FAO, 2018).

Against this challenging backdrop, precision agriculture emerges as a transformative innovation in agricultural resource management. Precision agriculture, or Agriculture 4.0, involves comprehensive data analysis and the application of advanced technological tools aimed at maximizing agricultural productivity, reducing environmental impact, and promoting sustainability (Getahun et al., 2024). Its implementation has demonstrated tangible benefits on multiple fronts. Precision agriculture not only optimizes the efficiency of agricultural systems but also addresses critical global challenges such as food security, the conservation of natural resources, and resilience to climate change.

By integrating technologies such as sensors, drones, and geographic information systems, the generated data enable farmers to make informed decisions that improve both crop performance and ecosystem health. Thus, precision agriculture is positioned as a vital solution for ensuring a sustainable and responsible agricultural future (Sanyaolu & Sadowski, 2024). Beyond the specific technologies it incorporates, what is relevant for this study is that the widespread adoption of these solutions has generated a growing body of patentable inventions, opening the possibility of studying the dynamics of the field through patent evidence.

In this context of accelerated digitalization, as sensors, data platforms, and automated systems become increasingly widespread, a growing volume of technical solutions, business models, and actors are emerging, competing, collaborating, or specializing in specific niches. This creates a clear methodological need: approaches that make it possible to observe the evolution of the field through evidence, identify the directions of innovation, and distinguish which developments are closest to becoming large-scale productive applications.

To address this need, various indicators are used to assess technological progress and its adoption dynamics. Among these, patent analysis occupies a prominent place because it captures, in a structured manner, technical and legal information on inventions, makes it possible to identify rights holders, territories where protection is sought, and temporal trajectories of innovative activity (Moscatelli et al., 2024). Furthermore, because patenting typically involves costs, time, and a deliberate effort to protect a competitive advantage, patent records can function as early signals of expectations for economic exploitation, particularly when sustained growth patterns are observed in specific subfields or technological families (Moscatelli et al., 2024; Trippe, 2015).

Beyond serving as a measure of inventive activity, patents make it possible to develop strategic insights. On the one hand, they facilitate comparisons among countries, regions, or sectors in terms of innovation intensity, technological priorities, and development orientation. On the other hand, they help map the ecosystem of actors—including companies, universities, research centers, and public agencies—that are driving solutions, as well as identify potential collaboration networks or concentrations of capabilities. In public policy and institutional planning, such evidence can support the definition of technological agendas, research and development investment priorities, and more realistic approaches to technology transfer (Trippe, 2015).

Specifically, a patentometric analysis of precision agriculture can contribute to at least four analytical objectives. First, it can characterize the temporal evolution of the field and its subdomains, such as remote monitoring, agronomic diagnostics, variable-rate application, smart irrigation, data management, decision-support platforms, autonomous machinery, and traceability systems. Second, it can compare protection dynamics across jurisdictions to infer where value capture is being pursued, and which markets are considered priorities. Third, it can identify leading actors and their institutional nature to understand the orientation of development, whether closer to research, commercialization, or applied deployment. Fourth, it can provide insights into the translational dimension of innovation, that is, the extent to which inventions are connected to operational implementation, scaling, and use under real production conditions (World Intellectual Property Organization (WIPO), 2026).

Based on the above, the present study aims to retrieve and refine the patent landscape related to precision agriculture and use this corpus to identify technological maturity, geographic distribution, leading actors, and technological dynamics within the field. In doing so, it seeks to provide an empirical foundation that complements the conceptual discussion on Agriculture 4.0 and serves as an input for decision-making in research, development, and technology transfer in the agricultural sector.

Methods

To ensure technical rigor, transparency, and reproducibility of the results, the methodological design (a 2025 cross-sectional observational study) of this research is strictly based on the international guidelines established by the World Intellectual Property Organization (WIPO).

Specifically, the framework described in the manual Guidelines for Preparing Patent Landscape Reports (Trippe, 2015) was adopted. This standard proposes a coherent structure that encompasses the definition of scope and search strategies in specialized databases, data normalization, and the generation of analytical indicators that support informed decision-making. The application of this international guideline helps mitigate information retrieval bias and ensures that the processing of patent families meets the quality criteria required in the scientific and professional field of industrial intellectual property.

Scope

For document retrieval, WIPO Patent Cooperation Treaty (PCT) applications were established as the inclusive filtering criterion and the central axis of the search strategy. The PCT system, administered by WIPO, enables applicants to seek protection for an invention in multiple countries through a single international application. Such an application has the same effect as filing national applications in member states. The PCT simplifies, centralizes, and increases the cost-efficiency of the process, while also facilitating examination by national offices and the technical disclosure of inventions (WIPO, 2026).

The selection of patents filed directly through this international office is based on three methodological considerations. First, WIPO patent applications are subject to highly demanding technical filing standards. Second, their international nature facilitates statistical comparison by relying on standardized filing conditions, thereby mitigating biases derived from the specific legislation of national patent offices. Finally, filing through international offices suggests an invention with significantly greater economic potential and global reach compared with purely local applications (Trippe, 2015).

Time frame

The analysis covers a complete 20-year period, from 2005 to 2025. This observation window makes it possible to identify the historical evolution and emerging trends within the field of study. It is important to note that the patent volume analyzed at the end of the period (2024–2025) does not necessarily reflect the total number of patents filed during those years. Due to the institutional structure of intellectual property processing, there is a standard delay of approximately 18 months between the priority filing date and the official publication date.

Therefore, while data up to 2023 provide complete coverage of innovation activity, the figures corresponding to the final 18 months of the study represent only a partial sample composed of inventions that have already completed the confidentiality period and have been released into the public domain.

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Data base

The searches were conducted using Espacenet, the open-access database of the European Patent Office. This platform was selected because it is considered one of the most robust publicly accessible tools with the broadest global coverage (WIPO, 2022). Its data integration capabilities provide access to a vast collection of technical documents from multiple jurisdictions, ensuring that the technology surveillance process is supported by the widest possible spectrum of information available within the state of the art.

Search strategy

A deliberately broad search strategy was applied with the objective of capturing, with high sensitivity, the largest possible share of the technological landscape related to precision agriculture. The query was structured by combining two complementary criteria. First, a set of IPC/CPC classification codes associated with the stages, components, and implications of precision agriculture was used (Table 1). These included, among others, agricultural activities and crop management, fertilization and phytosanitary control, applied biotechnology, sensing and measurement technologies, automation and control systems, information and communication technologies, and indicators related to sustainability.

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Table 1
IPC/CPC classification codes used

Segmentation	Code	Technological Area
Agriculture	A01B	Tillage and soil cultivation in agriculture or forestry, and agricultural machinery accessories.
Agriculture	A01C	Planting, sowing, and fertilization.
Agriculture	A01D	Harvesting, mowing, crop collection, and crop handling during harvest.
Agriculture	A01F	Post-harvest processing and handling, for example: threshing, packaging, storage of agricultural products, and associated equipment.
Agriculture	A01G	Horticulture, cultivation of vegetables, flowers, rice, fruit trees, vineyards, forestry, and irrigation.
Agriculture	A01H	New plants, plant breeding, plant reproduction, and tissue culture.
Agriculture	A01K	Livestock farming and breeding, poultry farming, beekeeping, aquaculture, fisheries, new breeds, or animal management.
Agriculture	A01M	Physical pest control (non-chemical).
Agriculture	A01N	Biocides, pest repellents/attractants, plant growth regulators, pesticides, herbicides, etc.
Agriculture	A01P	Biocidal and repellent activity.
Fertilizers	C05	Fertilizers, their composition, manufacture, and use.
Biotechnology	C12N	Microorganisms or enzymes, genetic engineering, biotechnological compositions, and applied molecular biology.
Sensors andcontrol	G01	Measurement and testing, sensors, and instrumentation.
Sensors andcontrol	G05	Automatic control or regulation systems.

Sensors andcontrol	G06	Computing or calculation, data processing, algorithms (from software to applied AI).
Sensors andcontrol	G07	Checking devices and methods, recording, counting, administrative control, or validation.
ICT	G16Y	Internet of Things, IoT.
ICT	G16Z	Information technology for specific application domains, including agriculture.
Communications	H04B	Transmission and electrical communication systems according to the medium or propagation path; covers different types of transmission.
Communications	H04L	Digital information transmission, protocols, data communications, digital telegraphy, etc.
Sustainability	Y02A	Technologies for climate change adaptation.
Sustainability	Y02D	ICT whose purpose is to reduce its own energy consumption.
Sustainability	Y02P	Climate change mitigation in production or goods-processing processes; includes agribusiness, agriculture, fisheries, and related sectors.

Second, to ensure the thematic relevance of the results, a textual filter was incorporated requiring the presence of terms related to agriculture and precision-based approaches in the title or abstract, using English keywords and truncation operators to capture morphological variations. In this way, broad coverage was balanced with a minimum level of relevance control, reducing the inclusion of documents unrelated to the domain of precision agriculture.

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Table 2
Keywords used by thematic block

Block	Theme	Keywords
Technological Approach	Precision	preci?ion; sustainab*; smart; remote*
Application	Agriculture	agricult*; farm*; crop*; soil*

Data analysis

For prospective assessment and technology forecasting, the following forecasting methods were applied: (a) CAGR (Compound Annual Growth Rate), which calculates the constant growth rate of a variable over a given period; (b) ARIMA (Autoregressive Integrated Moving Average), a statistical model that combines autoregressive, moving average, and integration components; and (c) ETS (Error, Trend, Seasonality), a forecasting model that decomposes a time series into its error, trend, and seasonal components (Chatfield, 2001).

Results and discussion

Retrieved documents

Figure 1 shows the refinement process based on the previously defined search strategy, using successive filters designed to reduce noise, narrow the scope, and retain only comparable and relevant records for subsequent analysis.

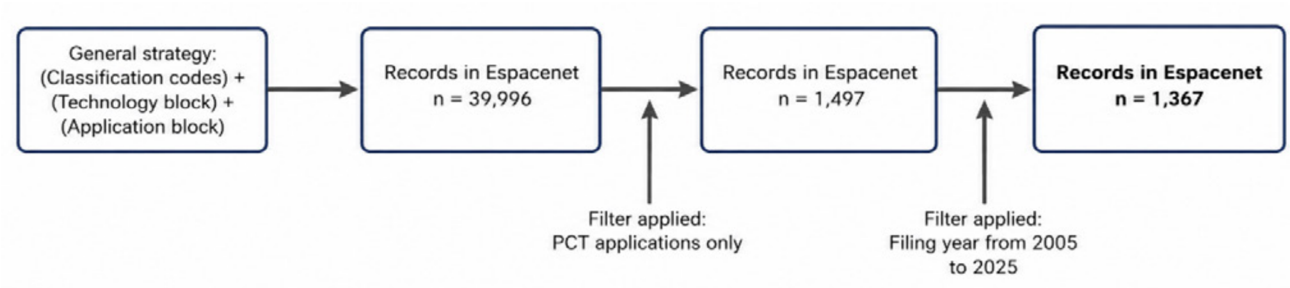


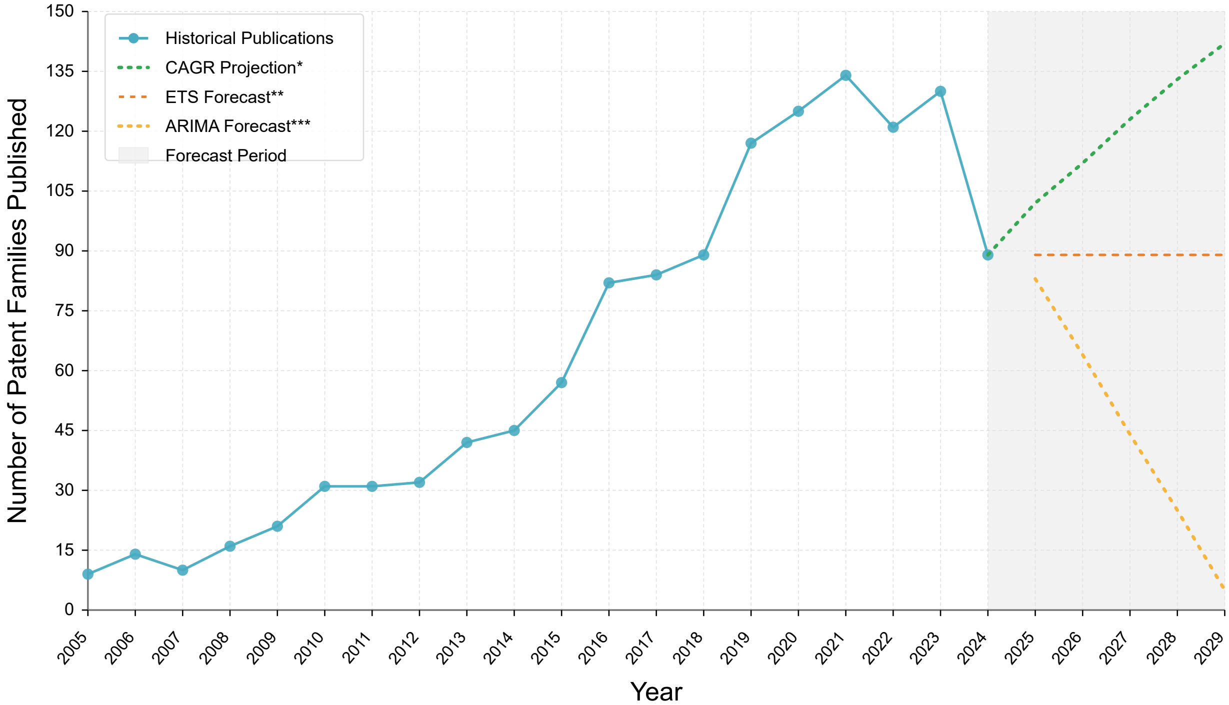
Figure 1

Results obtained from Espacenet

Figure 1 illustrates the refinement process. In the initial broad search, the combination of classification codes and keywords yielded 39,996 records after applying the regional scope filter. When restricted to PCT patent applications, the dataset was reduced to 1,497 documents, representing approximately 3.74% of the initial total. This decline suggests that a substantial portion of the prior art is concentrated in national filing routes, whereas the retained fraction tends to represent inventions with global market potential. Finally, applying the temporal filter for documents filed after 2005 reduced the dataset to 1,367 documents, retaining approximately 91.3% of the PCT subset. This indicates a relative stability of recent activity within the PCT route, consistent with current innovation cycles and contemporary regulatory conditions.

Technological evolution

Technological evolution and forecasting analyze the temporal trajectory of the field based on patent activity, understood as an observable indicator of applied invention, R&D intensity, and industrial consolidation. Growth patterns, phase transitions, and signals of stabilization or acceleration are examined, and trend lines and forecasting models are incorporated to estimate future dynamics. This approach provides quantitative evidence to support assessments of the technological maturity and expansion potential of the field (Trippe, 2015).



* CAGR indicates the average growth rate assuming accumulated growth.

** The ETS model decomposes the series to forecast trends and level, adapting to changes.

*** The ARIMA model projects future values considering historical patterns and trends.

**** The Compound Annual Growth Rate (CAGR) is 7.29% for the period 2014–2024.

Figure 2

Technological evolution and forecasts in precision agriculture

Figure 2 suggests a field that has evolved from an exploratory phase, characterized by isolated solutions, to a stage of accelerated growth driven by the convergence of technological advances. Year-to-year fluctuations, rather than indicating structural instability per se, are generally associated with investment cycles, shifts in technological focus, and, above all, publication delays and the maturation of patent families. Therefore, recent declines should be interpreted with caution before being viewed as evidence of technological decline.

Historically, technological evolution in agriculture has occurred gradually. From the domestication of plants and animals approximately 10,000 years ago to nineteenth-century mechanization and the Green Revolution of the twentieth century, the sector has undergone crucial technological leaps, although these have been widely spaced over time. Precision agriculture, however, represents a recent exponential disruption. The incorporation of digital technologies, remote sensing, artificial intelligence, and automated systems has triggered a new cycle of intensive innovation, as evidenced by the

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substantial increase in patenting activity over the past decade (Klerkx et al., 2019).

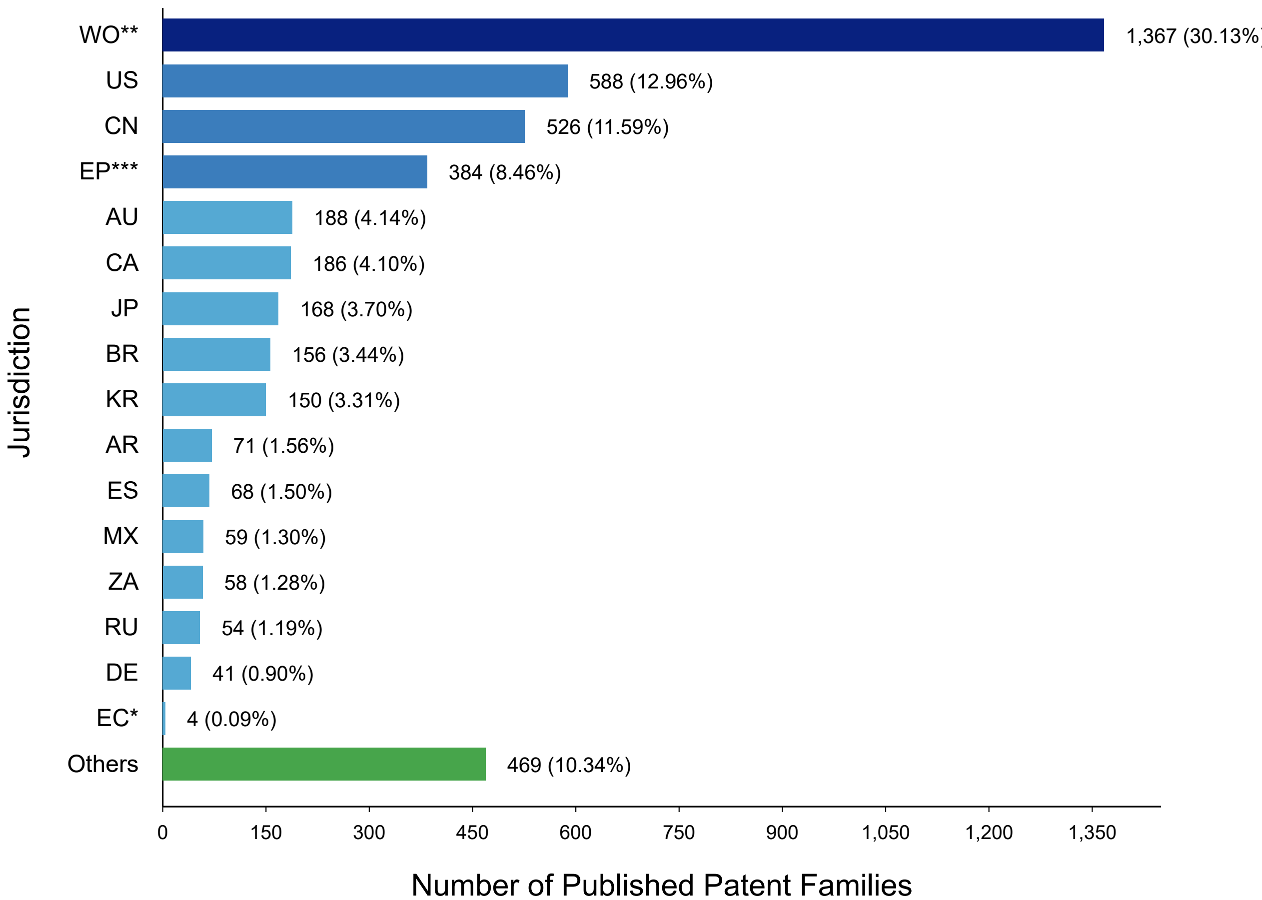
The historical trajectory shown in the figure illustrates a transition from a modest baseline of patent publications to significant expansion beginning in 2013, with a visible inflection point in 2017. This upward trend is consistent with declining costs and increased adoption of technologies such as remote sensing, geographic information systems, unmanned aerial vehicles, and spatial analysis models. This growth is associated with their broad range of applications in precision agriculture, including soil mapping, irrigation, spraying, yield prediction, and real-time monitoring of climatic variables.

Recent year-to-year fluctuations generate an uncertain outlook between stabilization and decline. This trend may be explained by the increasingly stringent regulatory requirements associated with the development of products based on nanoparticles and biological organisms, as well as the need for more extensive validation before commercialization (Kah et al., 2018; Krieger, 2015). In addition, the technological maturity achieved in this field, with at least 35 years of development, has enabled commercial scalability, facilitating the generation of patentable innovations (Mulla, 2013).

From a forecasting perspective, the CAGR trend line (7.29% for the period 2014–2024) supports continued long-term growth in the field, consistent with the expansion of enabling technologies and with regulatory and public policy initiatives promoting agricultural digitalization and innovation (World Bank, 2025). The divergence among forecasting models (ETS suggesting stabilization and ARIMA indicating a steeper

Jurisdictional distribution of patent protection

The geographical distribution of technological output is analyzed from the perspective of intellectual property jurisdictions rather than countries themselves (Trippe, 2015). Although this study is limited to patent families filed through the PCT route, this figure focuses on identifying the jurisdictions in which inventions enter the national phase, that is, where applicants decide to convert an international application into enforceable rights. This perspective is essential because the choice of jurisdiction determines the legal and strategic scope of patent protection. Identifying the jurisdictions where patent applications are concentrated provides insight not only into the most dynamic markets but also into those in which higher levels of competition or future demand are anticipated.



* Ecuador: Rank 46 (Number of Published Patent Families in Ecuador: 4).

** "WO" indicates that the patent publication is international under the Patent Cooperation Treaty (PCT), administered by WIPO.

*** "EP" indicates that the patent publication corresponds to the European Patent Office (EPO),

Figure 3

Jurisdictional distribution in precision agriculture

The jurisdictional distribution shows where precision agriculture inventions tend to enter the national phase after the PCT route, which generally reflects both R&D capacity and expectations regarding market opportunities and commercial appropriation. The leadership of the United States (US) and China (CN) suggests that the technological frontier is being shaped within ecosystems characterized by strong industrial dynamism, broad adoption of digital technologies, and agribusiness value chains capable of industrial-scale deployment. The prominence of the European Patent Office (EP) reinforces Europe's role as a major protection jurisdiction, associated with demanding markets and regulatory and standardization frameworks that may increase entry barriers and impose interoperability, traceability, and performance requirements (European Commission, 2025).

In the United States, the retrieved patent portfolio suggests that the technological frontier of precision agriculture is consolidating around three major axes, which are also reflected in the most frequent CPC classifications. First, agronomic decision-making based on models and data is represented by irrigation support solutions that integrate climate, crop, and soil variables to generate operational recommendations (Mewes, 2018). Second, intelligent field delineation and prescription are reflected in approaches combining remote sensing and artificial intelligence with large-scale soil inventories (J. G. White et al., 2023), as well as multi-year yield analyses for prescription mapping and variable-rate applications (Hunt, 2017). Third, there is a clear trajectory toward automation and proximal sensing, ranging from robotic remote sensing using multispectral systems for field monitoring (Kumar et al., 2019) to modular instrumented implements for agricultural operations and data acquisition (Antle et al., 2024).

In China, the patent landscape reveals a strong concentration on digital infrastructure for smart agriculture, emphasizing connectivity, platforms, and control, together with remote sensing and algorithms, in line with the combination of G06Q50 and computer vision and AI classifications such as G06V10, G06T7, G06T2207, and G06N3. A representative example is the control of agricultural machinery through terminal devices, satellite positioning, and messaging architectures that integrate data with ministerial interfaces or farm management platforms (Pan et al., 2021). The portfolio also includes management methods that integrate agronomic variables with meteorological information and, notably, economic variables such as market prices to support decisions such as harvest timing (Du, 2018). In addition, solutions focused on sensor networks and robust field communications are observed, including LoRa gateway architectures for remote monitoring and operational control (Cai et al., 2024).

The presence of patent families entering the European Patent Office suggests a protection strategy targeting high-value and highly regulated markets. Overall, the dominant classifications in this jurisdiction reflect a technological field driven by the convergence of agricultural management and decision-support software; sensing, analytics, and diagnostics; mechanization and field operations; and climate adaptation and sustainability (Y02A40, A01B79, G06Q50, A01C21, G06Q10, G01N33, A01C7). This combination is consistent with the European priority of digitalizing the agri-food sector and scaling efficient agricultural practices (FAO, 2018).

For example, decision-support approaches and agronomic zone management based on remote sensing and artificial intelligence are observed (J. White et al., 2023), together with field operation and control components such as guidance controllers for precision agriculture (Mortimer et al., 2018) and the use of mobile devices as operational interfaces for farmers (Ramachandran & Villela, 2022).

A second group comprises jurisdictions such as Australia (AU), Canada (CA), Japan (JP), and South Korea (KR), which typically function as technologically sophisticated, high-value markets where patent protection is associated with advanced mechanization, agricultural robotics, and data management solutions. The presence of Brazil (BR), together with Argentina (AR) and Mexico (MX), suggests an interest in capturing value in Latin America, particularly in large-scale agriculture and export-oriented value chains, although at a lower intensity than the leading jurisdictions. Ecuador does not appear among the principal jurisdictions in the dataset, indicating that national-pha-

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se entry into the country is a low priority within these patent families.

When expansion into Latin American jurisdictions, particularly Brazil and Mexico, is examined, the pattern appears to be more selective and oriented toward specific agricultural markets, with a strong emphasis on local adaptation, costs, and the protection of solutions that can be directly deployed in the field. Mexico provides examples of protected production systems focused on protected agriculture and soil and plant management (Eguiluz & Villegas, 2015). It also includes technologies for the release of biological pest control products using dispensers mounted on manned or unmanned vehicles (De Oliveira Machado & Rodwell, 2022). Brazil is associated with solutions directly applicable to field operations and sustainability, such as perimeter barrier methods for insect control in crops (Carvalho & Joelcio, 2020). This portfolio aligns with the CPC distribution emphasizing A01B79 and A01C21, related to agricultural operations and planting, together with G06Q50 for management and decision support, and Y02A40 for climate resilience.

Regarding innovation in agricultural technologies in Latin America, the Inter-American Development Bank's innovation laboratory (IDB Lab) identified more than 450 active agtech startups in 2020, all established within the previous five years. Of these, 51% were located in Brazil, 23% in Argentina, and 18% in the Andean subregion (Viton et al., 2020). Among the main areas driving the digitalization of Latin America's agricultural sector are specialized software, digital sensors, drones, robots, autonomous vehicles, territorial mapping systems, GPS, cloud technologies, the Internet of Things, big data, biotechnology, precision agriculture, and related technologies (Galvez & Galvez, 2024).

Leading patent applicants

Patent applicants may be either natural persons or legal entities that hold the legal and commercial rights associated with patent applications. Distinguishing the nature of applicants, whether companies, universities, or government institutions, provides insight into innovation dynamics, knowledge protection strategies, and the interests driving technological development. Furthermore, this analysis is closely related to the geographical distribution of intellectual output, as applicants tend to concentrate their filings in strategic jurisdictions that reflect market priorities and international protection strategies. Accordingly, the analysis of leading patent applicants provides essential information for mapping the competitive landscape, identifying potential collaborators, and anticipating technology transfer trends (Trippe, 2015).

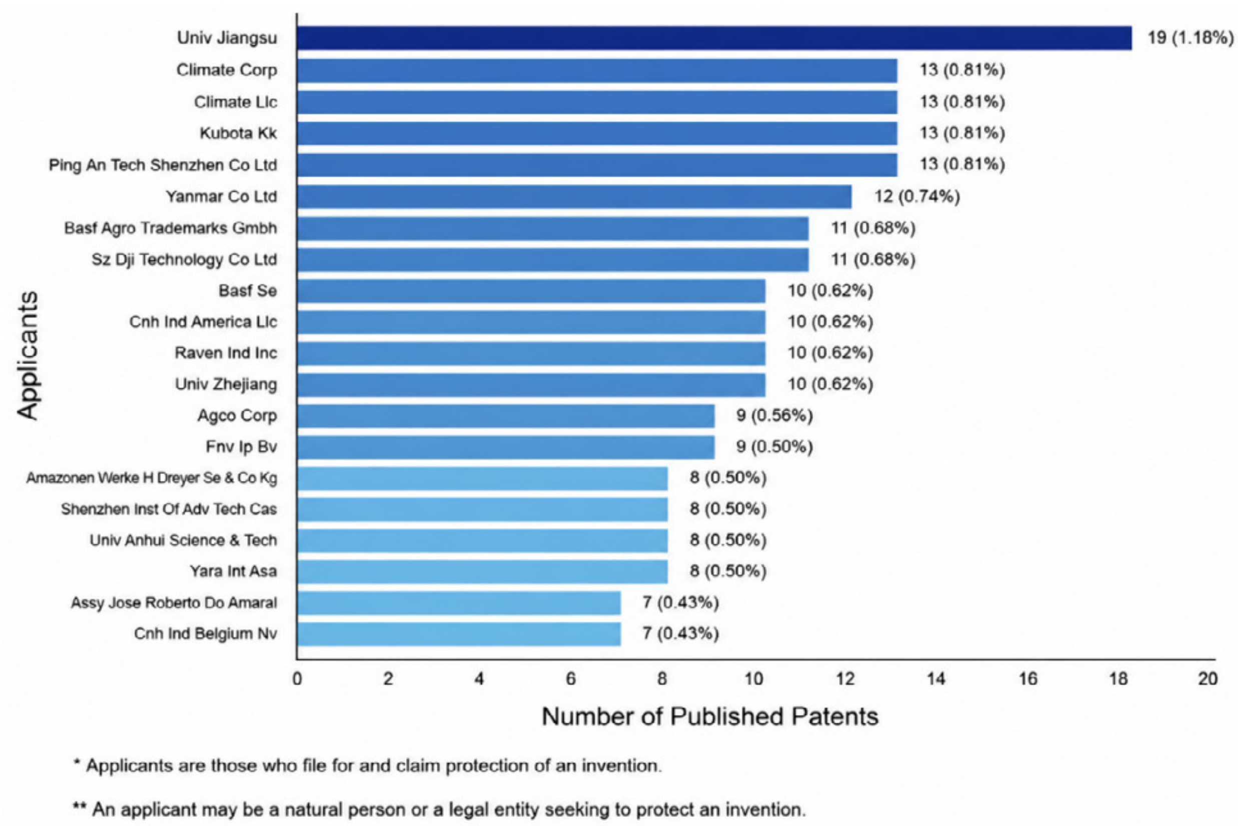

Figure 4

Main applicants in precision agriculture

Figure 4 presents the ranking of the top 20 applicants within the analyzed PCT corpus, ordered by the number of published patents. Jiangsu University leads the list with 19 documents (1.18% of the total), followed by a group of four industrial actors with 13 patents each (0.81%): Climate Corp, Climate LLC, Kubota KK, and Ping An Tech Shenzhen. These are followed by a relatively continuous descending distribution among the remaining applicants. Overall, no applicant exceeds a 1.2% share, and the difference between the first and the twentieth-ranked applicant is only 12 patents, revealing a ranking with no clear dominance. Leadership is distributed among Asian universities, European agrochemical conglomerates, Japanese and U.S. machinery manufacturers, and agricultural software and data companies, configuring a multi-actor landscape characteristic of technological fields in an expansion phase.

The applicant ranking reveals a mixed group of actors composed of universities and technology, chemical, and machinery corporations. The fact that the leading individual applicants each account for approximately 1% of the total suggests a competitive and relatively fragmented ecosystem, with multiple parallel lines of development and no clear dominance capable of independently limiting market access.

On the academic front, Zhejiang University is associated with methodological developments in remote sensing and analytics for critical agronomic variables, such as soil salinity, phenology, and yield estimation, strengthening the monitoring and prediction layer for site-specific decision-making (Lin et al., 2023; Z. Shi et al., 2023, 2024). Jiangsu University reflects an agenda more closely focused on instrumentation and automation under operational conditions, including mobile platforms and detection devices for greenhouses, as well as solutions related to irrigation, measurement, and implement control, bringing these developments closer to transferable prototypes (Li et al., 2019; J. Shi et al., 2023; Zhang et al., 2020; Zuo et al., 2019).

Within the industrial sector, a sample of the analyzed portfolio suggests a complete value chain. Kubota KK focuses on mechanized operations and control, particularly where precision depends on teleoperation and navigation systems, which are critical for implementing recommendations in the field with repeatability (Fujii, 2024; Matsuzaki, 2024). Climate LLC is positioned in digital agriculture, combining remote sensing, modeling, and recommendation generation for crop management, yield, and soil properties, providing a key layer for converting data into prescriptions (Baurer et al., 2024; Casas et al., 2022; Cisek et al., 2025; Xu & Xu, 2021).

BASF Agro Trademarks GmbH reinforces the optimization of application practices and agronomic decision-making through methods and devices aimed at improving efficiency and the controlled application of inputs (Hoss et al., 2024; Janssen et al., 2022; Kiepe et al., 2024; Peters et al., 2023, 2025). Finally, Ping An Tech Shenzhen Co. Ltd. illustrates the entry of data-driven actors into agricultural assessment and management based on agroclimatic and remote sensing information, thereby expanding the ecosystem toward digital services (Gao et al., 2022).

This academia–industry combination is consistent with the acceleration phase observed in the temporal evolution, where sustained growth in activity indicates the consolidation of solutions and market expansion. The fragmented leadership, together with recent growth, suggests room for technological differentiation through integration, interoperability, and field validation rather than through a single isolated invention.

Main technological areas

The Cooperative Patent Classification (CPC) and International Patent Classification (IPC) systems are hierarchical classification systems that organize patents according to their technical content at the section, class, subclass, and group levels. The key difference is that the IPC serves as the international baseline standard, facilitating broad comparability across patent offices and studies, whereas the CPC is a more granular extension used primarily by the European and U.S. patent offices, which typically captures technological nuances and specific applications in greater detail (WIPO, 2022).

Both classification systems are analyzed to obtain a more robust interpretation by combining the broad coverage and comparability of IPC codes with the greater technical granularity and specificity of CPC codes. Together, the distribution of classification codes makes it possible to identify the technological areas concentrating the greatest activity within the landscape, identify intersections among agriculture, sensing, data, and automation, and recognize the fronts where development shows the greatest dynamism and, consequently, the highest competitive pressure (Trippe, 2015).

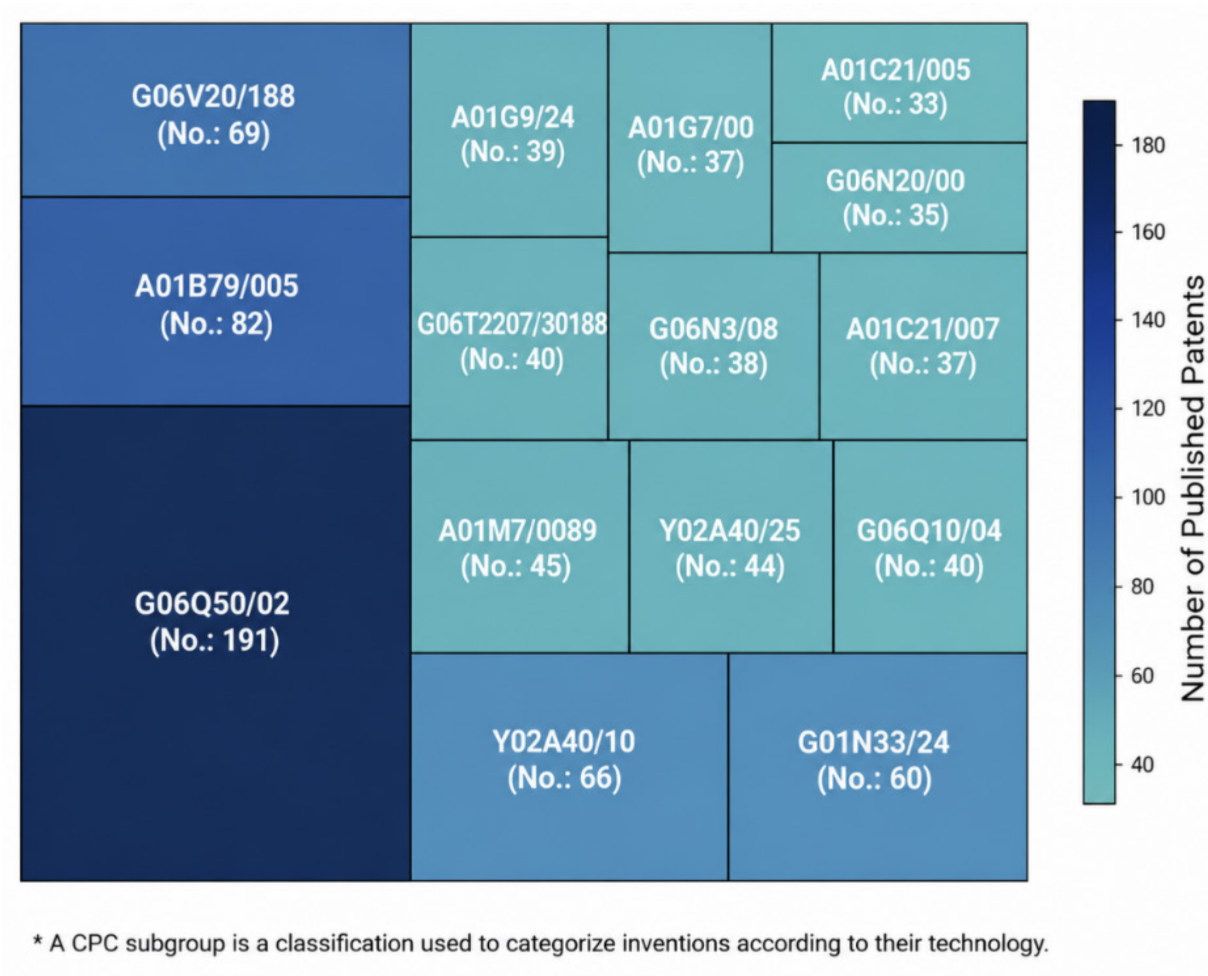

Figure 5

Main technological areas in precision agriculture

Based on the leading IPC/CPC codes, the field of precision agriculture is organized around a technological architecture with a digital core (management and decision-making), supported by an intensive sensing and analytics layer and complemented by mechanization and agronomic interventions. In addition, a cross-cutting layer of sustainability and climate adaptation spans multiple areas of development. This architecture can be summarized into four trends.

First, a core centered on agricultural management and decision support. The greatest emphasis is placed on platform-type solutions for agricultural management and operations, ranging from planning, resource allocation, and monitoring to actionable recommendations. This is reflected in codes related to administrative applications in agriculture (G06Q50/02) and forecasting or optimization for management purposes (G06Q10/04). From a competitive perspective, this core suggests that the “competitive space” is shifting toward software, decision models, and data orchestration rather than isolated devices.

Second, an enabling core based on sensing, remote sensing, and AI-driven analytics. This area brings together computer vision applied to vegetation and agricultural scenes (G06V20/188), image analysis schemes associated with vegetation (G06T2207/30188), and soil or agricultural sample analytics (G01N33/24), reinforced by machine learning methods (G06N20/00) and neural networks (G06N3/08). This cluster indicates that much of the differentiation occurs in how biophysical variables are captured, interpreted, and transformed into robust predictions at the field scale.

Third, field execution and crop management. This category includes technologies for precision agriculture and its implements (A01B79/005), controlled application of inputs, particularly fertilization with controlled application and dosing (A01C21/005 and A01C21/007), and spraying equipment (A01M7/0089). It also encompasses solutions for controlled environments or greenhouses (A01G9/24). This trend translates analytics into action and typically represents the segment of the state of the art closest to practical implementation when a project involves direct physical intervention in crop production.

A fourth cross-cutting trend encompasses sustainability and climate adaptation considerations. Codes Y02A40/10 and Y02A40/25 refer to climate change adaptation in agriculture and water management, indicating that water-use efficiency, resilience, and environmental risk mitigation have become design criteria integrated into both the digital core and the input application layer.

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Conclusions

The successive refinement of search results confirms that a broad search strategy based on IPC/CPC codes and text filters can capture the field with high sensitivity and that restricting the search to PCT applications selects a comparatively small fraction of the initial universe. The reduction from 39,996 records to 1,497 PCT documents, and subsequently to 1,367 documents published after 2005, suggests that a significant portion of the state of the art circulates through national filing routes, whereas the PCT subset concentrates inventions with global market aspirations and provides greater methodological comparability within the defined scope.

The observed temporal evolution describes a transition from an exploratory phase to a stage of acceleration, with marked growth beginning in 2013 and a visible inflection point in 2017. Although recent year-to-year fluctuations are observed, they should be interpreted in light of the approximately 18-month lag between priority filing and publication; therefore, declines near the end of the study period should not be interpreted as evidence of decline. The compound annual growth rate (CAGR) of 7.29% for the 2014–2024 period supports an overall upward trend, while the divergence among forecasting models, indicating either stabilization or decline depending on the method, suggests sensitivity to the most recent years and is consistent with a scenario of technological maturity and increased competition.

In practical terms, the patent landscape shows that the competitive space is shifting toward a digital core focused on management and decision support, reinforced by sensing, remote sensing, and artificial intelligence-based analytics, and integrated with field execution through mechanization and agronomic intervention. The concentration of protection in the United States, China, and the European route indicates that value capture is being contested in ecosystems with strong industrial and digital capabilities and that standardization, interoperability, traceability, and performance frameworks may raise barriers to entry in demanding markets. The fragmented leadership, together with the coexistence of universities and companies, suggests that inventions are increasingly associated with integration, interoperability, and validation under operational conditions rather than with a single isolated invention.

Based on the observed patterns and the study limitations, future research should expand coverage to include national filing routes to estimate differences between global and local innovation and update the analysis once publication of the final 18 months of the study period has been completed. It would also be advisable to complement the patentometric analysis with approaches that capture innovation not reflected in patents, such as scientific publications or market information, while maintaining clarity regarding the scope of each source of evidence.

Limitations

Despite the methodological rigor based on WIPO guidelines, this study has inherent limitations that should be considered when interpreting the results. The most significant limitation is the time lag between patent application and official publication. In addition, by using PCT applications as the primary filter, the analysis prioritizes inventions with high global potential, potentially underestimating innovations developed exclusively for national markets. It should also be noted that patent analysis does not capture the entire innovation ecosystem, excluding developments protected through trade secrets or copyright. Consequently, these findings should be interpreted as indicators of technological trends rather than as a comprehensive representation of the overall market (Moscatelli et al., 2024; Trippe, 2015).

Conflict of interest statement

The authors declare that they have no conflicts of interest.

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Declaration on the use of artificial intelligence

During the preparation of this manuscript, artificial intelligence tools, specifically ChatGPT and Google Gemini (versions available at the time of use), were used exclusively as technical support for structuring search queries employed in information retrieval processes and for generating scripts used to produce figures.

All content generated with the assistance of artificial intelligence was subsequently reviewed, validated, adapted, and manually edited by the authors, who verified its relevance, accuracy, and consistency with the objectives of the study. Consequently, the authors assume full responsibility for the content, its interpretation, and the conclusions presented.

Author contributions (CRediT):

Gabriela Valarezo: Conceptualization; methodology; investigation; resources; writing – original draft; supervision; project administration.

Gisselle Soto: Validation; resources; writing – review & editing.

Francisco Álvarez: Software; formal analysis; resources; data curation; visualization.

References

Antle, J. L., Snyder, S. T., & Larick, A. J. (2024). *Modular smart implement for precision agriculture* (Patent US12048300B2).

Banco Mundial. (2025). *Agriculture and Food*. https://www.worldbank.org/en/topic/agriculture/overview#2

Baurer, P., Koch, J., Sauder, D., & Stoller, B. (2024). *Systems and methods for image capture and analysis of agricultural fields* (Patent US11944043B2).

Cai, Y., Liu, L., Gao, X., Zhao, X., Wu, P., Song, X., Li, C., Chen, W., Ning, S., Yu, J., & Yang, M. (2024). *Intelligent agricultural control system* (Patent WO2024007559A1).

Carvalho, C., & Joelcio, E. (2020). Method for controlling lepidopterous insects by using a perimeter ultrasonic barrier in agricultural crops (Patent WO2020028961A1).

Casas, A., Yang, X., & Ward, S. (2022). *Mapping soil properties with satellite data using machine learning approaches* (Patent US11468669B2).

Chatfield, C. (2001). *TIME-SERIES FORECASTING.* Chapman & Hall.

Cisek, N., Koshnick, N., Xiang, H., & Yang, X. (2025). *Estimating soil properties within a field using hyperspectral remote sensing* (Patent US12366678B2).

Comisión Europea. (2025). *New Study Highlights State of play in Digitalisation in EU Agriculture.* https://agriculture.ec.europa.eu/media/news/new-study-highlights-state-play-digitalisation-eu-agriculture-2025-09-19_en

De Oliveira Machado, R. A., & Rodwell, M. N. (2022). *System and method for releasing loose or wrapped solid products for biological pest control in agriculture using dispensers coupled to or incorporated into manned or unmanned vehicles* (Patent MX2022000673A).

Du, G. (2018). *Smart agriculture management method and system* (Patent WO2018232845A1).

Eguiluz, J. M. G., & Villegas, J. (2015). *Protected soil-plant agriculture production system and method for low-height crops.* (Patent MX2013008823A).

FAO. (2018). *The future of food and agriculture – Alternative pathways to 2050.* Licence: CC BY-NC-SA 3.0 IGO

Fujii, T. (2024). *Travel control system for agricultural machine capable of performing remotely-manipulated traveling* (Patent US2024345603A1).

Galvez, D. P. C., & Galvez, W. P. C. (2024). Digital technologies in agricultural development: The experience of Latin American countries. *E3S Web of Conferences, 537.* https://doi.org/10.1051/e3sconf/202453708014

Gao, Y., Wang, W., Ren, C., & Zhao, Q. (2022). Agricultural danger data assessment method and apparatus, computer device, and storage medium (Patent WO2022198744A1).

Getahun, S., Kefale, H., & Gelaye, Y. (2024). Application of Precision Agriculture Technologies for Sustainable Crop Production and Environmental Sustainability: A Systematic Review. *In TheScientificWorldJournal* (Vol. 2024, p. 2126734). https://doi.org/10.1155/2024/2126734

Herrera, R. J., & Garcia-Bertrand, R. (2018). The Agricultural Revolutions. In *Ancestral DNA, Human Origins, and Migrations* (pp. 475–509). Elsevier. https://doi.org/10.1016/B978-0-12-804124-6.00013-6

Hoss, M. J., Kerkhoff, C., Johnen, A., & Schaefer, F. J. (2024). *Decision system for seed product and/or crop nutrition product application using remote sensing based soil parameters* (Patent US2024099184A1).

Hunt, A. D. (2017). *Weighted multi-year yield analysis for prescription mapping in site-specific variable rate applications in precision agriculture* (Patent US9563848B1).

Janssen, O., Schaefer, F. J., Kerkhoff, C., & Johnen, A. (2022). *Decision system for crop efficiency product application using remote sensing based soil parameters* (Patent US2022361473A1).

Kah, M., Kookana, R. S., Gogos, A., & Bucheli, T. D. (2018). A critical evaluation of nanopesticides and nanofertilizers against their conventional analogues. *Nature Nanotechnology*, 13(8), 677–684. https://doi.org/10.1038/s41565-018-0131-1

Kiepe, B., Delatree, C. C., & Wahabzada, M. (2024). *Reduced residual for smart spray* (Patent US2024000002A1).

Kim, M. Y., & Lee, K. H. (2022). Electrochemical Sensors for Sustainable Precision Agriculture—A Review. In *Frontiers in Chemistry,* 10, 848320. https://doi.org/10.3389/fchem.2022.848320

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS - Wageningen Journal of Life Sciences,* 90–91, 100315. https://doi.org/10.1016/j.njas.2019.100315

Krieger, E. (2015). New trends in intellectual property protection for plant innovations. In *24th Int. Eucarpia Symp. Section Ornamentals "Ornamental Breeding Worldwide".*

Kumar, R. V., Cross, G. B., Qu, C., Das, J., MakinenI, A., & Mulgaonkar, Y. S. (2019). *Systems, devices, and methods for robotic remote sensing for precision agriculture* (Patent US10395115B2). United States Patent and Trademark Office.

Li, J., Xu, J., Wei, X., & Sun, H. (2019). *System and method for real-time measurement of height of spray boom relative to crop canopy* (Patent WO2019218446A1). World Intellectual Property Organization.

Lin, T., Lin, Z., Jiang, H., & Ying, Y. (2023). *Large-scale crop phenology extraction method based on shape model fitting method* (Patent US11734925B2). United States Patent and Trademark Office.

Matsuzaki, Y. (2024). *Agricultural machine, sensing system, sensing method, remote operation system, and control method* (Patent US2024341215A1). United States Patent and Trademark Office.

Mewes, J. J. H. R. C. (2018). *Customized land surface modeling in a soil-crop system for irrigation decision support in precision agriculture* (Patent US10139797B2). United States Patent and Trademark Office.

Mortimer, R., Miller, S. R., Ganz, B., Hutchings, J., & Syverson, C. D. (2018). *Steering controller for precision farming* (Patent EP3365220A1). European Patent Office.

Moscatelli, F., C. Chacua, S. Gadgin Matha, H. Hartog, E. Hernandez Rodriguez, J.D. Raffo and M.A. Yildirim (2024). *Can we map innovation capabilities? WIPO Economic Research Working Paper No. 81.* World Intellectual Property Organization.

Mulla, D. J. (2013). Twenty five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering 114*(4), 358–371. https://doi.org/10.1016/j.biosystemseng.2012.08.009

OMPI. (2022). *The WIPO manual on open source patent analytics.* https://wipo-analytics.github.io/manual/

OMPI. (2026). *PCT – The international patent system*. https://www.wipo.int/en/web/pct-system

Pan, D., Chen, S., Ding, H., Gan, W., Wang, H., & Ye, Z. (2021). *Agricultural machine precision control method applied to smart agriculture* (Patent WO2021248678A1). World Intellectual Property Organization.

Peters, O., Hoffmann, H., Zhao, G., & Das, S. (2023). *Planning and implementing agricultural measures* (Patent US11818975B2). United States Patent and Trademark Office.

Peters, O., Selinger, S., Rommel, T., & Andree-Labsch, S. (2025). *Apparatus for determining agricultural relevant information* (Patent US12270966B2). United States Patent and Trademark Office.

Ramachandran, S., & Villela, M. A. (2022). *Using smart-phones and other hand-held mobile devices in precision agriculture* (Patent EP4002980A1). European Patent Office.

Santos Valle, S., & Kienzle, J. (2020). Agriculture 4.0: Agricultural robotics and automated equipment for sustainable crop production. *Integrated Crop Management*, Vol. 24. FAO.

Sanyaolu, M., & Sadowski, A. (2024). The role of precision agriculture technologies in enhancing sustainable agriculture. *Sustainability 16*(15), 6668. https://doi.org/10.3390/su16156668

Shi, J., Shi, Y., Zou, X., Huang, X., Li, Z., Guo, Z., & Qiao, C. (2023). *Small-grain agricultural product color selection method combining area scan and line scan photoelectric features* (Patent WO2023065396A1). World Intellectual Property Organization.

Shi, Z., Wang, N., Peng, J., & Xue, J. (2024). *Method for jointly estimating soil profile salinity by using time-series remote sensing image* (Patent US2024288602A1). United States Patent and Trademark Office.

Shi, Z., Wang, N., Xue, J., & Peng, J. (2023). *Method for estimating soil salinity of straw residue farmland by using remote sensing construction index* (Patent WO2023087630A1). World Intellectual Property Organization.

Trippe, A. (2015). *Guidelines for preparing patent landscape reports: guidelines prepared for the world intellectual property organization (WIPO).* http://www.wipo.int/tisc/en/

Viola, E. & Mendes, V. (2022). Agricultura 4.0 e mudanças climáticas no Brasil. *Ambiente & Sociedade, 25.* https://doi.org/https://doi.org/10.1590/1809-4422

Viton, R., Castillo, A., & Lopes Teixeira, T. (2020). *Mapa de la innovación Agtech en América Latina y el Caribe*. Banco Internacional de Desarrollo

White, J. G., Miller, B. A., & Bielski, J. (2023). *Enhanced management zones for precision agriculture* (Patent US11744168B2). United States Patent and Trademark Office.

World Intellectual Property Organization (WIPO). (2026). *World intellectual property report 2026: Technology on the move.* https://doi.org/10.34667/tind.59025

Xu, L., & Xu, Y. (2021). *Forecasting field level crop yield during a growing season* (Patent US11062223B2). United States Patent and Trademark Office.

Zhang, X., Mao, H., Gao, H., Zuo, Z., Qiu, B., Zhang, H., & Zhang, Y. (2020). *Smart mobile detection platform for greenhouse* (Patent US10591927B2). United States Patent and Trademark Office.

Zuo, Z., Qin, L., Mao, H., Zhang, X., Ni, J., Li, Q., & Lv, T. (2019). *Testing device for integrated irrigation and disinfection* (Patent US10317326B2). United States Patent and Trademark Office.