Precision Agricultural Studies in the United States of America: A Systematic Map

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ABSTRACT

Despite the United States' leadership in agricultural innovation, systematic mapping of precision agriculture (PA) research, particularly integrating livestock monitoring, remains limited. This study aims to comprehensively map the spatial and thematic distribution of PA research across the U.S. from 2012 to 2022, identify key focus areas, and highlight critical research gaps to inform future priorities. A systematic literature review was conducted using major scientific databases (EBSCO Host and Google Scholar), initially retrieving 25,568 publications. After applying rigorous inclusion and exclusion criteria, 239 peer-reviewed articles were selected for analysis. Studies were coded by focus area (e.g., sensor/GIS/remote sensing, livestock monitoring, IoT, AI) using a standardized coding framework. The screening process involved dual independent reviewers to ensure reliability. Data visualization and spatial analysis were performed using ArcGIS Pro, enabling the creation of a detailed systematic PA research map of the USA. The spatial mapping revealed that California (*n* = 80), Texas (*n* = 53), and Florida (*n* = 49) accounted for the majority of PA research output. Thematic analysis showed that 29.7% of studies focused on sensor, GIS, and remote sensing technologies, while only 1.5% addressed livestock monitoring. Research on emerging technologies such as IoT and AI was also notably sparse. These findings indicate significant regional and thematic disparities, with livestock monitoring and advanced digital technologies underrepresented in current U.S. PA research. This systematic mapping highlights a critical need to expand PA research beyond crop-focused applications, particularly in livestock monitoring and the adoption of IoT and AI technologies. To address geographic and thematic imbalances, targeted funding and support from agencies such as the USDA are recommended, especially for underrepresented states. Future research should prioritize the integration of real-time IoT livestock monitoring and AI-driven crop yield prediction, particularly in climate-sensitive regions, to ensure sustainable and equitable advancements in U.S. agriculture.

Keywords: Precision agriculture, precision farming, site-specific management, smart agriculture, United States

INTRODUCTION

Achieving global food security for a burgeoning populace in the face of numerous challenges will continue to be the agriculture industry's most difficult test (Kimilaris et al., 2017; De Clercq et al., 2018; Araujo et al., 2021). According to De Clercq et al. (2018), Searchinger et al. (2019), and the United Nations (2019), the global population is predicted to reach 10 billion by 2050, requiring farmers to produce 70% more food for an additional 2.4 billion people. Furthermore, climate change, food waste, increasing urbanization, soil degradation, water pollution, biodiversity loss, poverty, and hunger (De Clercq et al., 2018; Barrett & Rose, 2020), and the recent COVID-19 pandemic (Cevher et al., 2021) have made achieving this noble goal even more difficult. To address the global challenge of food security, Firbank et al. (2018) and Barrett and Rose (2020) recommend that agricultural production be increased sustainably, through technological advances such as the use of agriculture 4.0 technologies, which use big data technologies, for instance, precision agriculture (PA).

Agriculture, food, and related industries contribute significantly to the economy in the United States. Indeed, according to the United States Department of Agriculture (2021), nearly 18% of the country's economy and

29% of jobs in the United States in 2020 were related to agriculture, contributing to more than 43 million jobs and $182 billion in exports. For the United States to maintain its strong agricultural growth, key challenges impeding rapid agricultural growth must be addressed urgently. Swan (2012) noted that the challenges bedeviling US agriculture include resource depletion caused by increased demand for fossil fuels, water, and topsoil, land degradation caused by monoculture, food waste during agricultural production, post-harvest handling, and storage, processing, distribution, or consumption, demographic changes resulting in food deserts because most Americans (80%) live in cities, political issues, exponential increase in population and climate change. Onyango et al. (2021) stated that to achieve sustainable growth in agriculture, more efficient resource use, including the use of precision agriculture (PA), must be implemented.

Generally, PA is characterized as performing the appropriate practice at the appropriate location, timing, and intensity (Mulla & Khosla, 2016). PA, as defined by Yousefi and Razdari (2015), is “a way of agricultural production, which takes into account the in-field variability, a technology where the application-seeding, nutrients replacement, spraying, etc., has taken place to act on the local circumstances of a given field” (p.7). Similarly, the International Society of Precision Agriculture (ISPA) defined PA as a management strategy that applies a wide range of technologies to collect, process, and examine spatial, temporal, and individual data to guide targeted actions that improve the efficiency, productivity, and sustainability of agricultural procedures (ISPA, 2018). The overall goal of PA is to help farm operators optimize input management according to agronomic needs. However, Pierce and Nowak (1999) noted that PA has other goals, including reducing the negative impact associated with agricultural activities and contributing to environmental sustainability. Further, Thompson et al. (2019) and Pathak et al. (2019) concur that PA leads to increased efficiency, which in turn increases yield and provides extra utility to farmers by improving their general well-being (reduced operator fatigue) when using an autosteer system among other PA technologies.

There are various PA-enabling technologies, including the Global Positioning System (GPS), Geographical Positioning Systems (GIS), and a variety of different sensors for analyzing the site and crop variability, giving information to help producers manage agricultural systems more precisely (Mulla & Khosla, 2016; Yousefi & Razdari, 2015; Pathak et al., 2019). According to Duncan (2021), PA entails a variety of sophisticated technologies ranging from spatially aware sensors that harvest massive amounts of data via automated tractors and drones to algorithms that clean and make sense of this data in ways that help farmers make decisions that improve yields, conserve inputs, and increase their bottom line.

PA's success is strongly reliant on how swiftly and precisely its technology can identify temporal and geographical variability. Such data is critical for farmers to calculate the optimal quantity of inputs to improve crop yield while protecting the environment (Ge et al., 2011). While most PA technologies have been available for more than three decades, adoption rates in agricultural operations among farmers have been exceedingly low owing to socioeconomic factors (Munz & Schuele, 2022). However, certain PA technologies have seen higher rates of adoption than others (Tey & Brindal, 2022). In the United States, for example, corn producers increased their use of yield monitors, guiding systems, and variable rate applications by more than 40% in 2016 (USDA, 2019).

PA has evolved fast since Dr. Pierre Robert originally proposed it in the 1980s (Miles, 2019). To date, its technologies have seen constant progress. Satellites, drones with attached sensors, the internet of things, and now robotics all demonstrate advances in information collection and decision-making on the farm (Khanna & Kaur, 2019; Nair et al., 2021). This expansion foretells increased profitability due to savings from inputs and increased productivity, a decent environment, food security, and sustainability (Onyango et al., 2019). However, in the USA, the development of PA is impeded by both socio-economic and technical challenges that include fairly high costs and the complexity of PA technologies (Barnes et al., 2019; Ofori & El-Gayar, 2021) and increasing human population and decreasing arable land (Khosla, 2010). In addition, Lowenberg-DeBoer and Boehlje (1996) observed a lack of clarity in farm-level profitability among bulk commodities producers, impeding PA technologies adoption.

The rate of adoption of PA technology varies around the globe. According to Say et al. (2018), the United States is the most advanced in terms of PA technology adoption, with Australia, Canada, and European countries following close behind. Adoption rates in developing countries such as Argentina, Brazil, South

Africa, and Turkey have also increased significantly over time (Say et al., 2018). While there are several obstacles to may implementation of PA technologies in the United States, the prospect of increased adoption is strong owing to the huge farm sizes that promote PA technology adoption (Say et al., 2018; Barnes et al., 2019). Nonetheless, other factors could be propelling the United States to lead in PA adoption. Could it be the extent of the PA study?

Often, scientific research has been used to inform policy in different sectors. Therefore, knowledge of the PA studies carried out in the USA and specifically the success factors favoring PA adoption in the USA can act as a catalyst for the development of PA in other countries around the globe. The overall objective of the study was to spatially show the various research carried out on PA in the USA in the last decade (2012 – 2022). To be precise, the study sought to (1) create a systematic map of PA research in the USA for the past decade. (2) assess how the research on PA varied among the USA states for the last ten years. (3) find out the research gaps on PA in the USA to set a future research agenda. The evidence gathered from the three objectives helped in answering the question about the extent of PA research in the USA. It was hypothesized that the adoption of PA is high in the USA due to increased research output. This hypothesis was tested by assessing the number of empirical studies done in the USA as compared to the African continent, where the adoption of PA is low (Onyango et al., 2019; Say et al., 2018). The documentation of the PA research trends can help other researchers to focus on certain topics as well as inform the policy agenda.

MATERIALS AND METHODS

The systematic map was created using a method adapted from a methodology for systematic mapping in environmental sciences (James et al. 2016). Although systematic maps and reviews use similar methods (James et al., 2016), there exist some differences between the two in terms of the objective, question formulation, search strategy, article screening, data extraction, critical appraisal, synthesis, and report content. For instance, in a systematic map, critical appraisal is optional, while in a systematic review, all included studies are critically appraised. Similarly, the study results may not be extracted in the systematic map, while in a systematic review, both qualitative and quantitative results are extracted. In addition, systematic maps describe the state of knowledge for an open or closed-ended question, while systematic reviews provide either a qualitative or quantitative answer to closed-ended questions only. Figure 1 depicts the systematic mapping process according to Clapton et al. (2009) in Onyango et al. (2021).

Literature Search

The study employed a broad search of several sources of literature in EBSCO Host and Google Scholar databases to ensure an unbiased sample of published peer-reviewed literature. The search was limited to articles in English only. EBSCO Host database was used since it allowed for the search of articles across over 50 databases. In addition, EBSCO Host is flexible as it allows easy management of data. Articles from EBSCO Host were saved and imported into the EndNote file for extraction purposes. The importation process removed duplicate articles automatically. The extracted articles in both searches were then exported from EndNote to Excel forms.

Search Terms

The following was the combined search string used for the study. (United States of America OR USA OR US) AND (Precision agriculture OR Precision farming OR site-specific management OR site-specific farming OR variable rate application OR crop sensors OR soil sensors OR proximal soil sensors OR spatial variability OR temporal variability)

Inclusion and Exclusion Criteria

The extracted articles were then screened according to the following inclusion criteria by looking at:

(i) Only studies that were done in the United States of America and used (Precision agriculture OR Precision farming OR site-specific management OR site-specific farming OR variable rate application OR crop sensors OR soil sensors OR proximal soil sensors OR spatial variability OR temporal variability)) concepts fully or partially included.

(ii) Studies that were done elsewhere but with links with the United States of America and used (Precision agriculture OR Precision farming OR site-specific management OR site-specific farming OR variable rate application OR crop sensors OR soil sensors OR proximal soil sensors OR spatial variability OR temporal variability) Concepts fully or partially were included.

(iii) Only studies that were published between the year 2012 to 2022 and agree with criteria (i) and (ii) above were included.

(iv) Only articles on agriculture and the environment were included

(v) Only empirical /primary study articles were included. Systematic reviews and maps, books, book chapters, book reviews and articles, conference proceedings, bulletins, and poster presentations were excluded.

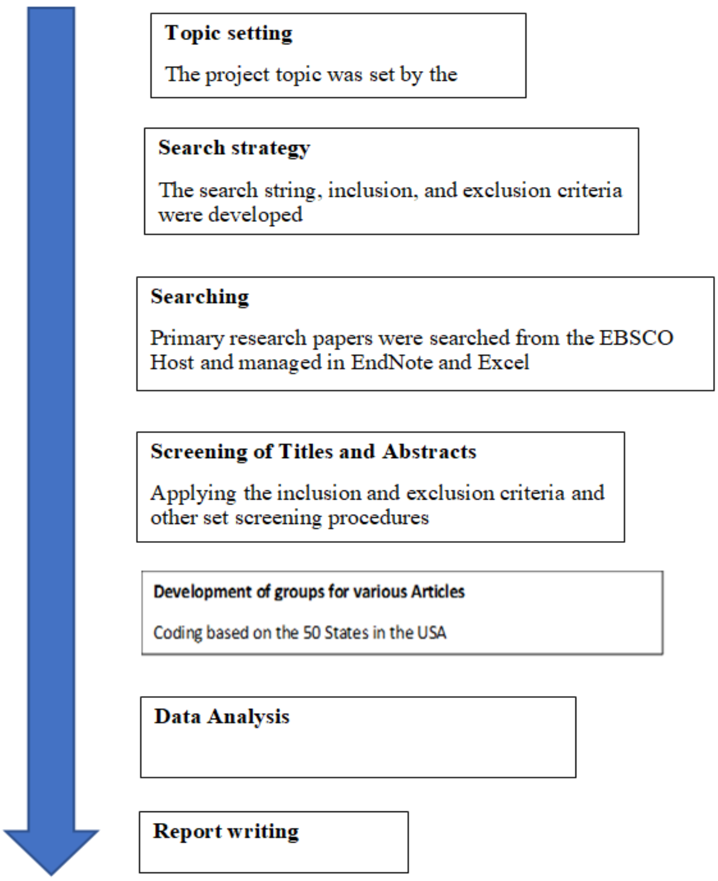
Further Screening and Selection of Articles

After subjecting the articles to the inclusion/exclusion criteria, the second screening was done at the title and abstract levels. The article titles were checked for suitability, while the abstracts outside the physical location of the United States of America or with a location not identified were excluded. Articles presented at conferences were also excluded. The inclusion and exclusion were only applied at one level since the project was an assignment to be graded. The articles were then classified according to the states in the United States of America (geographical location) and the PA technology used, for instance, microdosing, variable rate application, mobile phone, and related technologies, modeling, sensor and GIS, remote sensing, and drones.

Coding for the Systematic Map

The research papers were classified based on the fifty States in the United States of America. The type of symbology used was unique colors to clearly distinguish the differences that exist among the 50 states based on the number of peer-reviewed articles for the last decade (2012 to 2022).

Figure 1 Stages of Mapping



Note. Adopted from Clapton et al. (2009) in Onyango et al. (2021) with adjustments

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After screening, articles were classified into the geographic location (States) where the study was conducted, and the key subject area of the study addressed. The subject areas were based on the precision agricultural categories suggested in Onyango et al. (2021) with modifications. These were as follows:

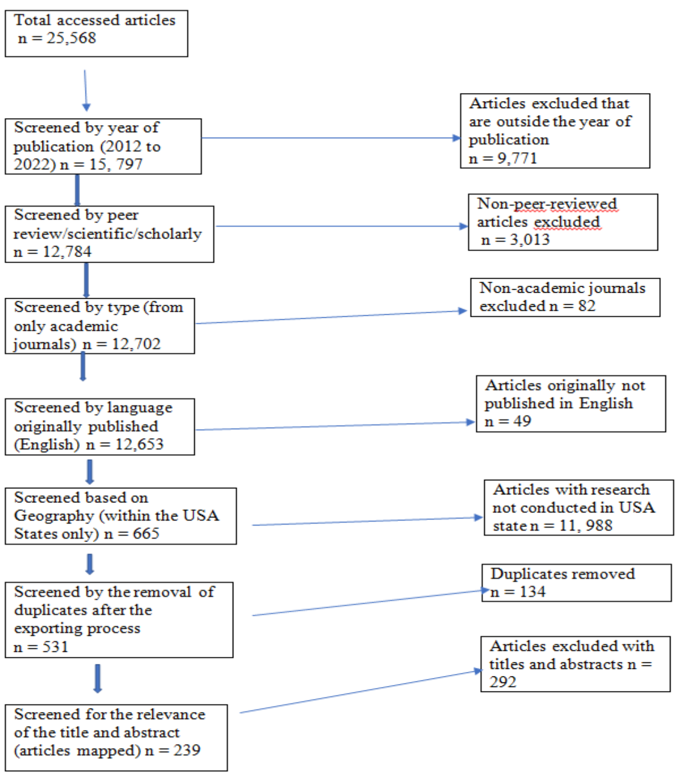
1. Soil sampling (determination of soil nutrients, fertilizer application, soil properties)
2. Crop mapping (estimation of area under a crop)
3. Conservation (control deforestation and pollution)
4. Monitoring of crop growth (determine plant's requirement)
5. Plant yield prediction (determine expected yields in different areas of the field)
6. Water management in crop (irrigation) – VR irrigation studies
7. Crop nutrient management (rates and requirements by crops)
8. Crop protection (disease/weed/pest control)
9. Animal monitoring and protection (any PA technology in animals e.g., a Sensor to track animals)
10. Testing sensors, GIS, and remote sensing (any study using the technologies)
11. Use of Models (any PA study using models)

RESULTS AND DISCUSSION

The articles included in the Search

A total of 25,568 articles were retrieved from the EBSCO Host databases. These articles were reduced to 15,797 after 9,771 items were removed that were not published within the specified years (2012 to 2022). In addition, 3,013 papers were excluded because they were neither scientific nor peer-reviewed, leaving 12,784 articles. Magazines, reports, and bulletins were also eliminated, reducing the number of items by 82. Further screening based on English as the original language in which the item was published resulted in the elimination of 49 articles, leaving 12,653. Geographic screening (where the research was done) excluded 11,988 items, leaving 665 articles. The 665 articles were then exported from EBSCO Host to EndNote, which automatically removed all the duplicates. The exporting procedure removed 134 articles, leaving 531. Following further screening based on the relevance of the titles and abstracts, only 239 publications were selected for mapping. This was accomplished mostly by determining if the item was related to agriculture or the environment and eliminating review articles. Figure 2 depicts a summary of the articles included and eliminated at each stage of the screening process.

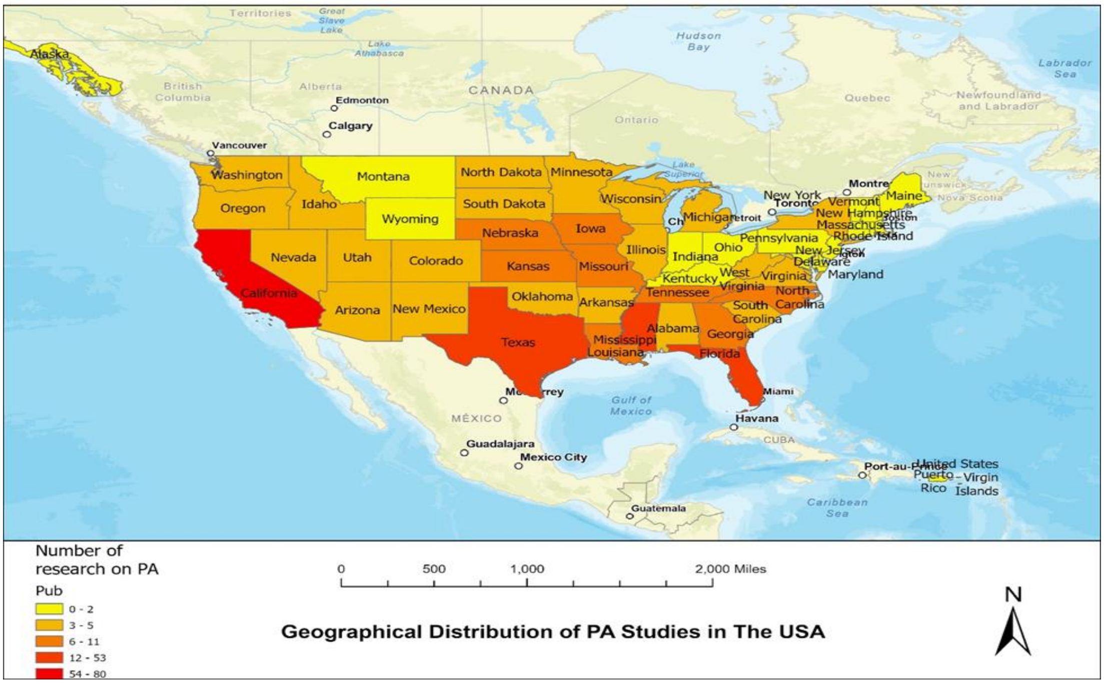
Figure 2 Articles Included and Excluded During the Search Process



Geographical Distribution of PA Articles by States in the USA (2012 to 2022)

The results indicated that out of the 50 states, 42 have witnessed precision agriculture research to different extents. California, Texas, Florida, and Mississippi had the highest number of studies, ranging from 31 to 80. Most of the USA States (*n* = 45, 90%) had less than 10 studies on precision agriculture, except for the States of California (*n* = 80, Texas (*n* = 53, Florida (*n* = 49, Mississippi 31, and Nebraska, which had 11.

Figure 3 Geographical Distribution Showing PA Studies (2012-2022) Shaded by Frequency in the USA



Focus Area of PA Studies in the USA (2012 to 2022)

In total, 407 PA studies were conducted in the USA over a decade (2012 to 2022). Most of the studies were conducted on testing sensors, GIS, and remote sensing (29.73%, *n* = 121), water management/ irrigation (15.72%, *n* = 64), crop nutrients management (10.07%, *n* = 41), monitoring of plant growth (8.35%, *n* = 34) and crop protection management (7.86%, *n* = 32). While most study areas were conducted at least 15 times and above, animal monitoring and protection had the fewest studies (1.47%, *n* = 6). This study's findings are consistent with those of Pallottino et al. (2018), who reported that field and yield mapping themes appear to be losing prominence in favor of emerging areas such as sensors, indices creation, and application. Furthermore, the scarcity of animal monitoring and protection studies is consistent with what Onyango et al. (2021) discovered in Sub-Saharan African nations.

Table 1 Number of PA Studies conducted by Focus area in USA (2012-2022) N=407

Focus Area of PA Studies	Number of Studies	Percentage (%)
Testing sensors, GIS, and Remote sensing	121	29.73
Water management in Crops (irrigation)	64	15.72
Crop nutrients, management	41	10.07
Monitoring of plant growth	34	8.35
Crop protection management	32	7.86
Plant yield prediction	26	6.39
Use of models (Modelling)	25	6.14
Conservation	24	5.90
Soil sampling	18	4.42
Crop mapping	16	3.93
Animal monitoring and protection	06	1.47
Total	407	100.00

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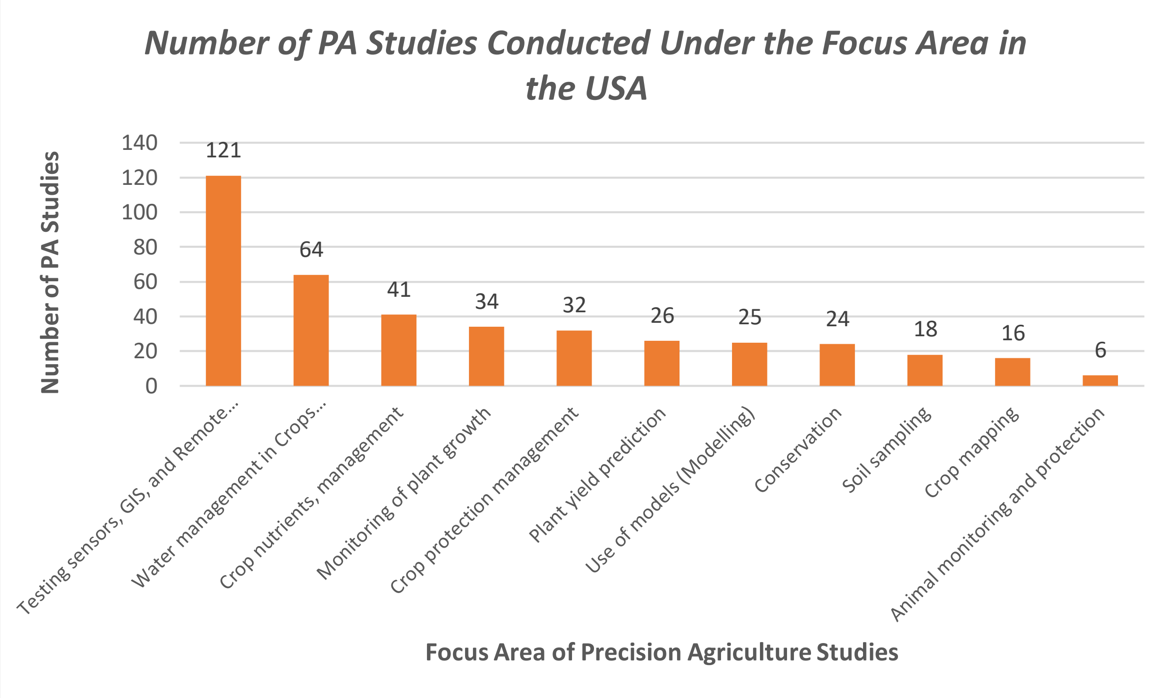
Figure 3



Research Gaps

This study documents important studies on PA in the United States between the years 2012 to 2022. This is a significant step in discovering what is not known. Regarding this, the study completely reveals the extent of PA research in the USA and the areas researched extensively, and those yet to be explored. Areas that could be researched further include:

1. Since a few States dominate the PA research chart, namely California, Texas, Florida, and Mississippi, there exists a potential to explore other states, too.
2. Few studies have been done on PA technologies in livestock. More studies in the area will help to explore and improve PA research in livestock.
3. The systematic mapping did not cover the extent of research on specific crops and the level of research in the adoption of PA technologies. Perhaps this can be looked at in the future, too.

Limitations of the Map

Since the search was only applied to EBSCO Host and Google Scholar databases, it is possible that articles in other databases, such as SCOPUS, AGRICOLA, and ProQuest, could have been excluded despite meeting the search criteria. More databases could have been used to avoid such problems. Secondly, it is possible that since PA is an area with many definitions, other key terms or concepts could have been left out, resulting in fewer articles for mapping. A thorough search for all possible terms would solve such problems. Lastly, limiting the search to titles and abstracts may also exclude some articles, especially if the keywords are missing in either section. Where possible, the search should be extended to the actual paper.

CONCLUSION

The study helps to improve knowledge of PA research in the United States by displaying the places (States) where the research has been done and the areas of focus of PA research over the last decade. According to this survey, the few states where PA research is focused include California, Texas, Florida, and Mississippi. The high PA activity in California and Texas could be linked to United States Department of Agriculture (USDA) funding hubs in the two land-grant universities, namely, the University of California [UC Davis] and Texas A&M that serve as centers for advancing PA research and technology adoption (Texas A & M, 2025). Moreover, the study revealed a strong U.S. focus on sensor-based crop management (e.g., GIS, irrigation, yield prediction) but noted minimal attention to livestock applications which is a sharp contrast to EU trends identified by Pallottino et al. (2018), where robotics and AI dominate precision agriculture innovations, particularly in automated harvesting, multi-robot coordination, and integrated data platforms for diverse tasks like pest control and soil analysis (Costa et al., 2018; European Commission, 2024). In addition, while U.S. research prioritizes optimizing field-scale crop systems, EU advancements emphasize cross-functional automation, blending aerial and ground robotics to address plant and broader farm management challenges (Allied Market Research, n.d.; European Commission, 2024).

Based on an analysis of 239 scientific articles published between 2012 and 2022 in the USA, it is possible to conclude that, despite PA being a relatively new technology, the scope of research in PA in the United States is extensive when compared to other regions such as Africa, which recorded only 128 studies in 14 databases (Onyango et al., 2021). Perhaps, the high amount of research on PA in the USA could be fueling the increased adoption noted by Say et al. (2018). Second, the primary research topic in PA is remote sensing and sensor testing, as well as GIS. Finally, PA research tends to concentrate on states recognized for agricultural output in the United States, such as California and Texas.

RECOMMENDATIONS AND IMPLICATIONS

To strengthen precision agriculture (PA) across the United States, policymakers need to address the uneven adoption of these technologies. While some states in the Midwest lead in PA use, many states in the Northeast and South are falling behind due to smaller farm sizes, limited digital infrastructure, and financial barriers. The USDA should consider providing more grants and support programs specifically for these underrepresented regions, making sure that all farmers have access to the latest PA tools and training.

Several practical steps can help advance PA nationwide. First, integrating Internet of Things (IoT) devices and edge computing can greatly improve livestock health monitoring. Wearable sensors, for example, allow farmers to track animal health in real time and respond quickly to any issues. Second, developing artificial intelligence (AI) models for predicting crop yields, especially for climate-sensitive crops like maize, can help farmers make better decisions and adapt to changing weather patterns. These AI tools should be made widely available, particularly in states that are vulnerable to climate change. By focusing on these areas, the U.S. can make precision agriculture more inclusive, sustainable, and effective, benefiting both farmers and the environment.

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