Data-driven solutions for farmer empowerment in smart agriculture: challenges and opportunities

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Abstract

The adoption of digital technologies in agriculture offers significant potential to enhance productivity, sustainability, and resilience. This paper presents initial insights derived from an ongoing study aimed at evaluating the challenges and opportunities for farmers in adopting data-driven solutions. During the initial phases, the study utilised an online workshop with 46 participants from various agri-stakeholder groups to conduct a comprehensive PESTLE analysis, exploring the political, economic, social, technological, legal, and environmental factors influencing the adoption of data-driven solutions in agriculture.

Key findings indicate that cohesive governmental policies, innovative business models, and targeted educational initiatives are essential for fostering digital transformation in agriculture. Political and regulatory challenges such as aligning cross-border data sharing frameworks and ensuring consistent policy implementation must be addressed. High costs and technical knowledge requirements are substantial economic barriers, particularly for smallholder farmers, necessitating tailored financial support and cooperative business models. Socially, the digital divide and trust issues in data security highlight the need for equitable infrastructure distribution and trust-building measures. Technological advancements like IoT and blockchain offer opportunities but require robust data governance and cybersecurity frameworks. From a legal perspective, simplifying regulatory compliance and clarifying data ownership are crucial for facilitating adoption. While digital agriculture practices support sustainability goals, environmental risks such as electronic waste and increased carbon footprint need careful management.

The insights gathered from diverse agri-stakeholders provide an understanding of the factors impacting digital transformation in agriculture. This research contributes to understanding the specific barriers faced by farmers in adopting data-driven solutions and offers actionable recommendations for creating inclusive and effective data-driven agricultural initiatives.

Keywords: smart farming, digitisation, smallholder farmers, technology adoption, climate resilience.

1. Introduction

Smart agriculture is revolutionising traditional farming practices by leveraging advanced technologies to optimise agricultural processes. The integration of various technologies such as cloud computing, remote sensing, big data analytics, and the Internet of Things (IoT) can potentially enable data-driven decision-making, enhance crop yields, and improve the quality of food products (Wolfert et al., 2017). The essence of smart agriculture lies in its data-driven approach, where data management and smart analytics play pivotal roles in supporting critical decision-making processes (Wolfert et al., 2017). The utilisation of Artificial Intelligence (AI) and Machine Learning (ML) algorithms further enhances the monitoring and efficiency of agricultural operations, contributing to improved ecological outcomes (Gupta et al., 2023). Despite the significant potential benefits, the adoption of smart farming technologies is not without challenges. Farmers, especially smallholders, face numerous obstacles, including climate change, low commodity prices, environmental degradation, and limited access to resources (Jiménez et al., 2019). Moreover, the acceptance and trust of farmers in these technologies are crucial for their successful implementation (Schukat & Heise, 2021).

Understanding the unique challenges and opportunities specific to farmers is vital in the context of smart agriculture. Most smart farming research focuses on technological advancements and their potential impacts on agricultural productivity, often overlooking the complexities involved in the adoption process from the farmers' perspective. This gap is particularly pronounced for smallholder farmers, who constitute a significant portion of the global farming community (FAO, 2021).

This study aims to address this gap by conducting a thorough exploration of the challenges and opportunities based on insights gathered from an online workshop involving diverse agri-stakeholders, including agricultural professionals, researchers, data scientists, policymakers, farmers, educators, agribusiness representatives, and students. Utilising a PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) analysis, this research examines the external factors influencing digital transformation in agriculture. The insights gained from this analysis provide valuable guidance for policymakers, industry leaders, and other stakeholders in crafting strategies to support the digital transformation of agriculture.

2. Methodology

2.1. Participants and Stakeholders

The online workshop was held, with a total of 46 participants joining out of 60 registered individuals. The participants represented a diverse array of agri-stakeholders, including agricultural professionals, researchers, data scientists, policymakers, farmers, educators, agribusiness representatives, and students. The diversity of the cohort allowed for obtaining a comprehensive perspective on the adoption of data technologies in agriculture. Participants registered by providing their names, email addresses, institutional affiliations, and occupation statuses.

2.2. Workshop Design, Data Collection and Data Analysis

The workshop was conducted using Microsoft Teams, with a Miro Board integrated to facilitate interactive activities and collect real-time feedback. The agenda was designed to ensure maximum engagement and effective data collection. The core of the workshop consisted of a brainstorming session focused on the PESTLE analysis. Participants added their own suggestions of challenges and opportunities related to each factor. The session concluded with discussions on future steps and closing remarks. The Miro Board captured all participant inputs during the brainstorming and discussion sessions. The data collected from the Miro Board was subjected to thematic analysis (Braun & Clarke, 2012). Each frame's content was reviewed to identify common themes and significant factors within each PESTLE category. This qualitative approach ensured that the analysis captured the depth and breadth of the participants' insights. Key themes were synthesised to provide a coherent PESTLE analysis.

3. Results and Discussion

3.1. Political Factors

The digital transformation in agriculture is inherently political, demanding a critical approach that incorporates local contexts and broader political economy perspectives (Benegiamo et al., 2023). Participants identified a significant need for a common contractual framework for cross-border data sharing, emphasising the importance of aligning member states within the European Union (EU) and subsequently expanding this framework globally. Such a framework would facilitate smoother and more secure data exchanges between countries, enhancing the effectiveness of digital technologies in agriculture. This need is supported by literature that underscores the necessity for robust governmental frameworks and enhanced data exchange among stakeholders (Nehrey et al., 2023).

Participants also highlighted that state-protected policies and activities can enhance trust among farmers towards these technologies, which is vital for their widespread adoption. Creating policies that focus on the needs and perspectives of farmers ensures they are practical and beneficial, further facilitating adoption. Literature supports this argument, noting the pressing need for comprehensive laws, regulatory frameworks, and public-private cooperation to foster trust and market structure (Kosior, 2020). Existing voluntary codes of conduct, like the EU Code of Conduct on agri-data sharing, offer guidance but highlight the need for modernised regulations to address data privacy and security issues (Kaur & Dara, 2023).

Participants identified the importance of partnerships with governmental agencies and policymakers in advancing digital transformation in agriculture. Participants indicated that many incentives provided by governments have the power to encourage farmers to adopt digital technologies. Subsidies and grants can reduce the financial burden of investing in new technologies, addressing one of the main reasons farmers hold back. Additionally, it was mentioned that some governments have introduced digital notebooks to track crop data, which help maintain records of crop activities and data, facilitating better decision-making and compliance with agricultural standards.

Despite these potentials, key policy challenges involve issues of data ownership, control, access to technology, and data security. Addressing these requires reshaping the political and economic landscape to ensure equitable agricultural practices, particularly in the context of tensions between digital agri-tech developments and agroecological approaches (Rotz et al., 2019). Moreover, the limitations of digital infrastructure, such as high-speed internet and mobile coverage pose barriers, emphasising the role of policy and investment in overcoming these technical challenges (Knierim et al., 2019).

3.2. Economic Factors

Economic constraints were a major focus of the workshop discussion. High costs and the required technical knowledge associated with digital tools were referenced as significant obstacles for many farmers. Participants noted that high costs and long amortisation processes often mean that by the time technology costs are recovered, the technology might already be obsolete. Literature supports this, highlighting that the high cost associated with adopting robotic technologies and smart farming systems remains a significant drawback, particularly for smallholder farmers (Yépez-Ponce et al., 2023). Farmers are particularly concerned about the return on investment (ROI) when implementing new technologies, as the scarcity of relevant on-farm examples and intangible benefits, such as simplifying farming tasks or increasing enjoyment, complicates ROI calculations (Yépez-Ponce et al., 2023). This uncertainty can reduce lenders' willingness to finance large technology investments due to the perceived high risk for early adopters, leading to inhibited or delayed financing (Eastwood et al., 2023).

Participants also mentioned that cooperation in sharing technologies can reduce costs, and aggregated data can provide better decision support, leading to efficiencies and risk management (Jakku et al., 2019; Regan, 2019). However, in case of cooperation, the literature indicates that farmers fear that competitors might use their data to outbid them in markets for land and other resources, that agribusinesses could target marketing efforts more effectively, and that governments might impose stricter regulations (Rozenstein et al., 2024). Even if issues of data ownership, privacy, and standardisation are resolved, economic and social constraints such as the lack of demonstrated value, mistrust of data aggregation organisations, and the cost of adopting new technologies will persist (Rozenstein et al., 2024). While anonymisation has facilitated data sharing in other sectors, anonymising farm field data is challenging due to the unique field signatures provided by soil type, yield maps, and other spatial information. Thus, anonymisation by a trusted organisation is essential, but financial or other incentives are necessary to motivate data collection (Rozenstein et al., 2024).

Participants raised concerns about the economic viability of products from startups, highlighting the challenges new entrants face in establishing financially sustainable operations. Literature shows that while there are inspiring examples of startup companies providing digital technologies to smallholder farmers in developing countries, such as the "Uber for Tractors" initiative, there is widespread concern that digital agriculture may enhance the market power of large agribusiness enterprises (Birner et al., 2021). Non-governmental organisations have expressed concerns that access to extensive data from numerous farmers could reinforce existing trends of concentration in the input industries, enabling manufacturers to optimise machinery costs and gain competitive advantages (Birner et al., 2021). Additionally, these manufacturers might exploit this information for pricing strategies, increasing their profit margins at the expense of farmers.Additionally, participants highlighted the importance of utilising market analytics to help farmers make informed decisions and gain monetary benefits. It was stated that the current business models do not generate sufficient income to justify the high costs of digital technologies, making them particularly prohibitive for smallholder farmers. Innovative business models, such as technology cooperatives or subscription-based services, could mitigate these issues by spreading costs and risks among multiple users.

Participants discussed the potential economic value of data. The economic value of information technologies hinges on the decisions altered by access to new information, which can be challenging to quantify as it requires comparing decisions made with and without the new information. The availability of economic incentives and financial support mechanisms was seen as essential to promoting the adoption of digital technologies. Financial support for research and development (R&D) and the availability of grants for tool implementation and training opportunities were also highlighted as crucial incentives that could drive adoption. These incentives should be designed to be more accessible and targeted towards the unique needs of all scales of farmers.

3.3. Social Factors

The social environment plays a crucial role in the adoption of digital technologies in agriculture, encompassing cultural attitudes, social norms, and equity issues. Participants in the workshop highlighted that cultural attitudes and social norms significantly impact the acceptance and integration of digital technologies. Educating local farmers and communities about the benefits of sustainable farming was seen as essential to enhancing this acceptance. However, there is a prevailing uncertainty and resistance among farmers regarding the trustworthiness of digital advice compared to traditional 'in the field' decisions. Literature supports this, noting that farmers often value traditional practices and peer recommendations over external directives, showing greater trust in data generated on their own farms (Eastwood et al., 2023; Jiménez et al., 2019).

A major barrier identified is the low level of trust in data security, with many farmers fearing that digital technologies might compromise their privacy. This is corroborated by studies indicating widespread discomfort among farmers with data sharing and concerns over the lack of transparency and control over their data (Wiseman et al., 2019; Falcão et al., 2023). Additionally, the unequal distribution of digital infrastructure and resources in rural areas exacerbates the digital divide. The World Bank's 2021 report highlights the critical need for rural broadband expansion to support digital agriculture. This divide is further deepened by generational differences, with younger farmers being more open to new technologies than older generations, and by gender inequities, which worsen existing disparities in agriculture (Kaur & Dara, 2023; Birner et al., 2021).

There are also concerns about the potential impact of digital agriculture on job roles and the overall number of jobs in the agricultural sector. Automation could shift farm work from hands-on activities to more management-focused tasks, potentially altering the sector's job landscape (van der Burg et al., 2019; Eastwood et al., 2023; Regan, 2019). Moreover, the increasing market power of large agribusinesses through digital agriculture could exacerbate the divide between different types of farms and regions. Nonetheless, public initiatives and the involvement of new actors could help mitigate these threats and promote equitable access to digital technologies (Birner et al., 2021).

For smallholder farmers, trust issues with agri-tech providers and a lack of clearly defined roles for data intermediaries pose significant barriers. However, fostering an open-minded mentality and self-awareness among farmers regarding new digital solutions can drive adoption.

Addressing these social barriers requires innovative approaches that consider ethical dimensions and ensure technology development and governance systems are inclusive and reflective of all stakeholders' needs, particularly small-scale farmers in developing regions (Eastwood et al., 2023). By fostering trust, transparency, and equitable access, the digital transformation in agriculture can be directed towards more inclusive and socially just outcomes.

3.4. Technological Factors

Participants identified technological innovations as offering unique advantages for improving agricultural productivity and efficiency. The potential for enhanced efficiency and improved quality of agricultural production through digital technology has been widely recognised in the literature, leading to increased awareness among farmers about the benefits of integrating computer and IT networks into their production processes (Yao & Sun, 2023).

Robust modelling based on weather and soil data, mentioned by the participants, can improve farm sustainability by optimising input usage and managing risks. Providing precise data to farmers through advanced data analytics and modelling techniques enhances decision-making, ensuring more sustainable agricultural practices (Fielke et al., 2019; Jakku et al., 2019). For instance, integrating weather station data was highlighted as a significant enhancement of agricultural productivity by providing farmers with precise information for critical decision-making. Participants also noted that IoT sensors are a vital innovation, allowing for the monitoring of various agricultural parameters such as soil moisture, crop health, and environmental conditions. Blockchain technology emerged as a valuable tool for ensuring transparency in agricultural processes, from farm to table, according to the participants. Automated technologies that require minimal maintenance, labour, or technical knowledge were discussed as ways to streamline agricultural operations, making them more efficient and less dependent on human intervention. However, significant disparities exist among agricultural producers in terms of their technological development, financial capabilities, and resource quality, creating substantial constraints on the widespread adoption of digital technologies in the sector (Kurnosova et al., 2021). Farmers may also struggle to access up-to-date and reliable technology performance reviews, further hindering the adoption of new technologies (Ingram et al., 2022).

Participants pointed out a lack of interoperability between agriculture and other industries. They stressed the importance of developing interoperable systems that enable communication and data exchange between different agricultural technologies and platforms to create a cohesive agricultural ecosystem. Inadequate data infrastructure, particularly in regions with fragmented smallholder farms, where public policy and access to digital infrastructure are insufficient, is a key barrier (Kaur & Dara, 2023). Participants also identified a low level of trust in data security and interoperability obstacles between on-farm machinery and data transfer between providers as major issues. Insufficient standards on data governance highlight the need for robust ethical frameworks for data exchange, ensuring data integrity and security. This is supported by literature, which notes that technical issues related to data quality, transfer, privacy, and ownership pose significant challenges at multiple scales, impacting the seamless integration and utilisation of digital technologies (Ingram et al., 2022; Eastwood et al., 2023). Developing new models of data ownership and governance that are transparent and inspire trust is vital. This includes the use of interoperable standards, publicly funded development of analytic tools, and responsible innovation approaches that incorporate ethical considerations (Eastwood et al., 2023).

Concerns about how collected data are stored and who has access to them were paramount among the participants. They noted that agricultural data might reveal sensitive personal information, such as farmers' financial situations, leading to privacy risks. To address these concerns, participants suggested the need for mediators between technological solutions and end-users, ensuring that privacy and security issues are adequately managed. Technical limitations and compatibility issues can hinder the seamless integration of digital tools across different farming systems. Literature suggests that this digital divide is exacerbated by differences in digital knowledge and expertise between agri-tech providers and farmers. Ag-tech providers, possessing advanced skills in collecting, aggregating, and analysing farm data, can dominate the establishment of processes and protocols, leading to power imbalances (Kaur & Dara, 2023). The performance and design of digital technologies must be robust enough to withstand on-farm conditions and align with farming practices (Eastwood et al., 2023). Cybersecurity vulnerabilities and data privacy concerns were also mentioned as significant risks to the integrity and reliability of digital agriculture systems. Participants, especially smallholder farmers, highlighted the significant risks from cyber-attacks, which can compromise farms' data and operations. Compliance with technical standards was identified as another barrier, as many small farmers find it difficult to understand and follow these standards. Participants stressed that technologies need to be both economically viable and easy to use, ensuring that smallholder farmers can see a tangible economic payback.

Developing a trust framework that is easy to understand and implement is essential to foster confidence among smallholder farmers in adopting digital technologies. Finally, poor internet connectivity in rural areas was noted by participants as a challenge that further exacerbates these issues. Literature supports this argument, noting that the lack of reliable rural internet access remains a critical challenge, as most data-driven agricultural technologies depend on robust internet connectivity, which is often sporadic or non-existent in many rural areas (Rozenstein et al., 2024).

3.5. Legal Factors

During the workshop, participants discussed various legal factors, highlighting the importance of regulatory frameworks, intellectual property rights, and data governance in enabling digital transformation in agriculture. They emphasised that ensuring regulatory compliance is not just about adherence but also about fostering an environment that encourages ongoing innovation in the agricultural sector. Adherence to local, national, and EU regulations, particularly in data handling and agricultural practices, is essential for protecting the innovation and adoption of digital technologies in agriculture. Compliance with these regulations ensures that digital practices are legally sound and can be safely integrated into existing agricultural systems. Literature further emphasises this, noting that the legal dimension of digital transformation in agriculture encompasses several challenges, primarily revolving around the protection and management of agricultural data. A significant hurdle is the absence of comprehensive regulatory frameworks for safeguarding farm data, often leading to terms of use being established through complex and potentially biased data license agreements (Kaur & Dara, 2023; Wiseman et al., 2019).

Participants highlighted those differences in data privacy regulations between Europe and other continents further complicate compliance, leading to challenges in managing data across borders. Literature supports this by pointing out that legislation often lacks clarity, particularly in distinguishing between data production and intellectual property rights related to information systems derived from that data (Ellixson & Griffin, 2017). Participants stressed the importance of clarifying data ownership—whether it belongs to the farmers or the agri-tech companies—to mitigate legal risks and ensure compliance. The ongoing nature of data streams complicates the establishment of ownership and usage rights, making it challenging to contract and manage these resources effectively. Data ownership disputes further complicate the landscape, with various sectors and stakeholders claiming ownership while having differing needs and interests (Rozenstein et al., 2024). The intertwining of private and commercial data, especially in family-run farms, adds another layer of complexity, as personal financial records and business data often overlap, raising privacy concerns (Brown et al., 2023). This ambiguity can hinder the buying, selling, sharing, and management of agri-data.

Workshop participants noted that complex regulatory requirements and a lack of clear guidance act as significant barriers, making it difficult for farmers to navigate the legal landscape. Simplifying these regulations and providing clear, accessible information can help farmers embrace digital technologies more readily. There is a pressing need for standardised, ready-to-use data sharing contract templates that farmers can utilise to protect their rights and facilitate smooth transactions. These templates can reduce the complexity of legal agreements and provide clear guidelines for data usage and sharing. Such frameworks, participants noted, facilitate international collaboration and data exchange, enhancing the global applicability of digital agricultural technologies. Literature supports this argument, highlighting the development and enforcement of legal frameworks that govern the collection, sharing, and usage of farm data as crucial to encouraging the adoption of smart farming technologies among farmers (Wiseman et al., 2019). Another issue discussed in the workshop is the context-dependent value of data. Data that might seem insignificant to one actor could be invaluable to another, creating obstacles in persuading stakeholders to share their data without clear compensation mechanisms (Kenney et al., 2020). The value of agri-data is complex and yet not clearly defined or measurable in literature. Additionally, the spatial component of agricultural data, essential for adding value through geolocation, can inadvertently disclose sensitive information about individual farms, posing additional privacy risks.

Participants also mentioned that establishing specific data standards and protocols could ensure compliance with regulations and facilitate data sharing and product traceability within the food chain, which is vital for maintaining the integrity and trustworthiness of digital agricultural practices. Positive incentives for data sharing, coupled with advanced legislation, could enable the utilisation of accumulated agricultural data for the public good (Rozenstein et al., 2024). Therefore, a trust-reinforcing regulatory framework is imperative for effective farm data gathering, sharing, and analysis.

3.6. Environmental Factors

Participants discussed both the potential benefits for sustainability and the environmental risks and challenges that digital technologies might entail. Precision agriculture, involving the use of digital tools to minimise inputs such as water, fertilisers, and pesticides, was cited as a method to significantly reduce the overall environmental footprint of farming activities and maintain biodiversity. They also pointed out that monitoring and optimising energy consumption can lead to more sustainable farming operations. Efficient use of resources like water and fertilisers not only conserves these vital inputs but also supports more sustainable farming practices. Additionally, digital tools can help farmers adapt to changing climatic conditions by providing timely information and forecasts, enhancing their resilience to climate change. Preventing desertification was highlighted as another significant benefit, with digital technologies able to monitor soil health and manage land use more effectively.Karunathilake et al. (2023) supports the argument by stating that precision agriculture demonstrates the potential of using technology to manage spatial and temporal variability in agricultural fields, enhancing performance and environmental quality. Site-specific management practices enable more accurate decision-making per unit area and time, which conserves agricultural inputs, reduces costs, and mitigates environmental impacts. Digital agriculture is often perceived as innovative and modern, with societal recognition of its potential to improve environmental stewardship

(Fielke et al., 2022; Eastwood et al., 2023). Enhanced food system traceability methods also facilitate the certification of goods based on their environmental performance or the sustainability of their production practices. The benefits of digital transformation extend beyond individual farms, creating broader environmental advantages that justify public policy support. The reduction in monitoring costs and ensuring that environmentally beneficial practices are applied have expanded the range of agri-environmental policy options (Weersink et al, 2018). Public policies play a crucial role in maximising these external benefits, ensuring that digital agriculture contributes positively to environmental sustainability while addressing the concerns and challenges faced by farmers.

Despite these benefits, participants acknowledged that the widespread use of digital technologies in farming can also pose environmental risks and lead to unintended consequences. One primary concern is the increase in electronic waste resulting from the higher usage of digital devices. The production and disposal of these devices contribute to the carbon footprint, and the energy consumption required for digital infrastructure can have an unintended environmental impact. Changes in the farming landscape, such as the encouragement of larger, more uniform fields, might result from the implementation of digital technologies. Participants also expressed concerns that over-reliance on digital solutions may lead to the loss of unique local farming knowledge, which is valuable for maintaining diverse and resilient agricultural practices. There were also concerns among farm groups about the potential misuse of data by environmental groups or regulatory agencies to penalise farms for non-compliance with regulations, particularly in nutrient management. However, data can also help farms demonstrate compliance with sustainability certifications more accurately, thereby reducing litigation risks (Coble et al., 2016). Environmental threats and climate-related challenges can disrupt agricultural production systems and undermine the effectiveness of digital interventions. Extreme weather conditions, such as floods, droughts, and storms, can damage digital infrastructure and limit the effectiveness of digital tools. Climatic suitability is crucial, as some digital devices may not function effectively in extreme conditions, limiting their usefulness. These climate extremes pose a direct threat to the reliability and functionality of digital agricultural technologies.

4. Conclusions

This study utilised an online workshop with 46 participants from various agri-stakeholder groups to conduct a comprehensive PESTLE analysis of the factors influencing the adoption of digital technologies in agriculture. The analysis revealed multifaceted challenges and opportunities across political, economic, social, technological, legal, and environmental dimensions. The workshop highlighted the necessity for cohesive and farmer-centric policies, innovative and accessible business models, and targeted education and support to bridge the digital divide. The importance of robust data governance, clear regulatory frameworks, and sustainable practices was also emphasised.

Key takeaways from the workshop include the need for governments to harmonise cross-border data sharing frameworks and develop cohesive policies that involve stakeholders at all levels in the decision-making process. Providing targeted incentives, such as subsidies and tax breaks, can encourage technology adoption across various farm sizes. Innovative business models, like cooperative cost-sharing schemes and subscription-based services, can make digital technologies more accessible and financially viable. Investing in rural broadband infrastructure and offering targeted education and training programmes to build digital literacy and trust in data security is essential to bridge the digital divide. Establishing robust data governance frameworks and developing privacy-preserving technologies will ensure data privacy and security, fostering a trustworthy digital ecosystem. Promoting the use of open data can empower farmers with access to valuable climate and market information, enhancing their decision-making capabilities and integration into the emerging data economy.

For smallholder farmers, these measures are particularly critical. Tailored business models, affordable technology solutions, and specific financial support mechanisms can help overcome the unique barriers they face. Additionally, supporting the environmental sustainability of digital agriculture by ensuring proper disposal of electronic waste, minimizing the carbon footprint of digital devices, and preserving local farming knowledge alongside digital innovations is crucial.

In conclusion, addressing these identified challenges holistically will be crucial for fostering a more productive, sustainable, and resilient agricultural sector. The insights gained from this workshop provide a valuable foundation for policymakers, industry leaders, and stakeholders to drive forward the digital transformation of agriculture, ensuring that all farmers, particularly smallholders, can benefit from these advancements.

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