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REVIEW ARTICLE

Exploring the factors influencing the adoption of smart farming technologies in agriculture - A bibliometric analysis literature review

Poorna Teja K[1], Senthilkumar M[2*], Manimekalai R[3], Saravanan P A[4] & Vanitha G[5]

[1]Department of Agricultural Extension and Rural Sociology, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[2]Training Division, Directorate of Extension Education, Tamil Nadu Agricultural University, Coimbatore 641 003. Tamil Nadu, India
[3]Department of Agricultural Extension and Rural Sociology, Tamil Nadu Agricultural University, Coimbatore 641 003. Tamil Nadu, India
[4]Department of Agricultural Entomology, ICAR - Krishi Vigyan Kendra, Tiruppur 641 667, Tamil Nadu, India
[5]School of Post Graduate Studies, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India

*Correspondence email - senthilmsk@tnau.ac.in

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Abstract

Smart Farming Technologies (SFTs) play a crucial role in enhancing agricultural productivity, sustainability and resource efficiency. However, a variety of technological, economic, social and policy-related issues influence their adoption. This study uses bibliometric analysis to highlight collaborative efforts in this field, uncover global research trends and investigate the major factors impacting the adoption of SFT. The study uses Visualization of Similarities (VOS) viewer and R studio to perform bibliographic coupling, keyword co-occurrence and citation network analysis using Scopus as the main database. The selection of excellent, peer-reviewed studies is guaranteed via a PRISMA-based methodology. The results show notable differences in adoption rates, with affluent countries making tremendous progress while underdeveloped regions struggle with digital literacy, inadequate infrastructure and budgetary restraints. High upfront expenditures, problems with interoperability, worries about data privacy and farmers' aversion to change are some of the main obstacles. Adoption rates are greatly impacted by social factors, institutional support and governmental regulations, underscoring the necessity of focused interventions. To close the gap between the development of technology and its practical application, the study emphasizes the value of collaborative research, interdisciplinary approaches and policy frameworks. To increase adoption, it is essential to address infrastructure and financial issues, improve farmer training and fortify policy measures. The findings deepen our understanding of the dynamics of smart farming adoption and provide evidence-based suggestions for industry executives, researchers and policymakers. To guarantee extensive SFT implementation and long-term agricultural resilience, future studies should concentrate on localized adoption models, sustainable financing and adaptable regulations.

Keywords: bibliometric analysis; precision agriculture; smart farming technologies; sustainable agriculture; technology adoption

Introduction

As the primary source of resources for industry, economic expansion and subsistence, agriculture has served as the cornerstone of human civilization. Since its inception, agricultural methods have consistently changed to satisfy the needs of expanding people and shifting environmental conditions (1). By 2050, the global population is expected by reach 9.7 billion people on the planet (2), a major obstacle facing contemporary agriculture is the rising demand for food and agricultural products (3). In addition to being the main source of food today, agriculture also powers the textile, pharmaceutical and energy production industries, which influences international trade and economies (4). However, traditional farming methods are finding it difficult to meet the rising demand for resources and food as issues including soil degradation, water scarcity and climate change threaten the stability of food systems (5, 6).

To maintain economic growth, maintain environmental balance and guarantee food security, there is an urgent need to increase agricultural output due to the growing population. Despite being deeply ingrained in agricultural history, traditional farming practices have limitations in terms of sustainability, efficiency and scalability (7). Unpredictable weather patterns, excessive water use, pest infestations and soil erosion are some of the problems that can lower crop yields and impede productivity (8, 9). Technology presents a game-changing alternative as the globe faces the pressing need for more sustainable farming methods. Modern agricultural technology can greatly enhance conventional farming methods, making them more effective, flexible and ecologically friendly (10, 11).

Smart farming technologies (SFTs) encompass a range of innovations that integrate modern information and communication technologies (ICT) into agricultural practices.

These technologies can be broadly classified into three key areas: farm management information systems (FMIS), precision agriculture (PA) and agricultural automation and robotics.

FMIS are software platforms designed to collect, process, store and disseminate essential data required for managing various farm operations. Precision agriculture, on the other hand, focuses on optimizing input usage through technologies that monitor and measure spatial and temporal variations within fields, ultimately improving economic returns and reducing environmental impact. Agricultural automation and robotics, closely linked to ICT, involve the use of automatic control systems, artificial intelligence and robotic solutions across all stages of agricultural production, enhancing efficiency and productivity.

To evaluate different environmental factors like soil health, crop conditions and climate, smart farming technologies allow for the real-time data collection, transmission, processing and analysis of data. This real-time data helps farmers make informed decisions, improving farm management and outcomes.

Collectively, these technologies form the core of smart farming, which is characterized by the application of cutting-edge ICT solutions in agriculture. This includes variable rate applicators (12), the Internet of Things (IoT) (13), geo-positioning systems (14), big data analytics (15, 16), unmanned aerial vehicles (UAVs or drones) (13, 17) and automated systems and robotics (18, 19). Together, these innovations enhance the precision, sustainability and overall efficiency of agricultural operations, revolutionizing how farming is done.

Smart farming technologies (SFTs) have become a disruptive force in agriculture in recent years, providing creative ways to increase resource efficiency, sustainability and productivity (20, 21). Farmers may make data-driven decisions that optimize operations and improve the sustainability of agricultural practices in the face of global issues by incorporating these digital developments (22).

Smart farming technologies in agriculture – an overview

Smart agricultural technology usage has been accelerating as the demand for more efficient and sustainable farming methods increases (23). To maximize every facet of their operations, farmers all around the world are starting to use technologies like IoT sensors, drones, autonomous machinery and big data analytics (24).

Precision farming, another name for smart farming, is the application of cutting-edge technologies to maximize agricultural operations, boost productivity and increase crop yields (25). This method responds to environmental circumstances while improving farming's precision and sustainability using digital tools, sensors and data analytics. Farmers can make well-informed decisions based on real-time data thanks to technologies like the Internet of Things (IoT), artificial intelligence (AI), machine learning, robotics and data analytics (26). As agriculture deals with issues like population growth, climate change and the need for increased food security, these inventions have gained popularity throughout the world. Although these technologies are already widely used in nations like the US, Brazil and the Netherlands, emerging nations like India are beginning to recognize how they might increase agricultural productivity while reducing their negative environmental effects (27).

Several important technologies are essential to the development of smart farming. Farmers can monitor and manage resources more effectively thanks to real-time data on crop health, temperature and soil moisture collected by IoT devices and sensors. By using drones for aerial observation and precise fertilizer and pesticide application, waste and chemical use are decreased. Large volumes of data from sensors and drones are analysed by AI and machine learning systems, allowing predictive models to detect possible pest outbreaks and optimize irrigation. Furthermore, by increasing productivity and lowering labour costs, robotics and automation, such as self-sufficient tractors and harvesters are revolutionizing conventional farming methods. Platforms for cloud computing help farmers even more by offering data-driven insights on market trends and crop management (28-30).

Smart farming has substantial economic and environmental advantages. Through resource optimization, these technologies contribute to sustainability by minimizing chemical dependence, reducing waste and lessening their influence on the environment. Additionally, smart farming improves profitability and resilience to market swings by raising agricultural output, lowering operating costs and empowering farmers to make well-informed financial decisions (31). Global acceptance of these technologies has been increasing and they are already widely used in places like North America and Europe (32). The usage of smart farming is growing in nations like India, especially because to reasonably priced solutions like smartphone apps and Internet of Things-based sensors that is backed by government programs and agritech businesses (33).

The numerous worldwide issues that agriculture faces, such as the growing demand for food and environmental sustainability, may be resolved by integrating smart farming technologies. The adoption of these technologies is not without obstacles, nevertheless, despite their potential. Important obstacles to overcome include problems like financial limitations, restricted access to technology and the requirement for farmer education (34, 35). By determining the major variables impacting the uptake of smart farming technology, this study seeks to investigate these issues. The study employs bibliometric analysis to look at worldwide trends, scientific output and collaboration in the field, offering important insights into how to speed up the adoption of new technologies. By examining the elements that influence adoption, the research will further knowledge of how smart farming may be applied more successfully, assisting in overcoming the drawbacks of conventional farming methods and satisfying the rising need for sustainably produced food.

This study primarily aims to examine the development and new directions in smart farming technology adoption research while using bibliometric analysis to find gaps in the body of knowledge. With a focus on an understudied field, this study seeks to:

- To evaluate research collaboration by studying citation networks and author contributions.
- To examine keyword trends to identify emerging themes and research gaps.
- To analyse global research on Smart Farming Technology (SFT) adoption across different countries.
- To identify the key factors studied in the scientific papers that influences the adoption of smart farming technologies.

Materials and Methods

To ensure that the search is thorough and focused, the technique starts by describing a methodical approach by locating pertinent literature on the adoption of smart agricultural technologies. The study includes several important phrases associated with smart farming technologies (e.g., "Smart Farm*", "Precision Agri*") and those that focus on adoption aspects (e.g., "Barriers", "Acceptance") using a set of carefully constructed search strings. This comprehensive search approach is essential for catching the several facets of the adoption of smart farming, making sure that the search is both enough to weed out irrelevant research and broad enough to cover a few related issues. The validity of any scientific technique depends on the utilization of high-quality data, which is provided by Scopus, a platform that, based on earlier research, is regarded as one of the two primary bibliographic databases and is widely recognized for its peer-reviewed content (36).

After searching through 26583 records, 12331 journal articles were found. The inclusion and exclusion criteria are carefully considered to preserve the caliber and applicability of the chosen articles. These were further reduced to 10117 by restricting the search to peer-reviewed journal papers written in English. To limit the findings to original research that is directly connected to the study question, it is also crucial to exclude review, non-full-text and non-open access papers. The publication timeline was used to further filter the search results, resulting in 1,088 open access papers.

The pool is initially reduced to 153 articles after the initial screening, which is based on titles and abstracts, enables the prompt removal of irrelevant articles. 96 papers are chosen because of the second screening, which looks at full-text publications to make sure the remaining studies are of a high caliber and closely relevant to the study's focus. A more selective selection of research is made possible by this tiered method, which also reduces the possibility of incorporating studies that might not satisfy the requirements for inclusion.

The selected articles were further examined using bibliometric techniques, with tools like R studio and VOS viewer employed to visualize citation analysis, trending themes and country collaboration networks. To enhance the robustness of the analysis, bibliometric methods were applied to investigate key authors, contributing countries and emerging research themes. For the author analysis, bibliographic coupling was used to identify clusters of researchers with similar citation patterns, offering insights into scholarly influence and thematic coherence. For the country level analysis, bibliographic coupling helped map global research networks, identifying primary contributors to smart agriculture and emerging research nations. For thematic analysis, co-occurrence analysis of author keywords was conducted to identify major research clusters and secondary themes, providing an overview of the key topics within the field. This approach facilitates a deeper understanding of collaboration patterns and the broader influence in the domain. Additionally, the study follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (37) guidelines (Fig. 1), ensuring a transparent and systematic process for synthesizing the results.

Future research and policy development in the sector will be guided by the themes, which include technological, economic and social concerns. These topics offer important insights into the difficulties of adoption. All things considered, the methodology shows a thorough approach to the selection and analysis of literature, which is crucial for guaranteeing the validity and dependability of the study findings.

Results and Discussion

Bibliographic coupling of authors

Using authors as the unit of analysis and bibliographic coupling (Fig. 2) offers important insights into the intellectual structure and interconnectedness of the topic of study. The graphic shows clear groups of writers with similar references, suggesting scholarly influence and thematic coherence. Leading writers like Pivoto (2018), Eastwood (2019) and Shepherd (2020) are grouped together in a highly interconnected cluster, indicating that they have a significant influence on the discourse in the field. A substantial degree of common citations is implied by their strong coupling strength, indicating a coherent body of work that has been regularly cited in later research.

Furthermore, writers that serve as links between the main research groups, such Balafouts (2020), Bolfe (2020) and Caffaro (2019), have a moderate level of connectedness. Smaller but separate clusters, such as those of Ahmad Tarmizi (2020), Kolady (2021) and Narwane (2022), suggest the development of specialized research avenues that might be specialized subfields or more recent viewpoints that are still finding their way into the larger academic conversation. These thematic divides are emphasized by the color-coded segmentation, which also identifies areas of research landscape convergence and divergence.

Additionally, the emergence of new authors such as Kendall (2022) and Li (2020) points to continuous progress and the field's continuous development, which may be a sign of changing research goals or the adoption of innovative approaches. The network structure also suggests that although some writers have a hegemonic influence, more recent works are gradually becoming part of the current system, promoting dynamic scholarly development. Overall, this bibliographic coupling analysis offers a path for comprehending how research themes are changing and which authors are spearheading innovation in the field in addition to identifying significant contributors and intellectual connections.

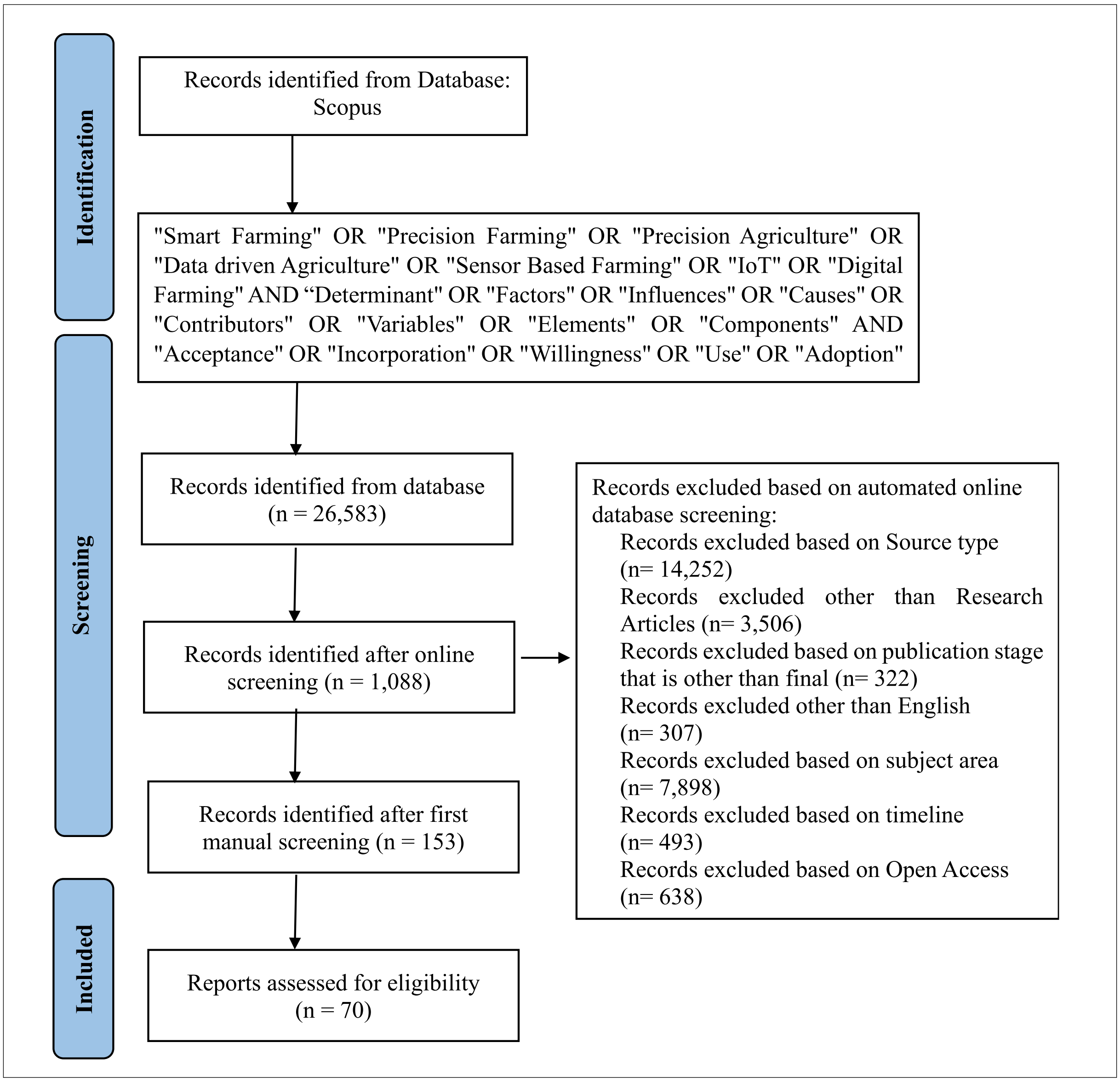

Fig. 1. PRISMA flowchart illustrating the process of literature search for a systematic review on the adoption of smart farming technologies in agriculture.

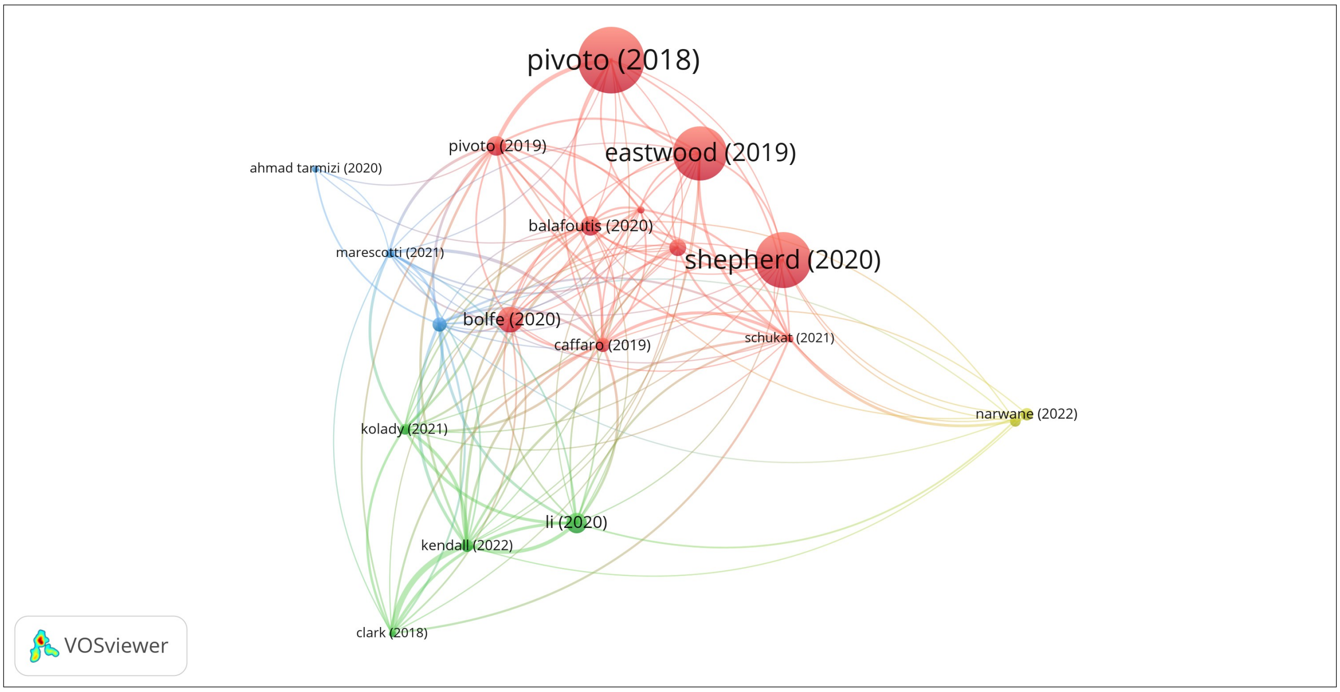

Fig. 2. Bibliographic coupling of authors in smart farming technologies adoption research.

Co-occurrence of author keywords

The primary areas of attention and links within the topic are shown by the depiction of commonly linked keywords (Fig. 3). Several prominent clusters that each reflects a different study focus while preserving connections with other areas are highlighted in the created network.

"Precision agriculture" is the most commonly appearing keyword at the centre of the network, indicating its crucial importance in contemporary farming innovations. Closely related to it, "precision farming" and "smart farming" create important clusters that emphasize the incorporation of cutting-edge technology like automation, digital agriculture and big data. Terms like "digital agriculture" and "agricultural innovation" are included in these clusters, indicating a strong focus on the use of technology in enhancing farming methods, increasing productivity and guaranteeing sustainability.

An additional noteworthy theme cluster centres on the "Internet of Things (IoT)," which is commonly associated with "smart agriculture," "irrigation" and "food security." This cluster highlights how IoT-based solutions are being used more and more in agricultural systems for automation, real-time monitoring and decision support. Additionally, this cluster's co-occurrence of the "technology acceptance model" indicates an increasing interest in researching the factors that promote and hinder the adoption of IoT-driven agricultural solutions.

"Technology adoption" is another crucial cluster that connects ideas like "innovation adoption," "farmers' perception" and "unified theory of acceptance". This highlights the elements that affect farmers' readiness to incorporate cutting-edge technologies into their operations and represents the socioeconomic and behavioural aspects of precision agriculture. The inclusion of "structural equation modelling" inside this cluster implies that researchers are applying quantitative methodologies to study the factors of technology adoption.

Furthermore, "sustainable agriculture" is the focus of a distinct but related cluster that is associated with terms like "IoT adoption", "perceived usefulness" and "barriers". This implies that although the adoption of technology is a major force behind the change of agriculture, issues with sustainability, viability and the perceived advantages of these technologies continue to be important areas of study. The connection between digital agriculture and sustainability emphasizes how important it is to strike a balance between economic and environmental factors and technological improvements.

All things considered; the co-occurrence analysis of author keywords offers insightful information on the interdisciplinary character of precision agriculture research. In addition to tackling issues with adoption, sustainability and socioeconomic considerations, the interconnected clusters show a significant emphasis on technology-driven innovation. These results open the door to more resilient and effective farming systems by pointing to a growing trend toward the integration of smart technologies with sustainable agricultural practices.

Bibliographic coupling of countries

Fig. 4 represents bibliographic coupling network of countries and offers important insights into the worldwide structure of research relationships. Three separate clusters, each representing geographical and theme research ties are revealed by the study to form a well-connected network. Other significant research nations including the United Kingdom, France and India are part of the blue cluster, which is dominated by China and the United States. The huge node sizes and extensive interconnectivity of China and the U.S. demonstrate their

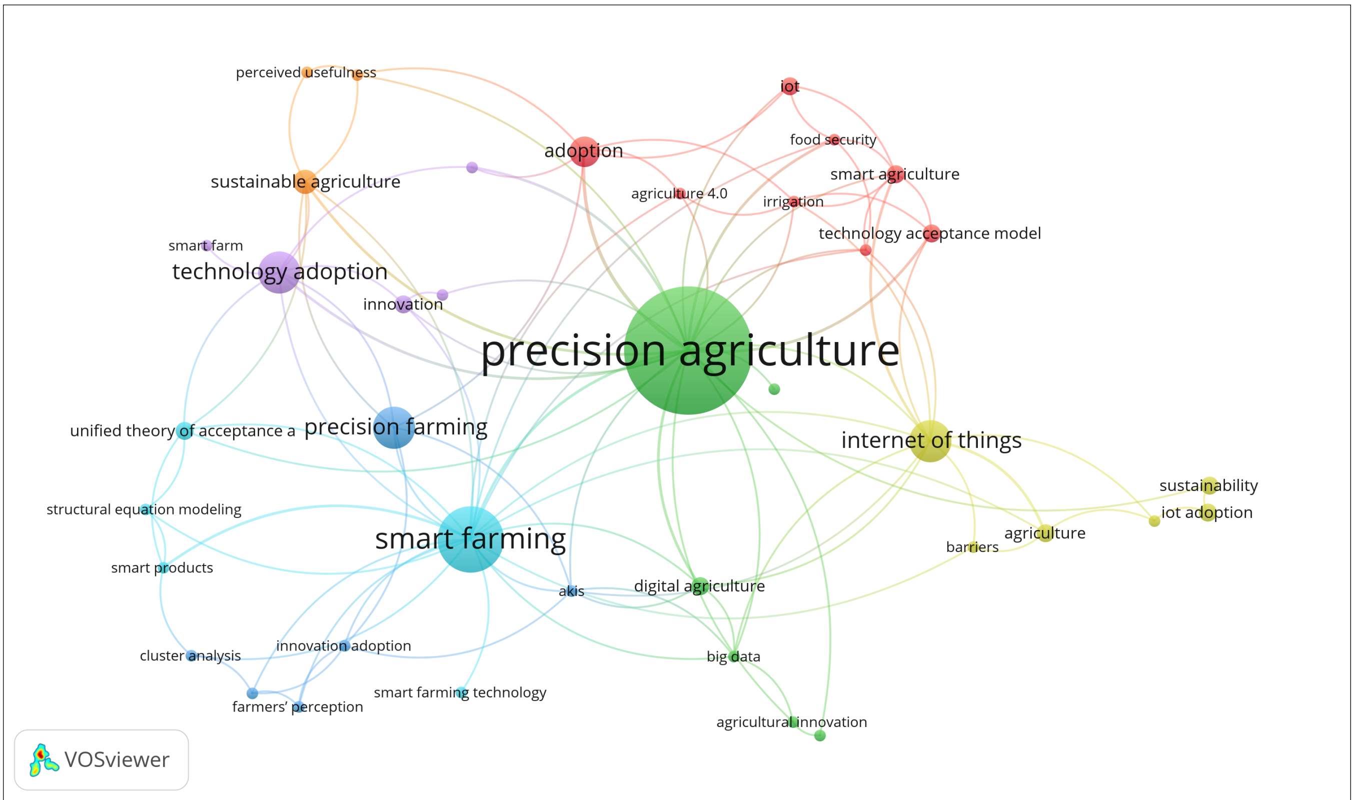

Fig. 3. Network visualization of author keyword co-occurrence in smart farming technology adoption studies.

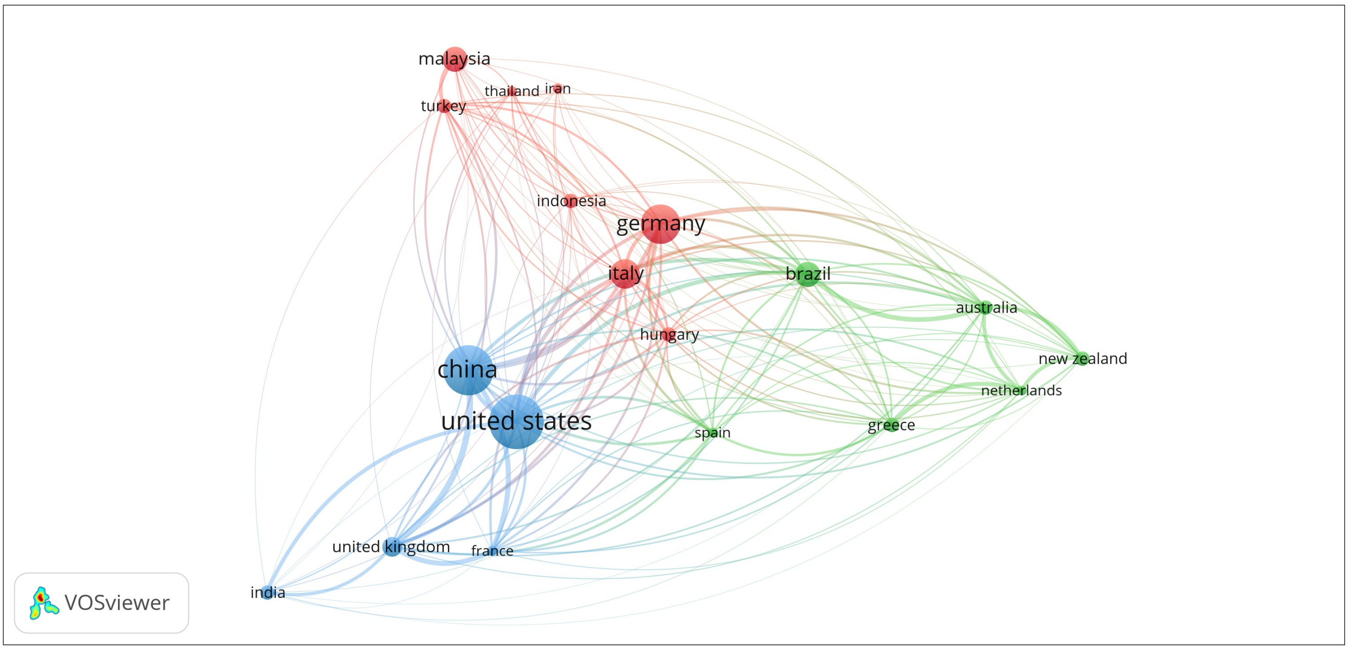

Fig. 4. Global bibliographic coupling network of countries in smart farming technology adoption research.

important position in bibliographic coupling, reflecting their dominance in global scientific discourse. Strong research collaborations and shared academic influences are suggested by the frequent shared citations between these nations.

Brazil, Australia, New Zealand, the Netherlands, Greece and Spain make up the green cluster, which consists of both well-established and up-coming research centres. With a high citation count while having comparatively fewer documents, Brazil stands out as a major participant in this cluster, indicating that their research has a particularly significant impact. Strong regional research ties, especially within the Oceania-Europe axis, are suggested by the close connections between New Zealand, Australia and European countries.

A major European Asian research link is shown by the red cluster, which is mostly made up of Germany, Italy, Hungary and several Southeast Asian and Middle Eastern nations (Malaysia, Turkey, Indonesia, Thailand and Iran). Italy and Germany stand out as important bridging countries that connect this cluster to the larger international research network. Their high overall link strength values show that they serve as bridges between the research communities in Asia, Europe and the United States, facilitating the spread of knowledge across regional boundaries. Furthermore, a sub-network between Middle Eastern and Southeast Asian countries indicates increasing regional cooperation in research, especially in developing scientific domains.

China and the United States are the most significant contributors to research worldwide, as evidenced by their dominance in both publication volume and bibliographic coupling across the network. Nonetheless, Brazil is notable for its high citation impact, while Germany and Italy are essential in promoting cross-continental research ties. The network's inclusion of developing research countries like Malaysia, Turkey and Indonesia highlights their growing involvement in international academics. The clustering pattern demonstrates how regional relationships are growing stronger and creating a more diverse and interconnected research environment, even as leading research nations continue to impact the global academic scene.

Key research themes in the adoption of smart farming technologies

The thematic map of an organized summary of the major themes impacting the use of smart farming technology in agriculture is shown in Fig. 5. The analysis highlights the key and auxiliary factors influencing this subject by grouping research themes into four quadrants: Motor Themes, Niche Themes, Emerging or Declining Themes and Basic Themes. The themes' distribution provides insightful information about the behavioural, financial and technological aspects affecting the uptake of smart agricultural technologies.

The three main study fields in the Motor Themes quadrant-precision agriculture, technology adoption and agricultural technology-represent highly developed and pertinent subjects. These themes' prominence indicates that incorporating cutting-edge technologies to improve agricultural output, efficiency and sustainability is highly valued. Furthermore, the inclusion of agricultural and human workers in this cluster emphasizes how important workforce transformation, skill development and labour adaptation are to the effective deployment of smart farming technologies. This emphasizes how crucial human-centred elements like education, training and social acceptance are in promoting adoption, in addition to technology

Key themes include rural region, unmanned vehicle, detection method and sustainability arise in the Niche Themes quadrant, which comprises well developed but fewer central issues. These subjects point to the need for continued research into specific uses of smart farming technologies, especially in rural regions. A growing interest in resource-efficient farming methods and environmental monitoring is indicated by the inclusion of sustainability and detection methods. Even though adoption studies may not focus on these issues now, their growing significance raises the possibility that they will eventually be incorporated into more general study.

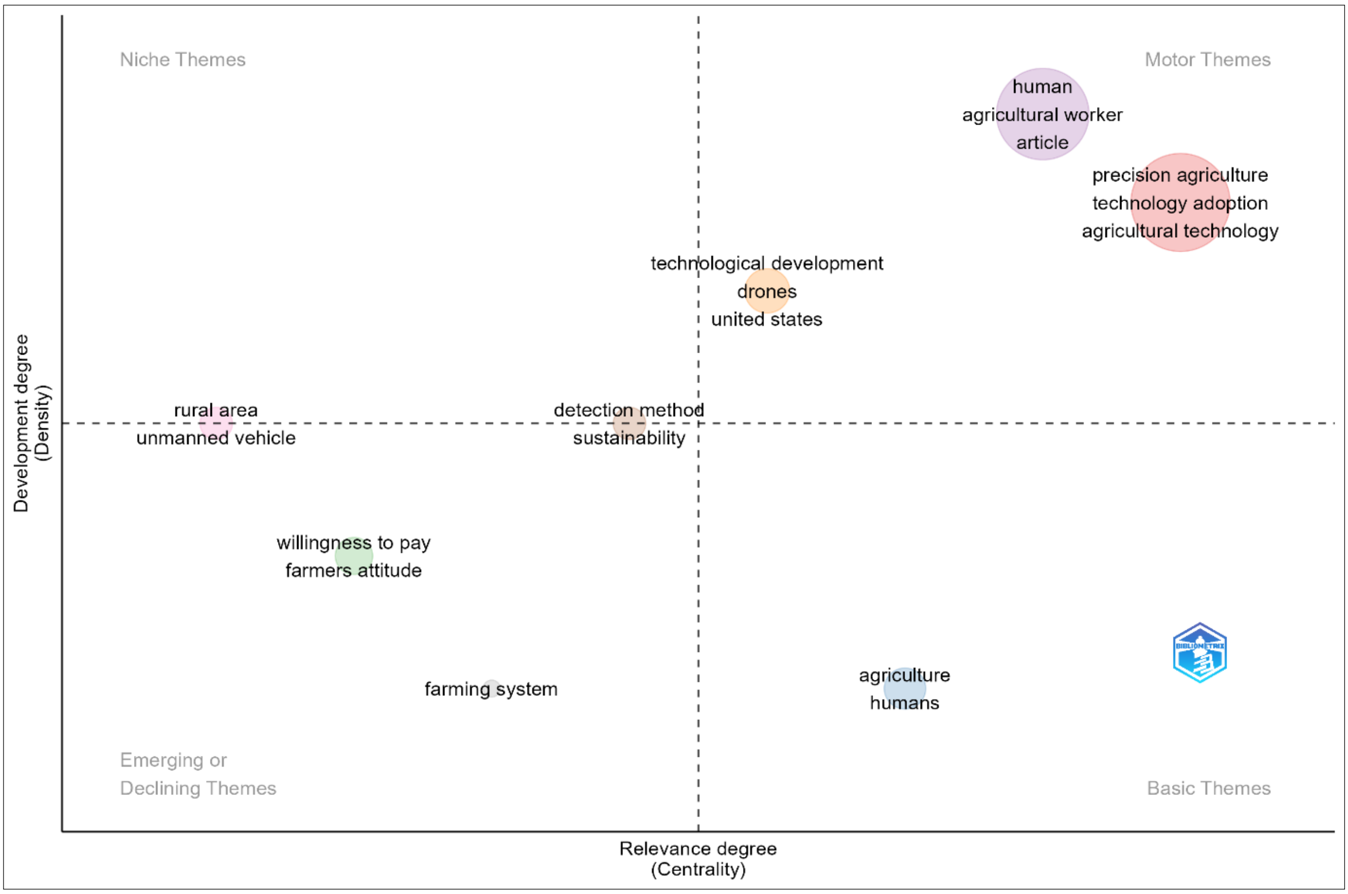

Fig. 5. Thematic mapping of key research areas in smart farming technology adoption.

Humans and agriculture are included in the Basic Themes quadrant, which encompasses basic but underdeveloped subjects. These themes show that although agriculture continues to be the main area of study, conversations about how human factors affect the adoption of technology are still in their infancy. This point to a possible gap in the literature, indicating that further study is required to comprehend how farmers use, view and incorporate smart farming technologies into their routine farming operations. Closing this gap may help us understand the psychological and behavioural aspects that affect adoption rates.

Topics including farmers' attitudes, farming systems and readiness to pay are noted in the Emerging or Declining Themes quadrant. These themes point to a growing understanding of the role that behavioural and economic considerations play in the uptake of smart farming technologies. Their positioning in this quadrant, however, suggests that these elements are either new fields of study or subjects that are losing steam. Given the significant importance of financial considerations and behavioural attitudes in technology adoption, future study should further explore these aspects. Research should specifically investigate how financial constraints, cost-benefit analyses and economic incentives affect farmers' propensity to invest in smart technologies.

The adoption of smart farming technology has several facets, including technical, economic and socio-behavioural viewpoints, as the thematic distribution highlights. The comparatively underdeveloped themes pertaining to farmer attitudes and willingness to pay suggest a possible research gap in understanding adoption barriers, even though the dominance of precision agriculture and technology adoption in the Motor Themes quadrant suggests that technological advancements are at the forefront of research. A more comprehensive strategy that considers adoption's economic and social determinants in addition to technological viability is needed to close this gap.

Future studies should concentrate on filling up these gaps by examining how cost-benefit analysis, subsidies and financial incentives affect adoption choices. Furthermore, studying agricultural workers' education, training and digital literacy might shed light on how to improve technology integration. Additionally, investigating legislative frameworks and government initiatives will be crucial to fostering an atmosphere that encourages the use of smart farming. Finally, evaluating the long-term sustainability effects of smart technology and precision agriculture can assist guarantee that these developments are in line with more general environmental and financial objectives.

Precision agriculture and technical improvements emerge as the main themes of the thematic analysis, which identifies important research directions in the use of smart farming technology. Future study has a lot of potential because economic, behavioural and policy-related issues are yet largely unexplored. The broad implementation of smart farming technology in contemporary agriculture will require a comprehensive strategy that combines technological advancement, economic viability and societal acceptance.

Key factors influencing the adoption of smart farming technologies

A wide range of factors from different geographic and socioeconomic contexts influence the adoption of Smart Farming Technologies (SFTs). A review of the literature reveals several important elements that impact adoption, such as technological features, financial considerations, institutional support, sociodemographic traits and behavioural attitudes.

1. Technological Factors

The adoption of Smart Farming Technologies (SFTs) is heavily influenced by technological considerations. Numerous technological obstacles prevent the broad implementation of these technologies, even though they provide notable improvements in automation, data-driven decision-making and precision agriculture. Perceived complexity, usability problems, system integration hurdles and data infrastructure constraints are the main issues noted in the literature. These obstacles make farmers reluctant to use SFTs, especially in areas with low levels of technical know-how and digital literacy.

Complexity and usability: A major technological barrier

The intricacy of smart farming technologies is a major obstacle for farmers. Research shows that farmers, especially those who lack technological expertise, find IoT, AI and automation technologies challenging to comprehend and operate (38, 39). According to research from Bangladesh and Thailand, where farmers found precision agriculture instruments difficult to use, the effort needed to learn and use these technologies has been a major disincentive (40, 41).

Another common topic is technology concern, especially among older farmers and in developing nations. Millennial farmers in Malaysia and Indonesia were more open to trying out smart agricultural equipment, while older farmers were more hesitant and anxious since they were not accustomed with digital systems (42, 43). This implies that focused digital literacy initiatives are needed to address the disparities in technology usage between generations.

Even if user-friendly interfaces are becoming more widely available, several studies stress the necessity of simplifying and tailoring SFTs to farmers' requirements. The creation of more user-friendly, localized and language-friendly interfaces is a major suggestion from the literature, especially in areas where English is not the primary language (39). Adoption rates are considerably slowed down by the perceived difficulty of learning new technology and the lack of suitable training programs.

System integration and compatibility: Challenges with existing farming practices

The challenge of incorporating SFTs into conventional farming systems represents another important technological obstacle. Since current farming infrastructure and equipment are frequently not made to integrate seamlessly with digital technology, farmers regularly face compatibility problems (44). This issue is especially common in cattle production, where research conducted in New Zealand revealed that automated tracking systems and smart feeders needed extra adjustments to conform to conventional management procedures, deterring uptake (44).

Furthermore, interoperability issues are still a big worry because farmers frequently employ a variety of digital products from various manufacturers that don't communicate well with one another (45). Farmers must manually compile and evaluate data from several sources due to operational inefficiencies caused by the lack of standardization across smart farming devices. Poor interoperability dramatically raised farmers' discontent and reluctance to make more investments in digital technologies, according to a study on precision agriculture applications conducted in India and the USA (45).

Adoption is further hampered by worries about the long-term viability and dependability of smart technologies. Ecuadorian farmers were hesitant because they were worried about how long IoT-based sensors and precision agricultural equipment would last and that frequent failures or maintenance problems would result in losses (46). To guarantee long-term usability, the literature highlights the necessity of enhancing the smart agricultural devices' dependability, robustness and field adaptability.

Data and infrastructure challenges: The digital divide in smart farming

Real-time communication, data processing and data collection are critical components of smart farming systems. Nonetheless, several studies draw attention to the serious issues with digital infrastructure, data scalability and power consumption that impede adoption.

Processing constraints and data scalability are two main issues. Large volumes of real-time data are produced by many smart farming technologies, necessitating sophisticated processing skills, yet smallholder farmers frequently lack the means to efficiently handle and analyse this data (47). Big data analytics for decision-making has been effectively incorporated into highly digitalized farms in the USA and Germany, but adoption has been hampered in developing nations due to limited access to computational resources and analytical know -how (47).

In rural and isolated farming regions, connectivity problems are another major obstacle. The efficacy of IoT-driven precision agriculture is limited by inadequate broadband infrastructure and a lack of high-speed internet connection, according to many studies from Germany, Ireland and Bangladesh (48, 49). It is challenging for farmers in areas with poor connectivity to completely incorporate smart farming technologies into their operations since they cannot employ remote automation or cloud-based monitoring systems. Trialability, or the capacity to test digital technologies prior to full implementation, was identified as a crucial element influencing acceptance in research conducted in Thailand's food supply chain (50).

Power consumption is another neglected problem that raises farm operations' expenses. An additional cost and logistical burden results from the fact that many IoT-based agricultural tools need constant energy or battery power (47). Farmers find it challenging to maintain sensors, automated irrigation systems and drones in remote locations with erratic electrical supplies, which makes them prefer more conventional, non-digital farming practices.

To overcome these obstacles, experts recommend building low-power IoT solutions that can operate efficiently with less energy consumption and growing rural digital infrastructure to facilitate automation and real-time data transfer (45, 48).

Economic and financial factors

Financial and economic considerations are key determinants of how Smart Farming Technologies (SFTs) are adopted. Farmers are frequently deterred from using these technologies by their high initial costs, ongoing maintenance requirements, financial limitations and market uncertainty, even though they offer long-term efficiency and productivity improvements. Major financial obstacles have been found by researchers in several studies, including capital investment, operating costs, loan availability and profitability issues. These sections examines these issues critically as well as how lease options, government assistance and financial incentives can help to lessen them.

High initial investment and maintenance costs

Purchasing smart equipment requires a large upfront expenditure, which is one of the biggest financial obstacles to SFT adoption. According to studies, large upfront expenditures pose significant challenges, especially for small and medium-sized farms that lack the funds to engage in cutting-edge technologies (51, 52).

Adoption is further discouraged by operating and maintenance costs, which go beyond the initial expenditure. IoT sensors, automated irrigation systems and precision agriculture equipment are examples of smart farming technology that demand ongoing financial investment for upkeep, software upgrades and training initiatives (53). Frequently, the expense of maintaining and improving machinery creates an ongoing financial strain, which deters farmers with limited resources from adopting new technologies.

The cost-benefit ratio and return on investment (ROI) uncertainty are two more significant issues. According to research, farmers are hesitant to make digital tool investments when the financial returns are uncertain or take time to materialize (54, 55). Even though precision agriculture is known to increase productivity and optimize production, research indicates that farmers find it difficult to estimate the short-term financial gains from implementing these technologies. Many people are deterred from making significant investments by the perceived risk of financial loss.

Financial constraints and support mechanisms

Another significant financial obstacle keeping farmers from implementing SFTs is limited access to finance and credit facilities. Many smallholder farmers lack the capital or financial knowledge needed to obtain loans for investing in contemporary technologies, especially in developing nations (56, 57).

To lower financial obstacles, government intervention is essential. Government financial incentives and subsidies greatly increase the adoption of smart farming technologies, according to studies conducted in China, Vietnam and Saudi Arabia (39, 58, 59). For instance, government-sponsored financial aid initiatives in China have significantly increased farmers' adoption of IoT (58). Like this, government initiatives in Vietnam that offer financial assistance and tax breaks have aided smallholder farmers in using digital tools into their farming operations (39).

Financial limitations, however, continue to be a major problem in areas with irregular or non-existent government assistance. Research indicates that farmers in South Asia and Africa frequently face difficulties obtaining grants or loans, rendering smart agricultural technologies costly (56, 57). Alternative financing structures, like cooperative funding and leasing schemes, have been suggested as workable remedies in these situations. According to Turkish research, farmers prefer leasing SFTs rather than buying them outright since it enables them to utilize cutting-edge technologies without having to pay for them all up front (60).

Market and profitability concerns

Adoption rates are still impacted by worries about market demand, profitability and long-term economic viability, even after farmers have surmounted initial financial obstacles. Research indicates that many farmers view SFTs as financially uncertain investments, especially when they are uncertain if the market would reward digital transformation efforts (61).

For example, studies show that smart farming technologies necessitate a change in conventional farming methods, which might not always be in line with consumer demands and market structures today. Farmers in some areas are reluctant to invest in new technologies due to the absence of established markets for precision-farmed products, which raises questions about profitability (61).

Adoption is also further slowed by worries about competition and market access. Research conducted in Malaysia shows that although automation and drones increase agricultural productivity, farmers are concerned about whether these advancements will give them a competitive edge in the marketplace (62). Many farmers postpone or give up plans to incorporate SFTs into their operations in the absence of guarantees of financial gains.

Social and behavioural factors

The adoption of Smart Farming Technologies (SFTs) is significantly shaped by social and behavioural variables. Trust, awareness, education and social influence are important factors that impact farmers' decision-making processes, even though financial incentives and technology developments aid in adoption. According to the research, farmers frequently put off implementing SFTs because they are resistant to change, lack technological expertise and worry about data security. Adoption trends are also influenced by gender-related inequities, generational variances and peer pressure. These elements and their effects on the adoption of smart farming technology are critically examined in this section.

Trust, awareness and perception: Overcoming skepticism in digital agriculture

Digital technology trust is one of the biggest social obstacles to SFT adoption. Concerns regarding data security, privacy and cloud-based system dependability are frequently voiced by farmers (63, 64). According to studies conducted in the USA and Malaysia, farmers are reluctant to employ precision farming systems and IoT-based agricultural technologies because they are concerned about misuse and illegal access to data (63, 64).

Furthermore, perceived risk and utility have a big impact on adoption. According to research, farmers are more inclined to implement SFTs if they can clearly perceive their advantages, which include higher productivity and cost savings (43, 59). However, adoption rates are still low in areas where farmers view smart technologies as complicated, unreliable, or expensive. For instance, research in Saudi Arabia and Indonesia indicates that farmers' propensity to incorporate smart technologies into their operations is significantly influenced by social influence and perceived risk (43, 59).

The worry of losing one's employment is another major issue. Some farmers fear that as automation and digitization grow, the demand for human labour will decline due to sophisticated smart agricultural instruments, resulting in job losses (65). This is especially noticeable in nations with high rates of traditional agricultural employment. According to studies conducted in Brazil and Germany, farmers oppose automation because they are worried about changes in the labour market and the socioeconomic effects of fewer jobs in rural areas (65). Clear communication about how smart farming technologies can enhance human labor rather than replace it is necessary to allay these worries.

Education, skills and training: Bridging the knowledge gap

Farmers' lack of technical expertise and digital literacy is another significant obstacle to the implementation of SFT. Research from Bangladesh and Hungary shows that farmers who have less education are less likely to use smart farming technologies because they find it difficult to comprehend and use sophisticated digital tools (66, 40).

Adoption rates are greatly increased when training and extension services are available. According to studies conducted in the USA and Belgium, farmers' trust in utilizing smart technologies rises when they obtain the appropriate training through demonstration programs (67, 68). Likewise, research in Malaysia and India highlights the necessity of farmer-focused digital education initiatives to promote adoption (62, 57).

Cooperatives and networks for exchanging knowledge are also essential in helping farmers make the switch to digital agriculture. Research from Italy and Hungary shows that farmers are more likely to adopt smart farming instruments when they participate in peer-driven knowledge-sharing networks (69, 70). Cooperatives can assist small-scale farmers in overcoming financial and technological obstacles by offering shared technology resources, financial support and group learning opportunities.

However, adoption rates are typically lower in areas with weak or non-existent cooperative institutions. Stronger institutional and community-based support mechanisms are necessary since research from Tanzania and Indonesia indicates that rural farmers who do not have access to digital advisory services find it difficult to successfully deploy smart technologies (56, 42).

Social influence and demographics: The role of community and individual differences

One important factor influencing the adoption of SFT is social impact. When farmers observe fellow farmers or the community using new technologies successfully, they are more likely to follow suit (43). Before choosing to invest in digital tools, farmers frequently rely on peer recommendations and experiences, according to studies conducted in Saudi Arabia and Indonesia (43, 59). According to these studies, early adopters have a significant impact on the general acceptance of technology, which makes case studies and on-field demonstrations useful resources for advancing smart farming.

Adoption trends are also influenced by generational disparities. Research from China, Italy and Germany shows that younger farmers are more likely to embrace smart technologies because they are more tech-savvy and willing to try new things (71-73, 58). On the other hand, older farmers frequently oppose the use of digital technologies, citing a preference for conventional techniques, technological complexity and unfamiliarity. Intergenerational training programs are necessary to assist elderly farmers in making the shift to digital agriculture, according to research conducted in Hungary and the USA (66, 67).

Adoption rates are also influenced by socioeconomic status and gender. According to a Tanzanian study, women use smart farming technologies more frequently than men do, mostly because of their participation in digital extension services and financial inclusion initiatives (56). However, studies conducted in Iran and Turkey indicates that sociocultural constraints and limited agricultural land ownership frequently make it more difficult for women to obtain smart farming instruments (60, 73). Targeted policies that support equitable access to financial resources, training and agricultural decision-making are necessary to address gender gaps in technology adoption.

Policy and institutional support

The implementation of Smart Farming Technologies (SFTs) is either aided or hindered by policy and institutional issues. Strong legal frameworks, governmental policies and infrastructure development can greatly speed up the adoption process, even though societal acceptability, financial assistance and technology improvements all have an impact. According to the literature, the key to removing adoption barriers is institutional support, government-backed incentives and research and development (R&D) spending. However, the broad use of SFTs in agriculture is still hampered by deficiencies in infrastructure, regulatory harmonization and policy execution. The contribution of institutional frameworks, research initiatives and government interventions to the adoption of smart farming is critically assessed in this section.

Government policies and support programs: The role of public intervention

Through financial incentives, regulatory laws and subsidies, governments significantly influence the agricultural environment. Strong governmental backing has increased the adoption rates of SFTs by offering financial aid, infrastructural improvements and training initiatives, according to research from China, Vietnam and Saudi Arabia (58, 39, 59).

For example, government-sponsored initiatives in China have effectively raised the adoption of IoT in agriculture through policy-driven digital transformation and subsidized technology prices (58). Like this, Vietnam's agriculture policies have prioritized lowering financial obstacles by providing money for digital farming projects and tax breaks, which has increased the country's adoption of technology (39). Precision farming has been greatly aided in Saudi Arabia by direct government participation in the form of awareness campaigns and financial incentives (59).

Nonetheless, a major obstacle to the implementation of smart farming in some areas is the lack of clear policy frameworks. Farmers in many poor countries are unable to invest in digital solutions due to inconsistent policies and a lack of funding. According to research, governments must develop well-structured regulations to guarantee sustained support for the application of SFT, especially in smallholder agricultural systems (74). Policies should also concentrate on encouraging technology companies to create affordable solutions for small and medium-sized farms.

The absence of standardization in data governance and IoT integration is a crucial problem in policy creation. According to studies, farmers are deterred from implementing smart technology by the lack of explicit regulatory requirements around data ownership, privacy and interoperability (75). Data-sharing procedures remain unclear in the absence of uniform standards, which breeds mistrust of digital instruments. This implies that to increase farmers' confidence in implementing smart farming solutions, governments should set clear regulations on cybersecurity and data governance.

Research, development and innovation: The need for localized solutions

To improve the usefulness, effectiveness and accessibility of smart farming technology, research and development (R&D) activities are essential. However, the efficiency of many SFT adoption models in a variety of farming situations is limited since they do not take regional agricultural variables into consideration (61, 76).

For instance, studies conducted in Brazil and Italy show that existing digital farming models frequently overlook the difficulties faced by smallholder farmers in favour of large -scale commercial agriculture (61, 76). This implies that a more customized strategy is required, one in which intelligent farming solutions are adjusted to the unique climatic, economic and cultural circumstances of various locales.

Furthermore, interdisciplinary and multidisciplinary research methodologies are becoming more and more necessary. To better understand farmers' decision-making processes, studies from Germany and Italy highlight the significance of incorporating behavioural, economic and environmental elements into adoption models (77, 78). Researchers can create thorough adoption methods that tackle both technical and socioeconomic obstacles by taking these elements into account.

The creation of open-access research platforms and knowledge-sharing networks is one of the literature's main recommendations. Many farmers do not have access to localized research and demonstration programs, especially in developing nations. The establishment of regional research centres that concentrate on best practices and adoption trends for smart farming can greatly enhance the transmission of knowledge and promote adoption at the local level.

Infrastructure and institutional support: addressing gaps in digital farming accessibility

It needs strong infrastructure and institutional support for smart farming technology to be implemented successfully. However, several studies point to significant deficiencies in digital connectivity, advisory services and rural infrastructure that impede adoption (45).

Poor rural infrastructure, such as restricted access to electricity, inadequate road networks and minimal digital connectivity, is one of the main problems. According to studies conducted in Africa, Indonesia and India, farmers in distant regions find it difficult to employ IoT-based agricultural products because of erratic power supplies and limited broadband availability (45). Digital farming is less effective without enough infrastructures because farmers cannot use automated irrigation, remote sensing, or real-time data monitoring systems.

Adoption is further deterred by restricted access to advising and extension services. According to research from the USA and Belgium, farmers are more inclined to incorporate smart technologies into their operations if they obtain expert advice and training (68, 67). Nonetheless, agricultural advising services are still in their infancy in many areas, depriving farmers of the assistance they need to make the switch to digital agriculture. To educate farmers and give practical demonstrations of smart farming instruments, it can be extremely beneficial to expand government-backed agricultural extension programs.

Another crucial tactic for enhancing institutional support and infrastructure is public-private partnerships or PPPs. Research from Germany and Malaysia shows that successful smart agricultural projects have resulted from cooperation between government organizations, private sector technology suppliers and academic institutions (79). To create affordable digital solutions, subsidize equipment purchases and extend digital infrastructure in disadvantaged areas, governments might collaborate with private businesses.

Conclusion

Modern agriculture is undergoing a radical change with the implementation of SFTs, which provide data-driven solutions to improve resource efficiency, sustainability and production. Global research trends are systematically evaluated by this bibliometric analysis, which also identifies important adoption barriers like legislative support, societal perceptions, budgetary limitations and technological complexity. The report draws attention to regional differences, showing that while affluent countries are making rapid progress, emerging regions are struggling with affordability and infrastructure. The results highlight how important institutional support; government policies and interdisciplinary cooperation are in promoting the adoption of SFT. This study adds to the current conversation on digital agriculture by providing a deeper understanding of research networks and topic trends through bibliometric coupling and keyword co-occurrence analysis. Targeted financial incentives, better farmer training and the creation of user-friendly technologies are all necessary to address adoption issues. To improve accessibility and implementation, more robust policy frameworks and public-private partnerships are also required. To guarantee the fair integration of SFTs in various agricultural contexts, future studies should concentrate on localized adoption models, sustainable finance and adaptable legislation. SFTs can enhance global food security and economic stability by bridging current gaps and utilizing technological breakthroughs to create a more resilient, sustainable and efficient agricultural industry.

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Authors' contributions

KPT conducted the survey, analysed the data and wrote the manuscript. SM supported the generating ideas, data collection and analysis during the research study. MR contributed to data collection, reviewing the manuscript and assistance. SPA assisted with summarizing and revising the manuscript. VG assisted in summarizing and offering additional support and contributions to the research study. All authors read and approved the final manuscript.

Compliance with ethical standards

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