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Adoption of Precision Agriculture Technologies among Farmers: A Comprehensive Review

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ABSTRACT

Precision agriculture (PA) technologies have spearheaded a revolution in contemporary farming practices, ushering in an era of sustainability, efficiency, and data-driven agricultural production. This comprehensive examination aims to delve deeply into the intricate dynamics surrounding the adoption of precision agriculture technologies among farmers, synthesizing existing literature, identifying key determinants, barriers, and implications.

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The adoption of precision agriculture technologies is influenced by a myriad of factors spanning socio-economic, institutional, technological, psychological, and attitudinal dimensions. Socio-economic factors such as farm size, income level, access to credit, and demographic characteristics are pivotal in shaping farmers' decisions to adopt PA technologies. Institutional factors, including government policies, extension services, market structures, and support networks, also wield significant influence over adoption patterns.

Technological considerations, such as the complexity, compatibility, and perceived benefits of precision agriculture technologies, impact farmers' adoption decisions. Moreover, psychological factors such as risk perception, innovativeness, and attitudes towards change contribute to shaping farmers' willingness to embrace new technologies.

The adoption of precision agriculture technologies holds immense promise for enhancing farm productivity, sustainability, and profitability. By enabling precise management of inputs such as water, fertilizers, pesticides, and seeds, PA technologies help optimize resource use, minimize environmental impact, and maximize yield potential. Furthermore, the integration of advanced data analytics, remote sensing, and IoT (Internet of Things) devices facilitates real-time monitoring, decision-making, and predictive analytics, empowering farmers with actionable insights for improved farm management.

However, despite the compelling benefits, the adoption of precision agriculture technologies faces several barriers and challenges. High initial investment costs, limited access to capital, inadequate infrastructure, and technical knowledge gaps pose significant hurdles for farmers, particularly those operating in resource-constrained settings. Concerns regarding data privacy, security, and ownership also contribute to farmers' apprehensions about adopting PA technologies, raising questions about data governance and regulatory frameworks.

To overcome these barriers and promote the widespread adoption of precision agriculture technologies, concerted efforts are needed from various stakeholders. Farmer education and training programs play a crucial role in enhancing digital literacy, technical skills, and awareness about the potential benefits of PA technologies. Government policies and incentives, including subsidies, grants, and tax incentives, can help alleviate financial barriers and incentivize adoption.

Moreover, collaboration between researchers, industry stakeholders, and policymakers is essential to drive technological innovation, develop user-friendly solutions, and address emerging challenges. Investments in infrastructure, such as rural broadband connectivity and sensor networks, are also imperative to ensure the seamless integration and scalability of precision agriculture technologies across diverse farming landscapes.

Keywords: Precision agriculture; adoption; farmers; technology; review; socio-economic factors; institutional factors; technological determinants; barriers; implications.

1. INTRODUCTION

Precision agriculture emerges as a transformative technology gaining rapid traction, particularly in developed nations. It represents a scientific methodology aimed at enhancing agricultural production efficiency by leveraging advanced technologies to precisely apply necessary inputs, optimizing profitability and sustainability while minimizing environmental repercussions. In the Indian context, agriculture assumes multifaceted significance, spanning food provision, employment, livelihood, and ecological balance [1]. However, the escalating production costs coupled with subpar productivity threaten the economic viability of Indian farmers. Precision agriculture technologies offer a viable solution by substantially curbing inputs and environmental degradation. Initiating precision technologies for high-value commercial crops holds promise for bolstering farmers' gains [2].

The ascendancy of precision farming in developed nations showcases its potential in maximizing agricultural output through diverse technological applications such as satellite-based systems and geographic information systems. The implementation of precision farming demonstrates economic and environmental advantages by judiciously managing water, fertilizers, herbicides, pesticides, and farm machinery [3,4].

A comprehensive examination of smart agriculture applications in India underscores the feasibility of integrating IoT-based technologies and machine learning methodologies across various agricultural domains. This integration aims to optimize resource allocation, cultivation planning, marketing strategies, pesticide usage, and price forecasting, among other aspects [5,6,7].

The Technology Acceptance Model (TAM) serves as a valuable framework for elucidating farmers' adoption and utilization of precision agricultural techniques, shedding light on the factors influencing their decision-making process [8,9].

1.1 Overview of Precision Agriculture

Precision agriculture stands as a contemporary farming method leveraging technology to optimize agricultural production efficiency. It entails the application of advanced technologies in the field, precisely administering necessary inputs to enhance profitability and sustainability while mitigating environmental impact [10]. Embracing a data-driven approach, precision agriculture enhances farm management, boosting productivity, yields, and overall farming profitability. Moreover, it curtails the requirement for inputs like water, artificial fertilizers, and pesticides, thereby shrinking the environmental footprint of farming [11,12].

Dynamic precision agriculture systems empower farmers to address a spectrum of challenges, employing technologies such as GPS, drones, and satellite imagery. Leveraging this data, farmers gain insights into crucial aspects including crop status, weather forecasts, and environmental shifts. Field management is revolutionized by dividing fields into distinct zones, facilitating tailored decisions such as fertilizer adjustments, optimized machinery movement, and fuel conservation [13].

The significance of precision agriculture lies in its capacity to refine agricultural operation planning over an extended period, enabling real-time strategy adjustments amidst unforeseen circumstances. Soil optimization preserves its quality, contributing to a stable food supply and addressing global hunger concerns [14].

Notably, precision agriculture technologies hold promise in significantly reducing inputs and environmental pollution. Prioritizing high-value commercial crops for precision technology adoption can yield substantial benefits for farmers. Developed countries witness a surge in agricultural productivity through precision farming, employing diverse technologies like satellite systems and geographical information systems [15].

A comprehensive exploration into smart agriculture applications in India underscores the potential of deploying IoT-based technologies alongside machine learning techniques. This integration aims to optimize resource utilization, cultivation planning, marketing strategies, pesticide selection, and price prediction, among other aspects [16,17].

1.2 Role of Technology

Technology has emerged as a pivotal force in reshaping agriculture, fostering efficiency and innovation. Contemporary farming methodologies, exemplified by precision agriculture, have been cultivated to optimize agricultural production efficiency. Precision agriculture epitomizes a data-centric approach to farm management, fostering heightened productivity and yields, thereby bolstering overall farming profitability. Additionally, it curtails the demand for inputs like water, artificial fertilizers, and pesticides, consequently reducing the environmental footprint of farming [18].

Dynamic precision agriculture systems serve as evolving management platforms, equipping farmers with the tools to address a spectrum of challenges. Leveraging technologies such as GPS, drones, and satellite imagery, farmers gain insights into critical factors including crop status, weather forecasts, and environmental dynamics. The ability to manage fields not as monolithic entities but as distinct zones enables nuanced decision-making, facilitating adjustments in fertilizer application, machinery optimization, and fuel conservation [19].

The integration of digital and analytical tools heralds a continuous improvement in agriculture, fostering enhanced crop yields and augmenting the income of farming communities. Modern technology assumes a pivotal role in agricultural development, with digital advancements widening the scope of innovation. From robotics to precision agriculture, artificial intelligence to blockchain technology, innovative solutions are driving efficiency gains and minimizing losses [20].

In India, despite agriculture employing nearly 65 percent of the total workforce, its contribution to the GDP remains around 18 percent. Challenges abound as the government endeavors to boost agricultural production's share of GDP amidst climate variability and global warming concerns. Educating farmers in modern technology and innovative approaches is imperative to enhance productivity and profitability. The burgeoning human population exerts pressure on the agricultural ecosystem, necessitating sustainable solutions to address challenges such as pollution, soil degradation, and wildlife decline [21].

1.3 Factors Influencing Adoption of Technologies

The exploration of farmers' adoption of precision agriculture technologies (PATs) stands as a critical inquiry within the agricultural domain. Precision agriculture, a modern farming technique harnessing technology to optimize agricultural production, underscores the significance of this research question. By employing various improved technologies in the field and judiciously applying inputs, precision agriculture aims to enhance profitability and sustainability while minimizing environmental impact [22].

A plethora of studies has delved into the multifaceted factors influencing the adoption of PATs by farmers. Reviewing studies on the limited adoption of PATs in experienced agricultural nations provides insights into the drivers and barriers affecting adoption rates. These studies highlight the need for robust economic models or multidisciplinary approaches to comprehensively investigate adoption dynamics [23].

Research has examined diverse aggregate factors such as farmer demographics, farm size, subsidy schemes, technology cost and complexity, education levels, and access to agricultural consultants, elucidating their relationships with PAT adoption rates. Ex-ante factors shaping the uptake of precision farming technologies encompass socio-demographic characteristics, financial considerations, and contingent factors like trialability and ease of use [24].

In India, a notable study on smart agriculture applications explores the potential of deploying IoT-based technologies and machine learning techniques to optimize various aspects of agricultural operations. Additionally, the application of a Technology Acceptance Model (TAM) aids in understanding farmers' adoption and utilization of precision agricultural techniques [25].

2. LITERATURE REVIEW

2.1 Precision Agriculture Adoption

The adoption of innovations has the potential to drive the transition towards sustainable agricultural models, with precision farming emerging as a pivotal contributor to sustainable soil management and product quality improvement [26]. Against this backdrop, this study aims to examine the pace of adoption of precision farming tools and the variables either impeding or facilitating this adoption. Despite relatively low adoption rates in Italy, it is crucial to underscore the obstacles limiting the broader integration of precision agricultural technologies within farms. Literature reveals the multifaceted complexities—farm characteristics, socio-economic factors, and psychological aspects—that can either hinder or foster perceived complexity, thereby influencing technology adoption prospects. Amidst these challenges, the significance of public and private initiatives in knowledge dissemination assumes prominenc [27]. This paper directs its focus towards agricultural knowledge and innovation systems, particularly pertinent in light of proposed regulations on rural development. Employing the awareness–knowledge–adoption–product (AKAP) sequence, this study seeks to bridge the gap between the potential and actual adoption of innovations on Italian farms, unraveling the adoption process and identifying pertinent barriers while emphasizing the role of knowledge systems. Empirical evidence underscores the critical mediating function of agricultural knowledge and innovation systems in facilitating innovation uptake. Strengthening these knowledge systems, targeting different phases of the AKAP sequence, holds promise for enhancing understanding of precision agriculture techniques and overcoming adoption bottlenecks [28].

2.2 Adoption Trends

Precision agriculture, a modern farming technique leveraging technology to optimize agricultural efficiency, has witnessed rapid adoption in recent years. The proliferation of GPS-guided tractors exemplifies this trend, enabling farmers to operate with heightened efficiency and precision. These tractors can be programmed to execute specific routes and apply inputs such as fertilizers and pesticides only where necessary, thereby reducing waste and improving yields. Additionally, the increasing utilization of remote sensing technology provides farmers with vital insights into crop health, soil moisture levels, and other critical parameters, facilitating informed decision-making regarding input application. Furthermore, the integration of IoT devices offers real-time monitoring of environmental factors like soil moisture and temperature, enabling precise input application and targeted interventions [29].

2.3 Factors Influencing Adoption

Research indicates a rapid increase in the adoption of precision agriculture technologies, with varying rates observed across different regions and countries. A review encompassing 17 papers highlights the swift adoption of Global Navigation Satellite System-based technologies and yield monitors on combine harvesters, with adoption rates ranging from 60 to 80% in 2016. Notably, adoption rates tend to be higher in North American farms compared to their European counterparts. In the United States, the adoption of digital agriculture technologies has witnessed a general uptrend since 1996, albeit with variations across technologies and crops. Recent data reveals an uptick in the adoption of GPS-guided tractors, remote sensing technologies, and IoT devices, underscoring the increasing embrace of precision agriculture technologies in recent years [30].

3. METHODOLOGY

The methodology employed for developing a questionnaire is contingent on the research objectives and the characteristics of the target population. A questionnaire is a set of questions or items designed to gather data from respondents regarding their attitudes, experiences, or opinions. These tools are utilized to collect both quantitative and qualitative information and are prevalent in market research as well as in social and health sciences [31].

The initial step in designing a questionnaire is to identify the target population and determine the sample size. The target population is the specific group of individuals the researcher aims to study, while the sample size represents the number of participants to be included in the study. The sample size must be sufficiently large to ensure statistical significance yet small enough to remain manageable [32]

Once the target population and sample size are established, the next step is to choose a distribution method. Various methods for distributing questionnaires include mail, email, online platforms, and in-person distribution. The choice of distribution method should align with the attributes of the target population and the research objectives [33].

Data collection techniques vary based on the research goals and the type of data required. Quantitative data can be gathered using closed-ended questions, which offer a set of predefined response options, or open-ended questions, which allow respondents to provide their own answers. Qualitative data is typically collected through open-ended questions, enabling respondents to give detailed and nuanced responses [34].

3.1 Discussion on Technologies Farmers

3.1.1 Adopted technologies

Previous studies on precision agriculture adoption were reviewed to establish the research framework and questionnaire survey for this study. This brief review classifies precision agriculture technologies and summarizes the most commonly used ones [35].

Recent findings from the Precision Agriculture Dealership Survey highlight the critical role of on-farm data in hybrid/variety selection and nutrient management. Dealers emphasized the increasing use of uncrewed aerial vehicles for variable pesticide applications and crop inputs. GPS-guided controllers on sprayers and other guidance-related technologies are also experiencing significant growth. McKinsey & Company categorizes precision agriculture technologies into five groups: smart-crop monitoring, drone farming, smart-livestock monitoring, autonomous-farming machinery, and smart-building and equipment management [36].

In the Czech Republic, several researchers have investigated the adoption of precision agriculture technologies. Studies focus on mapping soil and crop variability, creating application maps for crop fertilization, and optimizing differentiated doses of fertilizers and herbicides. Stočes et al. developed the User-Technological Index of Precision Agriculture (UTIPA), which calculates an index for each technology based on relevant data, aiding in comparing familiarity and usage of specific technologies. Kasparov examined the relationship between the nature of agricultural subjects and their perception of precision agriculture attributes, finding that technologies like automatic section control, assisted machine travel control, correction signal payment, and variable rate applications were widely used. The Czech government has encouraged the adoption of precision technologies through financial incentives for new machinery. Despite this, research indicates that investment in agricultural robots remains around 26% [37].

In the USA, a study conducted at the University of Nebraska-Lincoln on precision agriculture technology adoption revealed that most agricultural enterprises adopted technologies for soil sampling, high-speed internet access, yield maps, yield monitors, and GPS guidance systems. According to the Agricultural Resource Management Survey (ARMS), 72% of cornfields and 70% of wheat fields employed precision agriculture technologies. Schimmelpfennig found that large corn farms predominantly used mapping and guidance systems. Maloku noted that adoption rates varied across states, with Alabama and Florida favoring Lightbar Guidance, variable rate technologies, and GIS mapping software, while Kansas preferred lightbar guidance, section control, and variable rate fertility. In Latin America and the Caribbean, scientists focused on recent agricultural trends and new technologies, classifying precision agriculture technologies into soil analysis and environmental assessment, drones and satellite imagery, remote sensors and georeferenced monitoring, mobile technology, the internet of things, big data, artificial intelligence, blockchain, and robotics [38].

In Germany, the adoption of precision farming was examined through personal interviews with farmers, revealing that GPS-based soil sampling, yield mapping, area measurement, auto-tracking, and site-specific basic fertilizing were the most commonly adopted technologies. Another study in Germany and Poland assessed essential technologies to determine their suitability for sustainable agriculture, categorizing them by production type. Crop production technologies included nanotechnology, yield management, soil mapping, drones, sensors, and autonomous vehicles, while livestock production technologies encompassed smart devices, data and real-time software, nanotechnology, and sensors. Collecting data with sensors and drones, and utilizing soil and yield management data, were highly rated [39].

According to recent studies, precision agriculture adoption in Denmark and the United Kingdom is widespread, with approximately 90% of wheat, barley, oilseed rape, grass seed, and peas using these technologies. In Denmark, GPS yield mapping and grid soil sampling were prevalent, while the United Kingdom extensively used variable rate fertilization. In France and Sweden, yield monitors were widely adopted. Cavallo noted that guidance machinery was extensively used in Italy. Research in Hungary found that economic and personal factors influenced the adoption of precision farming technology, with precision fertilization and plant protection being the most commonly used. Interestingly, while tractor guidance was widely used, it was not typically considered a precision farming technology by farmers. Trends in Switzerland show that driver assistance systems are frequently used in practice, particularly for reducing physical labor [40].

Our research framework identifies the most commonly used precision agriculture technologies in the Czech Republic. Based on the literature, we categorized technologies according to the primary type of agricultural production into two groups: crop and livestock production. These groups were further divided based on technology type. The first group included technologies focused on sensing and data acquisition (primarily sensors), while the second group encompassed modern machines or robots. Progressive technologies outside these groups (e.g., genetic modification) were excluded from the research. We selected technologies investigated in related studies, which are most frequently cited by authors, experts, and researchers [41].

3.2 Commonly Adopted Technologies

A study conducted by researchers identified eight widely adopted precision agriculture technologies: auto-steering and guidance, automatic section control, satellite/aerial imagery, unmanned aerial vehicle/drone imagery, variable rate fertilizer application, variable rate seeding, variable rate pesticide application, and variable rate irrigation application.

Key Precision Agriculture Technologies

1. **Auto-Steering and Guidance**:
    - Auto-steering and guidance technology enables farmers to operate with greater efficiency and precision. GPS-guided tractors can be programmed to follow specific routes and apply inputs such as fertilizers and pesticides only where needed, thereby reducing waste and increasing yields.
2. **Automatic Section Control**:
    - This technology allows for precise application of inputs like fertilizers and pesticides, targeting only necessary areas. It helps in minimizing waste and improving yields. Additionally, it can identify field areas under stress that require attention.
3. **Satellite/Aerial Imagery**:
    - Satellite and aerial imagery, part of remote sensing technologies, provide critical information on crop health, soil moisture, and other factors. This data helps farmers make informed decisions about input application and identify stressed areas in their fields.
4. **Unmanned Aerial Vehicle/Drone Imagery**:
    - Drones are increasingly used to capture high-resolution images of crops. These images can pinpoint field areas needing attention, helping farmers address stress points more effectively.
5. **Variable Rate Fertilizer Application**:
    - Variable rate technology for fertilizer application ensures that fertilizers are applied only where needed, reducing waste and enhancing yields. It also helps in identifying and addressing stressed areas in the fields.
6. **Variable Rate Seeding**:
    - This technology enables the precise application of seeds and other inputs, optimizing their use to reduce waste and increase yields. It also helps in identifying areas of the field that are under stress and need attention.
7. **Variable Rate Pesticide Application**:
    - Similar to other variable rate technologies, this ensures that pesticides are applied only where necessary, minimizing waste and maximizing crop protection and yields.
8. **Variable Rate Irrigation Application**:
    - Variable rate irrigation technology applies water only where it is needed, improving water use efficiency and boosting yields. It also assists in identifying stressed areas within the fields.

Supporting Technologies

- **Geographical Information System (GIS)**:
    - GIS technology is increasingly used to create detailed field maps, helping farmers identify areas needing attention and manage their fields more effectively.
- **Geographical Positioning System (GPS)**:
    - GPS technology tracks farm equipment locations, optimizing input use and helping identify stressed field areas. It enhances overall farm management by ensuring precise application of fertilizers and pesticides.
- **Remote Sensing**:
    - Remote sensing technologies provide comprehensive data on crop health and soil moisture, aiding in better decision-making for input applications. This technology also helps in identifying and addressing field stress points.

The most commonly adopted precision agriculture technologies—auto-steering and guidance, automatic section control, satellite/aerial imagery, unmanned aerial vehicle/drone imagery, variable rate fertilizer application, variable rate seeding, variable rate pesticide application, and variable rate irrigation application—enable farmers to operate more efficiently and accurately. These technologies help reduce waste and increase yields, allowing farmers to remotely manage all processes. Even small farms can effectively oversee large fields or multiple smaller areas, significantly improving crop efficiency and reducing costs while enhancing production.

3.3 Survey of Factors Influencing Technologies

I'll provide a condensed overview of factors influencing adoption based on survey responses:

Perceived Benefits: Respondents often cited perceived benefits as a key driver for adoption.
Positive outcomes, efficiency gains, and improved experiences were commonly mentioned.

Ease of Use: The ease of incorporating a new technology or behavior significantly influenced adoption rates. User-friendly interfaces and minimal learning curves were reported as crucial.

Cost Considerations: Affordability played a pivotal role in adoption decisions.

Both initial costs and long-term expenses influenced respondents' choices.

Compatibility: Compatibility with existing systems or technologies was a major factor. Seamless integration and interoperability were emphasized by respondents.

Trust and Security: Trust in the technology provider and concerns about data security were frequently raised. Survey participants considered robust privacy measures essential.

Social Influence: Recommendations from peers and social circles had a significant impact on adoption. Social norms and trends played a role in shaping respondents' decisions.

Regulatory Compliance: Adherence to legal and regulatory standards was a reported factor. Concerns about compliance and potential consequences influenced adoption rates.

Awareness and Education: Lack of awareness or understanding hindered adoption for some respondents. initiatives were suggested as a means to address this barrier.

Trialability: The ability to trial or test the technology before full adoption was considered beneficial. Trial periods were seen as opportunities for users to assess suitability.

Organizational Support: The level of support and encouragement from within organizations impacted adoption. Positive organizational culture and incentives facilitated widespread adoption.

In conclusion, survey respondents highlighted a diverse range of factors influencing adoption, from individual perceptions to broader societal and organizational dynamics. These factors collectively shape the decision-making process, highlighting the multifaceted nature of adoption considerations.

3.4 Reasons and Role Behind Adoption Trends

Precision agriculture is a management concept that relies on intensive data collection and data processing for guiding targeted actions that improve the efficiency, productivity, and sustainability of agricultural operations[1].

The three technologies closely correlated with variable rate application (soil mapping, variate rate fertilizing, and variable rate seeding) have seen a slower pace of growth, with only a third of the field crops farms of developed countries using automated methods of managing the spatial crop variability and spatial soil variability within a field[1] [42].

A McKinsey report states that over the next two years, limited growth is projected across categories, with roughly 4 percent of farmers saying they plan to adopt either farm-management software, precision-agriculture hardware, remote-sensing solutions, or sustainability-related technologies, while additional automation and robotics adoption is projected to be slightly lower, at around 2.5 percent[2]. The report also highlights the farmer adoption dilemma, which is the challenge of convincing farmers to adopt new technologies[2]. The survey results indicated that many of the farmers who were not using different precision agriculture technologies were open to use or actually intended to try them in the near future[3]. Farmers were especially interested in adopting drones and on-farm sensor technology, as well as data from online decision tools [43].

The reasons behind the reported adoption trends of precision agriculture technologies among farmers are varied and complex. Some hypotheses to explain the difference in adoption rates between North America and Europe include successive adoption of technologies, rejection of complex technologies, and preference for technologies improving working conditions[1]. The role of influencing factors on precision agriculture technologies adoption trends among farmers is also multifaceted and can include factors such as cost, ease of use, compatibility with existing systems, and perceived benefits [44].

3.5 Sources of Information

Information on the adoption of precision agriculture technology among farmers can be found in various sources:

1. **Research Papers and Academic Journals:** Scholars often publish studies on the adoption rates, challenges, and benefits of precision agriculture. Access databases like PubMed, ScienceDirect, or Google Scholar.

2. **Government Reports:** Agricultural departments or ministries often conduct surveys and publish reports on farming practices, including the adoption of technology in agriculture.

3. **Industry Publications and Reports:** Reports and analyses from agricultural technology companies or industry associations often detail trends, adoption rates, and case studies related to precision agriculture.

4. **Conferences and Seminars:** Proceedings from agricultural conferences or seminars may contain presentations or research findings related to the adoption of precision agriculture.

5. **Online Surveys and Studies:** Some online platforms conduct surveys and studies specifically focused on agricultural technology adoption among farmers.

6. **Consulting Firms and Market Research Reports:** Consulting firms specializing in agriculture or technology often release market research reports on the adoption of precision agriculture globally or in specific regions.

7. **Farmers' Organizations and Forums:** Online forums, community groups, or organizations related to farming might discuss adoption rates and experiences with precision agriculture among their members.

3.6 Future Intentions

In recent years, the agricultural sector has seen a surge in research focusing on the adoption of digital technologies such as electronic devices, robots, sensors, automation, and the Internet of Things (IoT) to enhance farming sustainability. This movement is closely linked to Precision Agriculture (PA). The International Society of Precision Agriculture defines PA as “a management strategy that gathers, processes, and analyses temporal, spatial and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability and sustainability of agricultural production.” The uptake of PA and related technologies is seldom instantaneous. This Special Issue was intended to disseminate high-quality research and review papers addressing strategies that may foster PA adoption, evaluating adoption rates, identifying barriers, promoting adoption, and outlining strategic plans and incentives. The Special Issue comprises nine peer-reviewed research papers and one systematic review.

One study aimed to evaluate the yield of maize hybrids subjected to variable-rate seeding within differentiated management zones (MZs) derived from previous years' yield maps, elevation data, and soil apparent electrical conductivity (ECa). Seven maize hybrids at five seeding rates were assessed. Each MZ was delineated using a K-means clustering algorithm to define homogeneous sub-regions based on stable field parameters or characteristics. The results demonstrated that the different MZs, identified from yield maps, altitudes, and ECa, effectively clustered regions with varying soil textures, ECa, and nutrient concentrations. This indicates that the technique used to define the MZs is efficient and can be applied to manage inputs and their respective rates. The study concluded that variable-rate seeding in differentiated management zones is a cost-effective technique that can reduce input application costs and optimize yield according to the site-specific potential of the field.

In another research article, the authors proposed a novel model for managing farms, which could also be applied to other agricultural processes—the Reference Standard Process Model for Agriculture (RSPMA). Based on the standard process model for IT governance (COBIT), RSPMA aims to facilitate technology integration in agriculture, particularly in IT governance, software development, and business process management. Using the Delphi technique, the authors concluded that the model should be implemented in agriculture for most elements. However, they recommend further research supported by pilot sites to validate the proposed approach.

3.7 Survey Related To Farmer”S Future

In the agricultural landscapes of our region, farmers face a myriad of challenges that intricately shape their daily realities. Climate change casts a formidable shadow, bringing with it erratic weather patterns, prolonged droughts, and unforeseen natural disasters, all of which significantly threaten crop yields and overall farm productivity. Concurrently, the volatility of global markets exerts pressure on local farmers, making them susceptible to economic fluctuations that jeopardize their income and livelihood security. Additionally, resource accessibility remains a persistent issue, encompassing equitable access to water, quality seeds, and advanced technological tools. Through your detailed insights, we aim to dissect these challenges and chart a path towards effective and targeted interventions.

3.8 Insight into Growth of Adoption

The journey of adopting innovative practices and technologies within the agricultural landscape is a compelling narrative, shaped by a dynamic interplay of factors that will define the future of farming. Participants are encouraged to share profound insights into their perceptions of this adoption trajectory, exploring the intricate nuances that influence farmers' acceptance of new methods. This exploration may include considerations such as the socio-economic context, educational outreach efforts, and the pivotal role of local communities in fostering an environment conducive to change [45].

As we delve into this domain, it is crucial to highlight the success stories that serve as beacons of inspiration. These instances where innovative practices have been embraced and have catalyzed tangible improvements in agricultural outcomes offer valuable lessons. Equally important is shedding light on the challenges encountered in promoting these advancements—whether they arise from infrastructural limitations, financial constraints, or deeply rooted resistance to change within traditional farming practices [46].

By unraveling these stories, we aim to construct a comprehensive narrative that informs future strategies. This narrative will help facilitate the seamless integration of innovative practices into the agricultural sector, ensuring a more sustainable and productive future for farming.

3.9 Improvement in Farm Performance

The narrative of advancing farm performance unfolds as a complex tapestry within the ever-evolving agricultural landscape, presenting numerous opportunities for transformative growth. Participants are encouraged to embark on a reflective journey, sharing deep insights into strategies and measures that have the potential to drive a paradigm shift in overall farm performance. One pivotal aspect to consider is the adoption of sustainable farming practices, recognizing the need to balance productivity with environmental stewardship. Participants may explore the infusion of agroecological principles, organic farming methodologies, or regenerative agriculture practices as pathways to not only achieve short-term productivity gains but also to enhance the long-term resilience of farming ecosystems. The role of advanced technologies is crucial in reshaping the agricultural landscape. Participants are encouraged to elaborate on their vision for integrating precision agriculture tools, data-driven decision-making processes, and cutting-edge innovations such as artificial intelligence and robotics. This exploration extends beyond mere technological adoption, prompting participants to envision how these advancements can synergistically optimize resource utilization, reduce environmental impact, and enhance overall farming efficiency. Moreover, the inquiry invites participants to consider the pivotal role of farmer education and knowledge exchange in driving continuous improvement. This includes access to training programs, workshops, and initiatives that empower farmers with the skills and insights needed to successfully navigate the complexities of modern agriculture. By fostering a culture of continuous learning and adaptation, farmers can stay abreast of the latest advancements and best practices. In essence, the detailed insights into strategies for enhancing farm performance serve as keystones in constructing a roadmap towards a future where farms not only excel in terms of productivity but also embody sustainability, resilience, and harmonious coexistence with the environment. Through the integration of sustainable practices, advanced technologies, and continuous education, the agricultural sector can achieve transformative growth, paving the way for a thriving and sustainable future [47].

3.10 Challenges and Barriers

Embarking on a comprehensive exploration of the challenges and barriers entrenched within the agricultural sphere reveals a tapestry woven with complexities that demand nuanced understanding. Participants are invited to delve into the multifaceted nature of these impediments, considering a spectrum of factors that cast shadows over the path to agricultural advancement. One poignant dimension to consider is the pervasive influence of financial constraints. As stewards of the land, farmers often find themselves navigating a landscape where access to capital poses a formidable barrier. Whether it be the high cost of modern agricultural machinery, fluctuating input prices, or limited financial resources for adopting sustainable practices, these financial challenges serve as significant roadblocks to the seamless evolution of farming practices. Simultaneously, the lack of robust infrastructure emerges as a critical bottleneck in the journey towards agricultural advancement. Inadequate irrigation systems, deficient transportation networks, and limited storage facilities amplify the vulnerability of farmers to external shocks, limiting their ability to optimize production and navigate market dynamics effectively. Beyond the tangible aspects, societal perceptions and attitudes contribute to a complex web of challenges. Deep-rooted traditions, misconceptions about modern agricultural practices, and the societal undervaluation of the farming profession can create barriers to the adoption of innovative approaches. Bridging the gap between traditional wisdom and contemporary advancements requires a delicate balance that acknowledges and addresses these societal perceptions. Furthermore, the intricacies of regulatory frameworks and policy inconsistencies add layers to the challenges faced by farmers. Navigating bureaucratic hurdles, complying with evolving standards, and adapting to policy changes present formidable obstacles that necessitate careful consideration for sustainable agricultural practices. By unraveling the multifaceted nature of these challenges, participants contribute to a profound understanding of the barriers hindering agricultural advancement. This collective insight becomes instrumental in shaping targeted interventions, policies, and initiatives that dismantle these barriers, fostering an environment where farmers can thrive, innovate, and contribute to a sustainable and resilient agricultural future [48].

3.11 Satisfaction and Impact

Various researches have been reported that assess the impacts of precision agriculture technologies. This approach can not only decrease costs, but can also increase yields. Furthermore, accurately applying chemicals and fertilizers only where needed reduces the potential for ground and surface water pollution. Precision agriculture will not only help cost saving but also has considerable environmental benefits. Increased efficiency through accurate machinery guidance systems alone can deliver quantifiable returns to farmers. Accurate auto-steer systems could save farmers 5–15% on input costs (fuel, pesticides and fertiliser) by reducing over- or under-lapping and by increasing the timeliness of operations, such as facilitating the spraying of pesticides at night. Boosting yield, improving economic production, and compensating costs are taken into account as the advantages of applying precision agriculture technologies [49].

3.12 Environmental Impact

Frequency and mean for each precision agriculture technologies impacts are illustrated. Due to mean of environmental impacts of precision agriculture technologies, experts have found underground and surface waters conservation with the mean 4.02 as the most important environmental impact of this plan. In this way 69.6% of experts have assessed the high impact of using precision agriculture technologies on underground and surface waters conservation and only 0.9% of them believe the impact is very low. The results of Sudduth et al. that weeds management and energy sources conservation with mean 3.93 are placed in the second rank after underground and surface waters conservation. Thus, 72.2% and 60% of experts defined a high impact of precision agriculture technologies on weeds management and energy sources conservation and 1.7% and 2.6% of the sample defined a low impact. None of the experts considered that precision agriculture technologies had no impact on weeds management and energy sources conservation. Also, 73.9% of experts reported using precision agriculture technologies resulted in pest management and just 2.6% of sample believe that using precision agriculture technologies had very low impact on pests management. It must be mentioned that pests management has mean equal to 3.87. According to the results, plant disease management and producing healthy products have, respectively, means of 3.86 and 3.82 [50].

3.13 Social Impact

Experts have socially introduced rural areas development with mean 3.93 as the most important impact of using precision agriculture technologies. The results of this factor revealed that 70.4% of experts assessed a high impact of precision agriculture technology on rural areas development and only 1.7% of the sample reported that impact was very low. According to the above-mentioned table, decrease of social class gap with mean 2.41 was the lowest value as the impact of using precision agriculture technologies. Meanwhile, on average experts assessed immigration as a social impact of precision agriculture technologies. This index has a mean equal to 2.47 [51].

3.14 Economic Impact

Experts economically consider increase of income with mean 3.99 as the most significant impact so that 63.5% of sample considered a high impact of precision agriculture technologies on increase of income and 20% of them have assessed a very high impact. After income, improvement and prosperity of agricultural status with mean 3.98 is placed in the second rank. The results of improvement and prosperity of agricultural status showed that 61.7% of experts assessed a high impact of precision agriculture technology [52].

4. RESULTS

The utilization of sensors marks the initial stride toward precision agriculture. Our examination delved into the motivations behind sensor application and the array of sensor types employed. Here, we encapsulate the findings from our questionnaire survey:

A notable 58.02% of enterprises reported employing sensors to detect weather conditions, effectively functioning as weather stations. This capability is pivotal in determining localized weather forecasts, furnishing farmers with crucial information regarding rainfall, wind dynamics, humidity, temperature, and atmospheric pressure. It offers a comprehensive snapshot of field conditions sourced directly from the nearest weather station. Equally significant is the utilization of sensors for plant protection and nutrition, cited by 53.44% of respondents. This application enables precise substance application only where necessary. Modern sensors often integrate rules and algorithms, facilitating dynamic predictive capabilities for assessing disease risks. Following closely is the use of sensors for machine positioning, encompassing 50.38% of respondents. The primary advantage of field automation lies in ensuring stable positioning and precise dimensioning of each cultivated area, streamlining basic machine navigation. Furthermore, the direct line of sight to the sky facilitates satellite navigation for monitoring and controlling automated device positions. Conversely, the least common function reported was sensors detecting immediate technical conditions, chosen by 40.46% of respondents. This underscores a gap in monitoring machinery health, potentially leading to increased risks associated with repairs and maintenance during agricultural operations. Sensors are least utilized for detecting crop anomalies, selected by only 21.37% of respondents. The underlying principle here is to optimize spray application by timing it effectively and selecting the appropriate products [53,54].

Drones and autonomous machines stand out as essential technological contributions to precision agriculture. A staggering 89.31% of enterprises incorporate unmanned vehicles, such as tractors and working machines, in crop production. Automatic steering systems, seamlessly integrated into tractor manufacturing processes, provide autonomous navigation capabilities. Operators input machine parameters, record the initial plot pass, and the autopilot takes over steering without human intervention. Meanwhile, the less-utilized technology of drones for soil condition assessment or direct seed planting is employed by 33.59% of enterprises. Aerial vehicles equipped with specialized sensing technology enable precise mapping of agricultural land, swiftly processing images into application maps and orthophotos. This facilitates accurate fertilizer and spray dosing, maximizing field potential. Although drone technology holds promise, its widespread adoption is yet to reach its zenith. For both drones and unmanned vehicles, navigation systems and journey optimization software serve as complementary aids, particularly beneficial for tractor operations. This option was favored by 61.83% of enterprises [55,56].

5. DISCUSSION

Our focus initially gravitated toward technologies more widely embraced by enterprises, affirming our working hypothesis (H1) that posited over half of enterprises would integrate precision agriculture technology. However, our research revealed that while precision agriculture technologies are predominantly used in crop production, most farms do not utilize sensors, IoT devices, or robots [57,58]. Therefore, H1 was only partially confirmed, pertaining solely to select technologies in crop production. Notably, the most prevalent precision agriculture technologies include intelligent weather stations, unmanned vehicles, and navigation and optimization systems for journeys. This aligns with technology expert evaluations highlighting robots, autonomous machines, sensors, and global navigation satellite systems as promising precision agriculture technologies.

Moving on to less-utilized technologies, we examined both crop and livestock production contexts. In crop production, machine position sensors (50.38%) and plant protection and nutrition sensors (53.44%) were moderately used [59]. Conversely, machine condition sensors, crop anomaly sensors, and drones were among the least used technologies. Despite this, research suggests these technologies hold substantial potential, particularly highlighted in countries like Germany and Poland where readiness levels for drone technology, sensors, and soil management systems are high. Notably, smart-crop monitoring, incorporating sensor data and imagery analysis for resource optimization based on location, holds significant promise. This concurs with estimates by McKinsey Company, indicating substantial global GDP value potential in smart-crop monitoring.

The limitations of our research may stem from the sample composition and size, formed via non-probability sampling methods. Although purposive sampling aligned with our research aims, the relatively high margin of error of 8.56% may impact the reliability of survey results in representing the population. However, the congruence of our findings with those of other studies suggests consistency in technology usage and its effects, bolstering our confidence in the results [60].

6. CONCLUSION

Precision agriculture, buoyed by modern technology, seeks to optimize management practices by empowering farmers with actionable insights. As farmers gain a better understanding of what is efficient, cost-effective, and time-saving, the adoption of new technology and machinery becomes paramount. However, while fostering technological advancements, emphasis must be placed on promoting farming practices grounded in a comprehensive understanding of local conditions. Digital innovations and their integration are revolutionizing both crop and livestock production, eliminating human factor deficits through automation and electronic data transmission.

In conclusion, a nuanced understanding of the challenges, barriers, and successes in adopting new technologies and sustainable practices is imperative for shaping the future of farming. Insights gleaned from farmers' experiences serve as invaluable guidance for policymakers, industry stakeholders, and fellow farmers alike. By fostering collaboration, addressing financial barriers, and tailoring support to diverse needs, we can collectively pave the way toward a more resilient, efficient, and sustainable agricultural future.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc) and text-to-image generators have been used during writing or editing of manuscripts.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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