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Practices, Challenges, and Future of Digital Transformation in Smallholder Agriculture: Insights from a Literature Review

Yuyang Yuan and Yong Sun *

School of Public Administration & Institute of Rural Revitalization, Guangzhou University, Guangzhou 510006, China; yyy@gzhu.edu.cn
* Correspondence: sunyong@gzhu.edu.cn

Abstract: Smallholder farmers play a crucial role in global agricultural development. The digital transformation of smallholder agriculture can enhance productivity, increase farmers' income, ensure food security, and promote sustainable rural development. However, existing studies often fail to analyze the holistic nature of this transformation and lack a systematic review of the relevant literature. Therefore, this study aims to provide a comprehensive presentation of the current studies on the digital transformation of smallholder agriculture through logical synthesis and reflective summarization, thereby offering valuable academic insights and practical guidance for the digital transformation of smallholder farming. This study constructs an analytical framework centered on "government–technology–smallholders" using a literature review methodology, systematically examining the main practices, challenges, and future strategies for the digital transformation of smallholder agriculture. Our review reveals that current practices primarily focus on digital agricultural production, rural e-commerce, and agricultural information exchange. We identify key challenges at the government, technical, and smallholder levels, including inadequate digital agriculture policies, limited availability of digital applications, difficulties in adapting uniform technologies to the diverse contexts of smallholders, insufficient resources and endowment among smallholder farmers, significant group disparities, and constraints imposed by social and cultural factors. To enhance the digital transformation of smallholder agriculture, it is essential to improve the supply of policy resources, increase attention to and responsiveness toward smallholder needs, and refine digital governance policies. Additionally, we must develop user-friendly digital applications that cater to the varied digital needs of farmers, reduce access costs, enhance digital literacy, foster an inclusive environment for digital agricultural development, and respect and integrate the social and cultural contexts of smallholder communities. This study deepens the understanding of digital transformation in smallholder agriculture and provides theoretical insights and practical guidance for policymakers, technology developers, and smallholder communities. It contributes to sustainable agricultural development and supports rural revitalization and shared prosperity.

Keywords: smallholder farmers; agriculture; digital transformation; digital agriculture; literature review; rural development; digital inclusion; technology adoption

1. Introduction

Smallholder farmers play a crucial role in agricultural production and ensuring food security worldwide. They are the backbone of agriculture in developing countries [1], with over 98% of agricultural operations in China being run by smallholders. In today's digital society, many countries and regions have promoted agricultural ICT initiatives to support various stakeholders, including smallholders [2,3]. Consequently, the phenomenon of smallholder digitization has gained significant prominence [4,5], attracting the attention of scholars globally. Amid the rapid advancement of digital technologies—ranging from basic technologies such as telephony to medium technologies such as drones, sensors, and smartphones, as well as high technologies, including AI and precision agriculture—these

innovations are increasingly being integrated into the development of smallholder agriculture [6]. Technologies such as the Internet, mobile apps, digital platforms, agricultural big data, IoT, and AI have become essential tools for the digital transformation of smallholder agriculture [7,8]. This transformation represents a vital pathway for enhancing the benefits to smallholder farmers and driving rural development [9–11].

In China, smallholder farmers receive agricultural information through subscriptions to WeChat accounts, effectively reducing their production costs [12]. In South Africa, small farmers are integrating into the global market via the Internet [13]. In both Africa and Asia, smallholders are utilizing agricultural extension services to enhance interaction and organization among themselves [14]. In Kenya and India, the use of mobile technology and SMS for sharing agricultural information has led to increased crop yields [15,16]. Ethiopia is promoting the commercialization of smallholder farming through agricultural hotline services and information systems [17]. In Sri Lanka, mobile phones provide tea farmers with vital information, boosting their productivity [18]. Furthermore, in numerous countries worldwide, digital applications, including mobile agricultural apps, offer scientific support for decision making, enabling farmers to make informed choices regarding agricultural production [19–21]. Overall, the digital transformation of smallholder agriculture enhances productivity and yields long-term pro-poor benefits [22], contributing to the Sustainable Development Goals (SDGs) [23].

Current research has focused on the digital transformation of smallholder agriculture, addressing various aspects such as technology application [7,15], digital literacy [8], policy support [9], and market impact [24]. These studies have provided valuable insights into this phenomenon. However, the digital transformation of smallholder farmers is a complex process involving multiple stakeholders [25], profoundly affecting the economic, social, technological, and institutional domains and their interrelationships [26]. It encompasses all aspects of smallholder farmers' production and daily lives [9], necessitating a holistic perspective and systematic approach to analyze the issue. Existing studies tend to focus on the isolated aspects of digital transformation, often examining the impacts of specific factors without providing a systematic review or comprehensive analysis. Moreover, the few related reviews that do exist lack a thorough presentation of the practices, challenges, and future prospects of digital transformation in smallholder agriculture [27]. This narrow focus limits the understanding of the broader landscape of the agricultural digital transformation for smallholders and hinders the ability to provide well-rounded recommendations and solutions. Thus, there is an urgent need for a systematic literature review that incorporates multiple stakeholders and various factors into a cohesive framework to analyze the digital transformation of smallholder agriculture. This approach will enable a deeper understanding of the current state, challenges, and future trends in this area from a holistic perspective.

To gain a full and deeper understanding of the current state of digital transformation in smallholder agriculture and explore how to promote sustainable development through effective digital strategies, this study constructed an analytical framework of "government–technology–smallholders" based on a literature review methodology. It systematically examined the main practices, challenges, and countermeasures related to the digital transformation of smallholder agriculture. The research questions addressed in this study include the following: (1) a systematic synthesis of the primary practices of digital transformation in smallholder agriculture globally; (2) a comprehensive presentation of the various challenges faced by smallholder agriculture in this digital transformation, analyzed from the perspectives of government, technology, and smallholders; (3) the identification of future pathways for advancing the digital transformation of smallholder agriculture in response to these challenges. The contributions of this study are as follows: (1) it establishes a comprehensive analytical framework that integrates multi-dimensional factors at the governmental, technological, and smallholder levels, providing a theoretical foundation for a holistic understanding of the digital transformation process of smallholder agriculture; (2) through a systematic review of the existing literature, it summarizes the key practices,

challenges, and targeted strategies for the future development of digital transformation in smallholder agriculture.

2. Materials and Methods

This study employed a literature review methodology to provide a comprehensive overview of the current status, practices, challenges, and future development trends of digital transformation in smallholder agriculture. The specific steps are listed below.

Firstly, we conducted a comprehensive literature search by using the Web of Science database, focusing on the core databases to ensure the accuracy and relevance of our search results. While we acknowledged that Scopus, IEEE Xplore, and Google Scholar also contain a wealth of literature, we found that most of the high-quality, closely related studies were duplicates, and IEEE Xplore did not yield any relevant literature. The Web of Science itself encompasses a wide range of academic journals, conference papers, and other scholarly resources, particularly in our field of study, providing highly relevant and rigorously vetted literature. We carefully designed our search keyword combinations to ensure comprehensive coverage of studies related to the digital transformation of smallholder agriculture. Given the complexity of this topic, we used a combination of keywords, including "digital", "digital economy", "digital technology", "Information and Communication Technology", "e-commerce", "smart", and "Internet of Things". These keywords address various aspects of digital transformation, such as digital technology, ICT, e-commerce, smart agriculture, and IoT. Additionally, we included the keywords "smallholder" and "small farmer" to ensure that the search results were directly related to the digital transformation of smallholder agriculture.

Secondly, during the search process, we initially identified 320 articles that appeared relevant. However, to ensure the robustness and reliability of our literature selection, we established a set of strict inclusion and exclusion criteria, as outlined in Table 1. First, we conducted a preliminary screening based on the topics and languages of the literature. We excluded studies that did not directly address the digital transformation of smallholder agriculture, as well as those published in non-English languages due to language constraints. Next, we performed a further screening by evaluating the research methods and processes of the identified articles. We critically assessed each article for methodological quality, looking for any signs of flaws, such as an inadequate sample size, biases in data selection, or a lack of rigor in analysis. Finally, we evaluated the research conclusions presented in the literature. We ensured that articles provided inspirational, practical, and comprehensive findings. To further enhance the quality and relevance of the literature, we performed a refined screening based on the title, abstract, keywords, framework, content, collections and accessibility, etc., eliminating any studies that were unrelated to our research topic, not peer-reviewed, or of low quality. This rigorous process, guided by our established criteria, yielded a more precise collection of 86 closely related documents, providing a solid and reputable foundation for our subsequent analysis.

Table 1. Inclusion and exclusion criteria for article assessment and screening.

Criterion	Inclusion	Exclusion
Relevance to Topic	Articles directly addressing digital transformation in smallholder agriculture	Studies not focused on digital transformation in smallholder agriculture
Language	English articles	Non-English articles
Methodological Quality	Studies with scientific and clear methodologies, and appropriate data collection and analysis techniques	Studies with methodological flaws, such as inadequate sample size, bias in data selection, or lack of rigor in analysis
Research Results Quality	Articles with inspirational, practical, and comprehensive findings	Studies with inadequate or unclear results, lacking essential details or transparency

Table 1. *Cont.*

Criterion	Inclusion	Exclusion
Publication Type	Peer-reviewed journal articles, conference papers, and authoritative reports	Non-peer-reviewed articles and opinion pieces
Relevance to Smallholder Context	Studies specifically targeting or including smallholder farmers or agriculture	Studies focused on large-scale agriculture or other non-smallholder contexts
Accessibility	Articles available through academic databases, libraries, or directly from authors	Articles that are inaccessible due to paywalls, copyright restrictions, or unavailable sources

Finally, we adopted a holistic perspective to summarize and synthesize the selected literature. We systematically organized and reflectively categorized the information according to three dimensions: practices, challenges, and future directions. To ensure scientific rigor and credibility in our analysis, we implemented additional measures such as literature thematic coding and cross-validation. Each piece of the literature was carefully coded according to its primary themes and sub-themes, allowing for easy identification and comparison across studies. Cross-validation was conducted by two authors of this article to verify the accuracy and consistency of the coding, reducing the risk of one author's subjective bias and wrong understanding. Furthermore, the synthesis step involved a meticulous, reflective integration of findings from multiple sources, ensuring that all reasonable perspectives and viewpoints were considered. This comprehensive approach allowed us to present a panoramic view of the digital transformation in smallholder agriculture, leading to a deeper understanding of the current situation, the challenges faced, and the potential future developing directions in this field (Figure 1).
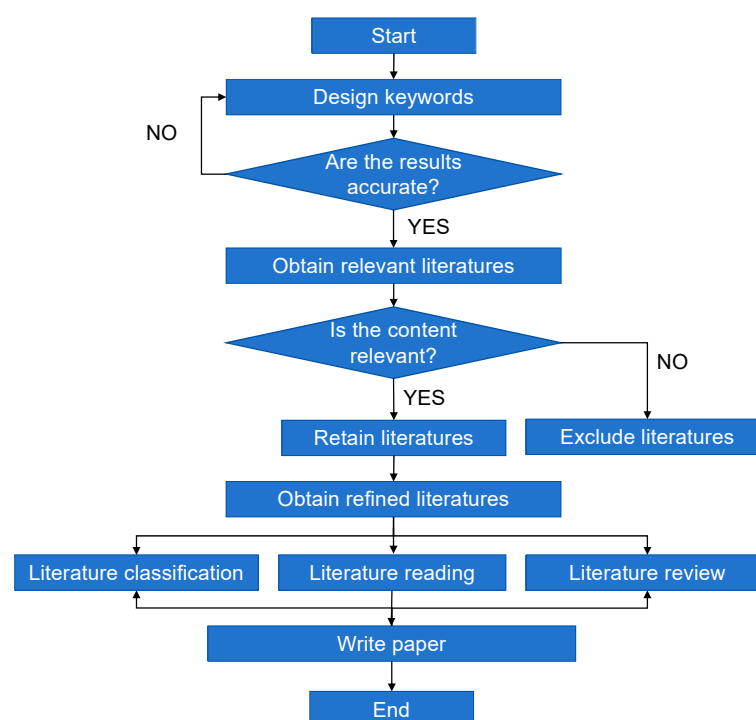

Figure 1. Research methodology.

3. Practices of Digital Transformation in Smallholder Agriculture

Digital technology can facilitate the modernization and transformation of smallholder farmers across various levels of agricultural production, distribution, market dynamics, information, and management [28,29]. A systematic review of the literature reveals that the current digital transformation of smallholder farmers primarily focuses on three key areas:

digital agricultural production, rural e-commerce, and agricultural information exchange. This transformation can be summarized into three broad aspects—production, circulation, and interaction—along with five typical practices (Table 2).

Table 2. Practices of digital transformation in smallholder agriculture.

Area	Category	Typical Example
Digital transformation of smallholder agricultural production	Digital transformation of production tools	Uber-style tractor rental [10]; remote sensing and GPS for field location [30,31]; sensors, smartphones, and soil nutrient mapping to assist smallholders in affordable soil health management [32–35].
	Digital transformation of production decisions	SMS services [36], RiceAdvice, Nutrient Expert, mKRISHI, Pusa Krishi, Agriapp, and other agricultural applications support decision making for smallholders [19,37].
	Digital risk management for agricultural production	Climate-Smart Agriculture and Climate Information Services provide forecasts for extreme weather events such as rainfall, drought, and flooding, as well as alerts for pest outbreaks, helping smallholders mitigate production risks [38–41].
Digital transformation of agricultural distribution	Rural e-commerce model innovation	Digital platforms such as WeChat, TikTok, WhatsApp, Facebook, Twitter, and YouTube allow smallholders to find and expand consumer channels for agricultural products, connecting directly with potential buyers in local, national, and even international markets [42,43].
Digital transformation of agricultural interaction	Digital exchange of agricultural information	Smallholders use digital applications to connect and share agricultural information with other farmers, government officials, experts, and researchers, creating a digital agricultural community [44–46].

3.1. Digital Production: Digital Transformation of Smallholder Agricultural Production

Digital technology enhances input distribution efficiency [12], enables smallholder farmers to optimize their agricultural production processes [47], improves operational efficiency [48], and fundamentally reshapes the methods of agricultural production for smallholders. Consequently, it significantly boosts the overall efficiency of smallholder agricultural production.

(1) Digital transformation of production tools: By leveraging digital tools, smallholder farmers can enhance their production capabilities by replacing outdated, low-productivity equipment with more efficient modern agricultural tools. For instance, information and communication technology can lower transaction costs, enabling smallholder farmers to access high-cost agricultural machinery at reduced rates, such as through Uber-style tractor leasing [10]. Technologies such as remote sensing and GPS can boost productivity and food production by accurately identifying farmland locations [30,31]. Additionally, internet devices and web service platforms can monitor agricultural production environments and planting records [49,50]. Furthermore, tools such as sensors and smartphones, along with soil nutrient mapping, can assist small farmers in achieving affordable soil health management [32–35].

(2) Digital transformation of production decisions: Decision support tools based on electronic information technology can assist smallholder farmers in various agricultural production processes, including planning, sowing, and harvesting [51]. Specifically, smallholder farmers can access information on agricultural production through digital tools such as social media, SMS, and radio, aiding them in making informed production decisions [52–55]. For example, SMS messages containing expert-verified information can support agricultural decision making [36]. Additionally, digital decision-support tools such as RiceAdvice and Nutrient Expert are effective in helping large-scale smallholder farmers adopt scientific nutrient management decisions [37]. Agricultural apps such as mKRISHI, Pusa Krishi, and Agriapp provide valuable advice on soil suitability and crop protection measures, aiding smallholders in making better production decisions [19].

(3)   Digital risk management for agricultural production: Natural risks are undoubtedly the most significant challenge faced by smallholder farmers and serve as major obstacles that hinder agricultural production. Digital tools can enhance smallholder resilience to climate change [56] by enabling farmers to effectively execute agricultural tasks based on weather forecasts [9]. Currently, technologies such as Climate-Smart Agriculture and Climate Information Services provide smallholder farmers with essential weather forecasts, including predictions of extreme events such as rainfall, droughts, and floods, as well as alerts for disease and pest outbreaks. These tools help smallholder farmers mitigate the natural risks they may encounter during agricultural production [38–41] and empower their agricultural practices with digital climate services.

3.2. Rural E-Commerce: Digital Transformation of Smallholder Agricultural Distribution

For a long time, the market reach of traditional smallholder farmers has been limited to local villages and suburban towns, resulting in restricted marketing channels for agricultural products and challenges in integrating them into modern distribution systems. Digital technology can enhance the market efficiency of smallholder farmers by directly connecting them with consumers and improving their price-negotiation capabilities [57,58]. Rural e-commerce significantly expands the market reach of smallholder farmers and facilitates the widespread distribution of their products.

The Internet can specifically address information asymmetries and gaps for smallholder farmers [59], increase information transparency, reduce the need for intermediaries, and create a broad customer base that transcends geographical boundaries [60]. For instance, smallholder farmers can use digital social applications such as WeChat, TikTok, WhatsApp, Facebook, Twitter, and YouTube to connect with potential customers, thereby finding and expanding agricultural sales channels [42,43]. This enhances their access to market information and enables them to gather insights related to the sale of agricultural products. As producers, smallholder farmers can directly engage with consumers in the digital marketplace, facilitating access to a wider array of local, national, and global markets [13,24,55,61]. Consequently, the rural e-commerce model supported by digital technology helps improve the agricultural supply chain for smallholder farmers, broadens agricultural distribution channels, and enhances the bargaining power and profitability of these farmers [60,62–64]. Additionally, smallholder farmers can securely connect with their supply chain partners through blockchain technology [1].

3.3. Information Sharing: Digital Transformation of Smallholder Agricultural Interaction

Access to information is a crucial issue in smallholder agricultural production [16]. The exchange of agricultural information is beneficial to smallholders [65]. Digital technology has greatly expanded the social networks of smallholder farmers, who are increasingly relying on digital tools to share their agricultural experiences and information with a wider audience.

For a long time, the social networks of smallholder farmers have primarily comprised members of their acquaintance networks [66], resulting in limited access to and exchange of agricultural information. However, information and communication technology enables farmers to reconstruct their social relationships [44]. This facilitates the sharing of agricultural information among broader audiences [45,46], enhances the exchange of agricultural information among smallholder farmers, and enriches the channels and overall volume of agricultural information available to them. Examples of this transformation include the Digital Extension Tool [67], which allows for the sharing and discussion of agricultural information, the Ushauri Mobile Advisory Service in Tanzania [68], which enables communication with agricultural extension workers via social media [66], the Farmer Digital Information System [69], which provides information on quality agricultural advisory services, credit, and subsidies, and the GeoFarmer digital system [65], which allows smallholder farmers to share their experiences with various stakeholders, including experts.

Other notable platforms include MP Modelling [70], which facilitates exchanges among researchers, farmers, and extension workers, Access Agriculture [71], a digital platform for free viewing or downloading information on sustainable agricultural innovations, and Wefarm [16], an agricultural technology platform. Because of this digital transformation, smallholder farmers are gradually moving beyond localized social relationships and building broader social networks, thus expanding and enriching their social capital, which is increasingly advantageous for agricultural production.

4. Challenges of Digital Transformation in Smallholder Agriculture

Reflectively drawing on the "state–society" theory [72,73] and socio-technical systems theory [74,75] to analyze the digital transformation of smallholder agriculture, we observe that while smallholder agriculture retains significant traditional characteristics, its digital transformation embodies modernizing traits. This transformation cannot occur without robust support from government-led public policies and adequate resources in rural areas, enabling the government to facilitate the evolution of traditional smallholders into modern ones and reshape both their production and living structures.

In this process, the government plays a leading role, digital technology serves as an intermediary, and smallholders are the primary agents. The success of this transformation relies on the synergy among these three components [25], which is embedded in the bidirectional interactions between the government and smallholders concerning digital technology and mutual adjustments. Effective digital transformation requires governmental policy support for the development of digital agriculture, the precise integration of agricultural digital technologies, and the digital adaptation of smallholder farmers. This collaborative approach aims to create a digital agriculture development community with the government, technology providers, and smallholder farmers as key participants, ultimately promoting the sustainable digital transformation of smallholder agriculture. Based on this understanding, this study constructs an analytical framework of "government–technology–smallholders", as illustrated in Figure 2.
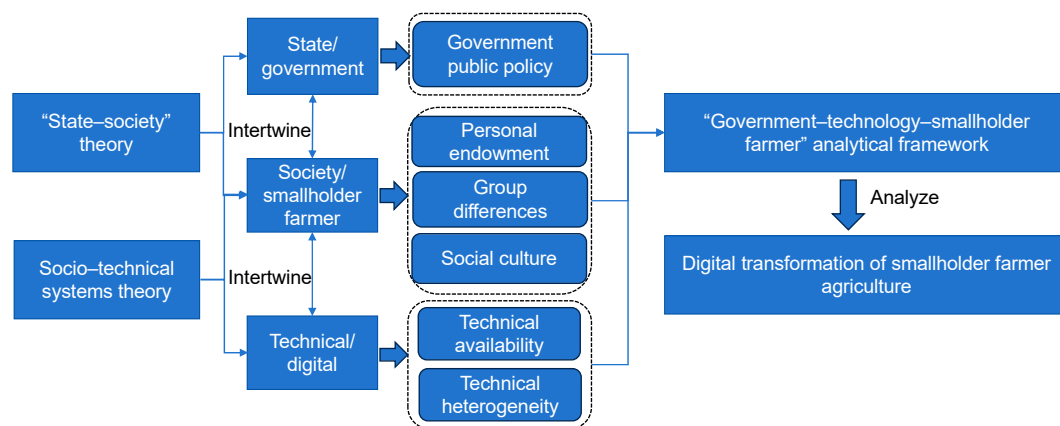
Figure 2. Analysis framework.

At the governmental, technological, and smallholder levels, the real-life challenges to the digital transformation of smallholder agriculture primarily include inadequate digital agriculture policies, limited access to digital applications, difficulties in adapting standardized technologies to diverse smallholder contexts, and endowment, discrepancy, sociocultural factors in smallholder level (Table 3).

Table 3. Challenges of digital transformation in smallholder agriculture.

Dimension	Type	Content
Government Level	Insufficient policy resource supply	Insufficient funding and limited access to digital resources for smallholder farmers [2,37,76].
	Lack of attention to smallholder needs	Policies may not align with the realities faced by smallholder farmers, leading to inadequate responses to their actual demands, and a lack of farmer representation [20,46].
	Inadequate digital governance policies	Need for stronger governance mechanisms in digital agriculture [47,64].
Technical Level	Insufficient availability of digital agriculture applications	Lack of support for local languages, unclear content provided by digital applications, and inaccuracies in the information shared [15,34,39,41], among others.
	Homogeneous technologies struggling to meet diverse needs	One-size-fits-all solutions that overlook the differences among smallholder farmers [32,51,77].
Smallholder Level	Inadequate endowment of smallholders	Low incomes make it difficult to afford costly hardware [59,69,77] and data access [34,78]. Low literacy rates and limited digital literacy contribute to the digital divide [29,50,79].
	Disparities in smallholder groups	Younger male farmers with higher educational levels have better access to digital resources and the achievement of digital transformation [15,22,52,61].
	Sociocultural constraints on smallholders	Moral and ethical considerations, as well as sociocultural factors in rural communities, may impact the digital transformation process for smallholder agriculture [1,17,48].

4.1. Government Level: Inadequate Digital Agriculture Policies

Policies play a crucial role in smallholder farmers' adoption of digital technology [76], and digital agriculture may fail without effective policies [48]. Firstly, there is a significant lack of policy resources in rural areas. The development of digital infrastructure and the accompanying resource allocation are essential prerequisites for the digital transformation of smallholder farmers. This transformation relies heavily on a range of digital infrastructure and related resources, including the Internet, 5G technology, signal towers, big data, remote sensing, sensors, smartphones, and computers. However, traditional smallholder farming communities often lack the capacity and conditions to create and sustain these modern infrastructures. Therefore, it is crucial for the government to take responsibility for building digital infrastructure in rural areas. Currently, insufficient financial investment and inadequate rural digital infrastructure present major challenges, while the lack of effective policies and support for the development of digital agriculture further complicates the digital transformation of smallholder farming [31,39]. Outdated infrastructure is one of the primary obstacles to digital transformation in smallholder agriculture [2,76], and digital adoption may fail without adequate infrastructure [48]. Compared with that in urban areas, rural digital infrastructure lags behind, and it is characterized by low levels of Internet access and a pronounced digital divide [11]. The lack of communication infrastructure and stable Internet connectivity in some rural regions hinders the adoption of digital services [55,62,68]. There is an urgent need for government investment in rural digital infrastructure. Furthermore, due to resource endowments and geographical characteristics, rural areas and smallholder farmers in remote and disadvantaged positions may be overlooked by policies. Some rural regions receive insufficient policy attention, leading to issues of digital exclusion and resulting in unequal outcomes in the digital transformation of smallholder agriculture across different areas. Relevant policies do not encompass all regions [37], and many areas still require strengthened policy support for digital transformation.

Moreover, there is insufficient attention and responsiveness to smallholder farmers in policymaking. Smallholder farmers are direct stakeholders in the digital transformation of agriculture and are significantly affected by various related policies. The current absence of smallholder farmers in the policymaking process is concerning, as it may result in policies that fail to accurately address their real needs and concerns. The government has often overlooked and underestimated the role and capacity of various stakeholders in the agricultural production process [46]. The lack of effective communication and collaborative governance between the government and smallholder farmers has resulted in some regions where farmers are more willing to cooperate with researchers than with government [20]. There is an urgent need to optimize the formulation and implementation of public policies on digital agriculture, emphasizing the importance of smallholder farmer participation.

Finally, the digital governance policies are inadequate. A robust digital agricultural governance mechanism is essential for ensuring the sustainable digital transformation of smallholder agriculture, helping to mitigate potential uncertainties and challenges. Currently, smallholder farmers may face disenfranchisement during this digital transformation [47], grappling with issues such as data privacy concerns [64]. For instance, as smallholders utilize digital applications, their usage records and personal data may be collected by platforms, raising the risk of their privacy being compromised through unauthorized sales or misuse. This poses significant socioeconomic risks for smallholders embarking on digital transformation [24].

4.2. Technology Level: Lack of Precision in Technology Embedding

(1) Insufficient availability of digital agriculture applications: The usability of some ICT applications is so poor that many smallholders struggle to adapt to and use them [65,77]. For instance, many applications do not support local languages. The vast majority of smallholder farmers prefer local languages, and the language barrier significantly hampers their use of technology and digital apps [34,41]. Additionally, the content of digital applications can be obscure. Farmers' literacy levels are crucial for understanding the information they receive [36]. Many smallholder farmers in developing countries have low literacy rates [2,19,24,36], with some being completely illiterate. This makes it difficult for them to grasp obscure and confusing information presented by digital applications [15]. Digital applications often disseminate inaccurate information. For example, the unreliable information from Digital Climate-Smart Agriculture is a significant barrier [39], leading smallholder farmers to question the validity of the information provided through digital services [58].

(2) Homogeneous technologies struggling to meet diverse needs: Rural areas across different regions exhibit significant variations in natural resources, infrastructure, demographic structures, organizational systems, traditional customs, and social cultures, leading to diverse digitalization demands. For instance, in Rwanda, smallholder banana farmers can be categorized into three distinct types, each with varying needs for and applications of mobile technology. Relying solely on a single smartphone-based service and content delivery could result in some smallholders missing out on opportunities for digital transformation [77]. However, current agricultural technologies frequently overlook the localized characteristics of villages and the complexities of heterogeneous smallholders, often promoting a "one-size-fits-all" approach [32,51,77]. There is also an overemphasis on the information provided by researchers, which tends to ignore the perspectives of smallholder farmers [65]. This leads to the neglect of the diverse digital transformation needs of smallholders, resulting in certain groups being excluded from the digital transformation process.

4.3. Smallholder Level: Endowments, Differences and Socio-Cultural Factors in Smallholder Farmers

Digital literacy, education level, gender, and other factors significantly impact the digital transformation of smallholder farmers [38,80]. The endowments, differences and sociocultural factors in smallholder can create challenges and inequalities in this transformation.

(1) Inadequate endowment of smallholders: On the one hand, smallholder farmers typically have lower incomes. Operating on a small scale, they generally face limited financial resources. The high costs associated with digital transformation make it difficult for low-income farmers to afford essential digital hardware and network access fees [39], which hinders their ability to adopt digital technologies in agriculture [7,80]. This situation results in digital exclusion for many smallholder farmers. In terms of hardware, the costs of ICT equipment can be prohibitive [77], and smallholder farmers often lack the financial support needed [59] to invest in modern digital farming tools [69]. Additionally, the high costs of Internet data pose a significant barrier for low-income farmers [34,78], making network access difficult.

On the other hand, many smallholder farmers struggle with low digital literacy. Tools used for the digital transformation of agriculture, such as smartphones, computers, drones, and various digital applications, come with certain usage requirements and barriers to entry. Smallholder farmers need to possess relevant digital skills, understanding, and literacy to effectively utilize these technologies. This lack of digital skills presents a major obstacle to the digital transformation of smallholder agriculture [50,56]. High illiteracy rates and limited digital skills hinder their ability to adopt digital agriculture practices [29,78]. Many smallholder farmers possess below-average ICT skills [79] and lack the ability to use smartphones effectively [21,45]. Furthermore, an insufficient understanding of emerging digital technologies [43] places them further behind the digital divide, complicating their transformation efforts [8,49]. Additionally, a lack of support and training to improve digital literacy [18] makes it challenging for them to bridge this gap and access the benefits of digital technology.

(2) Disparities in smallholder groups: Women, older individuals, and smallholder farmers with limited educational backgrounds face significant inequalities in digital adoption, making them less likely to use and access digital agricultural applications [42,66,67]. First, educational disparities contribute to digital inequality. The number of years of education has a significant positive effect on Internet adoption [22], and challenges related to mobile phone usage are primarily linked to low education levels among farmers [77]. Farmers with higher education levels are better equipped to understand the requirements for effectively adopting agricultural technologies [61] and are more likely to use social media to access agriculture-related information [52]. Second, age differences can lead to digital inequalities. ICT literacy is significantly and negatively correlated with age [56], impacting the digital adoption of smallholder farmers [52]. Older individuals often struggle to utilize the Internet for agricultural information [71]. Third, gender differences exacerbate digital inequality. The digital transformation of smallholder farmers appears to favor men [15], while women often face barriers to participation [81], further contributing to the digital divide.

(3) Sociocultural constraints on smallholders: Digitalization is set to transform the production methods and daily lives of smallholder farmers [9]. As traditional smallholder farmers engage with modern digital technologies, they inevitably face a range of challenges. Ignoring the cultural context of smallholder farmers can jeopardize the success of technological practices in the digital transformation of agriculture [1,48]. For instance, when the information provided by digital advisory services conflicts with traditional farming practices, smallholders may experience digital exclusion [4], as it does not align with their long-established "habitat" of production and lifestyle. Additionally, in traditional rural societies, community values serve to protect smallholder farmers; however, digital transformation has thrust them into the uncertainties

of the digital marketplace, distancing them from informal practices of reciprocity [17]. Furthermore, the social networks and social capitals of smallholders may also influence the process of digital transformation [82]. As a result, smallholder farmers may resist adopting digital technologies due to the perceived risks associated with these new environments.

5. The Future of Digital Transformation in Smallholder Agriculture

At the government, technology, and smallholder levels, it is essential to continue advancing the digital transformation of smallholder farmers. This can be achieved by enhancing the supply of policy resources, increasing attention to and responsiveness toward smallholder needs, optimizing the governance mechanisms for digital agriculture, and creating more user-friendly digital agricultural applications. Additionally, it is important to recognize the diverse digital aspirations of smallholder farmers, reduce the costs associated with digital access, improve digital literacy among these farmers, foster an inclusive environment for the development of digital agriculture and respect the sociocultural characteristics of smallholder communities (Table 4).

Table 4. The future of digital transformation in smallholder agriculture.

Dimension	Type	Content
Government level	Enhance policy resource allocation and accelerate digital outreach to rural areas	Increase investment to bridge the digital infrastructure gap between urban and rural areas [14,22,55].
	Improve policy focus and responsiveness toward smallholders	Develop farmer-centered public policies [9,25].
	Optimize governance mechanisms for digital agriculture	Promote data security legislation,strengthen review [16,21,59].
Technical level	Optimize digital applications to enhance user experience for smallholders	Design user-friendly interfaces and systems that support local languages [31,34,49].
	Respect the diverse digital needs of smallholders	Collaborate with smallholders to develop localized applications, engaging farmers to incorporate traditional culture and specific needs while providing tailored technological solutions [4,55,63,68].
Smallholder level	Reduce the cost of digital access for smallholders	Ensure that mobile broadband becomes a public good, enabling farmers to access affordable data and technology services [11,80,83].
	Enhance digital literacy among smallholders	Strengthen ICT education to improve smallholders' skills in using digital applications [19,42,55].
	Create an inclusive environment for digital agricultural development	Adhere to principles of inclusivity [76,83]; foster rural social capital [34,50,66].
	Respect the sociocultural characteristics of smallholder communities	Consider the sociocultural factors that influence digital adoption [4,63].

5.1. Government Level: Enhancing Policy Support for Digital Agricultural Development

The government plays a crucial role in driving digital transformation in rural areas and facilitating the adoption of ICT among smallholder farmers, which is essential for overcoming challenges in ICT adoption [78,79].

(1) Enhance policy resource allocation, accelerate digital outreach to rural areas, and increase economic investment in rural digital infrastructure: Compared with urban areas, rural digital infrastructure requires significant strengthening, particularly in terms of connectivity and development [14,22,55]. The government needs to invest in infrastructure [52] to sustainably improve rural Internet access and electricity supply, thereby facilitating smallholder farmers' access to digital devices such as smartphones [29,58]. This investment is vital for enhancing digital accessibility among

smallholder farmers. For instance, in recent years, China has introduced a series of rural revitalization strategies and digital rural development policies, which have rapidly expanded Internet access in rural areas and improved digital literacy among smallholder farmers, creating a solid foundation for their digital transformation. At the same time, there is an urgent need to develop phased, long-term digital agriculture development plans [84]. Additionally, innovative initiatives should be established, such as improving existing digital centers in rural areas to allow farmers to experience digital agriculture services firsthand [38], creating official social media channels [42], and promoting hands-on training for smallholder farmers [76].

(2) Improve policy focus and responsiveness toward smallholders: Smallholders are key participants and primary beneficiaries of relevant policies, so it is essential to fully incorporate the demands of stakeholders, including smallholders, into the design and formulation of digital transformation policies. This involves paying attention to, listening to, and addressing the inherent digital needs of smallholders, as well as establishing a collaborative governance mechanism that integrates the government, smallholders, and enterprises [25]. Additionally, it is crucial to develop farmer-centered public policies [9] that align more closely with the specific interests of local smallholders. A practical approach is to conduct thorough field research, surveys, interviews, discussions, and focus groups prior to policy formulation and implementation to gain a comprehensive understanding of local smallholder demands. For instance, through focus group discussions, we can gain insights into the diverse digital transformation needs of smallholders and identify key factors for effective technology integration, thereby enabling the development of more relevant policies [44].

(3) Optimize the governance mechanism of digital agriculture [59]: Given the uncertainties associated with digital technology, smallholder farmers face various risks during the digital transformation process. The government should strengthen the review of digital agriculture procedures to ensure their effectiveness [16] while promoting data security legislation [21] to protect the privacy and data rights of smallholder farmers [15,24].

5.2. Technology Level: Facilitating the Precise Embedding of Digital Technologies

(1) Optimize digital applications to enhance user experience for smallholders: Digital platforms should be designed with user-friendly interfaces and intuitive systems that support local languages and are tailored specifically to the needs of smallholder farmers [31,34,49]. Additionally, incorporating images and voice messages to deliver relevant information can significantly improve engagement and acceptance among smallholder farmers [51]. It is essential to effectively filter the vast amount of information available online [49], improve the ease of information retrieval [43], and increase the accuracy of content in digital agricultural applications. This will help build trust in these digital tools among smallholder farmers. Additionally, there is the potential to create one-stop digital service platforms that provide access to all basic agricultural services through a single interface [28]. Furthermore, developing discussion platforms where smallholder farmers can interact, share experiences, and consult with researchers online can greatly enhance their engagement and satisfaction [51].

(2) Respect the diverse digital needs of smallholders: Smallholder farmers exhibit significant heterogeneity and have varied needs for digital transformation [4]. Successful digital agriculture applications must reflect the unique sociocultural characteristics of specific locations, fully consider the preferences and traits of different types of rural communities and smallholder farmers [65], and respect local knowledge and practices [31]. Therefore, technologists should actively link and engage with smallholder farmers [22,67], adhere to user-centered design principles [68], and adopt a proactive approach to understanding the needs of smallholder farmers from the outset [35]. This collaboration ensures that the development of localized digital agricultural applications meets the diverse and heterogeneous agricultural needs of

smallholder farmers [55]. For instance, sensors can help document the characteristics of different rural soils, thereby facilitating informed management decisions tailored to those specific soil types. Moreover, effective communication among researchers, technology providers, and smallholder farmers can motivate the adoption of these technologies [32]. Additionally, collaborating with local farmers to create agricultural promotion videos can significantly enhance the success rate of these initiatives [67]. Technology providers should collaborate with smallholder farmers in various ways to offer tailored digital services and technological solutions that address the diverse needs of these farmers.

5.3. Smallholder Level: Building Inclusive Digital Agricultural Environment in Smallholder Community

(1) Reduce the cost of digital access for smallholders: Ensuring that farmers have access to affordable digital agricultural technology services is essential [39]. For instance, low-cost digital technologies can be made available to smallholder farmers through partnerships with agricultural input suppliers [69] or by establishing reliable financing mechanisms for ICT development [78,80]. Additionally, it is important to gradually position mobile broadband as a public good, empowering smallholder farmers to afford and utilize digital tools [11,83]. This approach will help reduce the cost of digital access and ICT connectivity for smallholder farmers, create opportunities for low-income farmers to embrace digital transformation, and promote digital equality and shared prosperity.

(2) Enhance digital literacy among smallholders: Literacy and digital literacy are crucial for bridging the digital divide for smallholder farmers [48,59]. Education is the most effective way to enhance digital literacy. Agricultural education and extension agencies should focus on equipping smallholder farmers with the necessary skills and support [42]. By enhancing ICT education [19], we can continue to improve smallholder farmers' digital literacy [6,55] and their capacity to use digital applications [31]. Furthermore, increasing smallholder farmers' awareness of the value and importance of digital agriculture [76] will help them identify with digital practices and stimulate their intrinsic motivation for digital transformation. For instance, engaging short videos could be used to highlight the advantages of digital agriculture, thereby igniting the internal drive for digital transformation among smallholder farmers. Special attention should also be given to enhancing the digital literacy of young smallholder farmers, as they are key advocates for digital agriculture [29]. Young farmers with higher digital literacy can provide support to older farmers, thus driving overall improvements in digital literacy across smallholder farming communities [77]. For instance, by training a select group of tea farmers to become digital agriculture experts, we can facilitate the sharing of experiences and skills with other tea farmers, leading to a collective increase in digital literacy [18].

(3) Create an inclusive environment for digital agricultural development in smallholder community: Agri-tech companies should take sociodemographic factors into account when developing, managing, and deploying digital agriculture solutions for farmers [61]. It is essential to promote innovations that benefit all farmers to foster an inclusive environment for digital agricultural development [40]. On one hand, the principle of universality should guide these efforts. While advanced technologies are available, it remains important to implement simpler solutions, such as mobile SMS, in rural areas to benefit all smallholder farmers [83]. This approach helps avoid the digital exclusion that can arise from individual endowment differences and varying sociodemographic characteristics. Additionally, establishing differentiated incentives [76] is crucial to provide tailored digital tools and services to smallholder farmers with diverse needs, facilitating the sharing of digital benefits among as many farmers as possible. On the other hand, it is vital to stimulate rural social capital. Insufficient stakeholder participation is a significant barrier to the digital transforma-

tion of agriculture [25]. Trust within communities and relationship networks greatly influences the adoption of digital technologies and the participation of smallholder farmers in digital services [81,83]. Strengthening these networks can help mitigate the inequalities arising from sociodemographic differences and address the absence of smallholder farmers in policymaking and the development of digital technologies. Encouraging farmers to join associations and cooperatives [34] can expand their social interactions, while increasing the use of social media in agricultural activities [66] can promote information sharing and community empowerment [18,71]. This multifaceted cooperation mechanism can connect various stakeholders, including smallholder farmers, government entities, and technologists [50,52], enabling collaborative solutions to the challenges faced during the digital transformation of agriculture [46] and fostering a supportive community for the development of digital agriculture for smallholder farmers.

(4) Respect the sociocultural characteristics of smallholder communities: It is crucial to fully consider the sociocultural factors that influence digital practice and digital adoption [4,63]. It is necessary to acknowledge the non-economic and social contexts surrounding digital technology applications [44,85] and to integrate cultural considerations into the development and design of digital applications while respecting local knowledge and practices [31]. This approach can help mitigate the uncertainties that may arise during the digital transformation process [86]. For instance, smallholder farmers often adhere to a smallholder logic in their agricultural production and daily lives, placing greater trust in local communities built on personal relationships. Therefore, when promoting digital policies and technologies, it is essential to use local languages and adopt interaction methods that align with smallholder practices. Creating an interactive environment and context that resembles smallholder communities can help accommodate their social and cultural characteristics, ultimately enhancing their acceptance of digital solutions [44].

6. Conclusions

Based on a comprehensive review, it is evident that the current practice of digital transformation among smallholder farmers primarily focuses on agricultural production, the distribution of agricultural products, and the exchange of agricultural information. Smallholder farmers are gradually integrating digital agricultural tools, rural e-commerce platforms, and information exchange systems into their agricultural practices and daily lives. From the perspective of the "government–technology–smallholders" framework, smallholder farmers face several key challenges in the digital transformation of agriculture. These include inadequate digital agriculture policies, limited access to digital applications, and difficulty with adapting standardized technologies to meet the diverse needs of smallholder farmers. Additionally, challenges arise from the varying endowments of smallholder farmers, significant group differences, and constraints imposed by social and cultural factors. Looking ahead, it is essential to promote the sustainable digital transformation of smallholder farmers worldwide. This can be achieved by enhancing the supply of policy resources, increasing attention to and responsiveness toward smallholder needs, and improving digital governance policies. Furthermore, creating and designing more user-friendly digital applications, respecting the diverse digital aspirations of smallholder farmers, reducing the costs of digital access, improving digital literacy, fostering an inclusive environment for the growth of digital agriculture and considering sociocultural factors are crucial steps. These efforts aim to harness the inclusive and income-generating potential of digital technology within rural communities.

Based on a comprehensive analysis, this study aims to provide a complete set of recommendations for stakeholders involved in the digital transformation of smallholder agriculture. For policymakers, it is essential to leverage tools such as big data and artificial intelligence, employing extensive field research methods to gain insights into the diverse digital needs of rural areas and smallholders in specific regions. This understanding will

enable the development of more targeted digital resource provisions and the design of smallholder-centered policies for digital transformation in agriculture. Additionally, there should be a strong push for public-interest initiatives that enhance digital literacy through educational training, thereby strengthening digital education and improving smallholders' practical skills, digital awareness, and overall digital competence. For technology developers, it is crucial to align digital applications with the actual needs of smallholders by incorporating local languages, prioritizing image and voice functionalities, and offering customized services. Enhancing user interaction with experts and incorporating feedback mechanisms will further improve the usability of these applications. Lastly, smallholders themselves should continuously work on improving their digital literacy and actively engage in the policymaking and technological development processes related to agricultural digital transformation. By voicing their thoughts, attitudes, and local sociocultural knowledge, they can contribute to the creation of a truly collaborative model for digital transformation in smallholder agriculture, involving a diverse range of stakeholders: government, smallholders, and technology providers.

Despite the numerous benefits associated with the digital transformation of smallholder agriculture, many smallholder farmers worldwide still lack access to scientific agricultural advice [15]. Moreover, the underlying mechanisms through which digitalization has impacted smallholder farming require further investigation [9]. The findings of this study deepen our understanding of the value of digital transformation in smallholder agriculture. This transformation is crucial for the agricultural modernization of developing countries, where smallholders are the primary agricultural actors. This study takes into account most of the factors and challenges that may influence the digital transformation of smallholder farmers, providing valuable insights for relevant agricultural sectors on how to sustainably advance this process. Looking ahead, it is essential to deepen research on the digital transformation of smallholder farmers. This will provide both theoretical insights and practical references to facilitate their sustainable digital transition, help them escape poverty, increase their income, and enhance their overall well-being.

While we have made every effort to conduct a systematic and comprehensive analysis, certain limitations may still exist. First, this study primarily relied on core databases within the Web of Science for the literature searches, potentially overlooking the relevant literature from other important databases, which may have restricted the comprehensiveness of our findings. Second, although we employed in-depth reading and analytical methods to screen and summarize the literature, this approach offers a thorough understanding of content but lacks the ability to quantitatively reveal correlations between studies and research trends. Third, the literature reviewed in this study predominantly consists of English articles, which may not fully capture global smallholder digitalization. There is a need for greater attention to and synthesis of the literature published in non-English languages related to smallholder agricultural digitalization. Future studies can improve in several areas. First, broadening the literature search scope and utilizing multiple databases will enhance the comprehensiveness of research results. Second, integrating bibliometric methods, such as co-word analysis and citation analysis, can quantitatively illuminate the relationships and research trends in the literature, providing quantitative support for a deeper understanding of the digital transformation of smallholders. Finally, future research should include reviews of articles and papers published in non-English languages related to smallholder and digital transformation. This will enhance our understanding of the digital transformation of smallholders across more different regions and cultural contexts, strengthen comparative studies of smallholder digital transformation, and identify commonalities and differences. Such efforts will provide a scientific basis for developing more targeted policies and measures, thereby further enhancing the explanatory power and applicability of the research.

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