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RESEARCH PAPER

Drivers and barriers in embracing digital farming: Insights from the smallholder farmers in the NENA region*

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Abstract

This paper explores the possibilities for boosting the role of agricultural economics, in particular, the role of family-based farming, through the use of digital technologies. Overcoming the barriers to digital technology adoption is essential for driving meaningful transformation within agriculture. In our study, we conducted a regional pilot survey on attitudes of farmers towards digital agriculture in three countries within the NENA region. The methodology is based on existing documentation and strives to gather fresh insights by means of a survey questionnaire to identify and assess needs, gaps and challenges of adopting digital agriculture. Farmers survey revealed that the adoption of digital technologies has led to improved productivity, increased efficiency and reduced costs. The use of drones and satellite imagery optimized the use of fertilizers, water and other inputs. Similarly, the use of mobile apps and online marketplaces facilitated access to information, connection with buyers and access to financial services. Nonetheless, farmers highlighted difficulties of inadequate availability of digital infrastructure and services, insufficient digital skills, and apprehensions regarding data protection and confidentiality. This study addresses a gap in the literature by providing insights to design tailored programs and ensuring that digital agriculture is more accessible and beneficial. This study reports how farmers perceive digital tools, particularly, how does digital agriculture diffuse amongst farmers, and its impact on the resilience of farming communities. This research presents diverse pathways through which digital agriculture can tackle key issues within farming systems and contribute to shifts in social norms and behaviours that remains underrepresented in existing literature, particularly within the current digital agriculture landscape of the NENA region.

Keywords

Availability of knowledge resources, Adoption of technology, Smallholder farmers, Data-driven farming practices, Sustainable socioeconomic development, Rural economic growth

Introduction

Public research institutions are placing growing emphasis on devising effective strategies to scale agricultural innovations, with the aim of extending their benefits to a broader population particularly smallholder farmers and ensuring sustainable, long-term impact. In this context, digital agriculture, including the use of Information and Communication Technologies (ICTs), holds significant potential to enhance the adoption and diffusion of such innovations (Lehmann et al. 2012). Instruments and strategies for information exchange promote synergy among

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stakeholders, spread awareness of advancements in agriculture to target audiences, and support the provision of corresponding resources, assistance, and commodities (Klerkx and Leeuwis 2009). In the Near East and North Africa (NENA) region, farming systems are primarily conventional and dominated by smallholder producers. These systems rely heavily on rainfall, generate modest output levels, and are often deprived of essential knowledge, market linkages, and access to financial support mechanisms. Global institutions acknowledge the transformative potential of digital technologies in agriculture to tackle these pressing issues (Bahn et al. 2021a; Maru et al. 2018). However, smallholder farmers are largely missing out on the advantages offered by the rapid advancement of digital technologies such as mobile and web-based tools, innovation ecosystems, smart farming techniques, digital financial services, e-commerce platforms, and Internet of Things (IoT)-enabled irrigation systems. Their limited involvement in shaping and overseeing digital agriculture initiatives frequently leads to solutions that fail to reflect their realities and priorities, ultimately hindering their willingness and ability to adopt these technologies (Maru et al. 2018). Consequently, the potential of digital agriculture to enhance farmers' livelihoods and strengthen their ability to cope with shocks, while also improving the performance, openness, and fairness of agri-food systems, and contributing to both climate change mitigation and adaptation remains largely untapped.

The term "digital food systems" broadly encompass the application of digital technologies across every component of the food ecosystem from agricultural production to supply chains, policy-making, advisory services, market dynamics, consumer behaviour, and public health. While "digital agriculture" is occasionally used interchangeably, it typically denotes a more focused segment within this spectrum, concentrating on technology-driven farming practices such as precision agriculture, digital extension and advisory tools, open-access agricultural data, and traceability within value chains (Bahn et al. 2021a, 2021b). Intelligent or technology-driven agriculture has the potential to significantly boost earnings, improve the quality of decisions, elevate the standard of services and goods, and increase both efficiency and financial returns (Saiz-Rubio and Rovira-Más 2020). However, while digital technologies can streamline tasks and enable remote command execution, their intelligent capabilities that drive autonomous decision-making and enhance efficiency are entirely reliant on robust data foundations. Without input gathered directly from the field or derived from external datasets, these technologies lack the insight required to function intelligently.

Digital agriculture has proven valuable in delivering critical insights to farmers, particularly regarding market price trends (Deichmann et al. 2016; Jouanjean et al. 2020). Nevertheless, its uptake, especially among smallholder farmers, faces several hurdles that must be overcome. This calls for a deeper exploration of their perceptions, limitations, and needs, as well as inclusive dialogue to shape effective strategies and substantial investment in knowledge enhancement and skills development. In countries such as Jordan, Egypt, and Tunisia, smallholder producers often remain passive recipients of digital content; therefore, empowering them to actively engage with and benefit from interactive digital platforms is essential for maximizing impact. Achieving this shift will necessitate a transformation in mind-set and increased awareness across all stakeholders involved in the digital innovation ecosystem. Rural communities are often resistant to change, making the adoption of essential digital services such as weather updates and corresponding guidance delivered through Short Messaging Services (SMS), mobile apps, or online platforms a gradual process. It will take time for farmers to fully engage with and integrate these tools into their decision-making routines (Ayim et al. 2020).

It is widely acknowledged that unlocking the full potential of digital transformation in agriculture hinges on actively involving farmers in shaping and managing digital tools, as well as in negotiating data-related practices and business models (Maru et al. 2018). This stems from the notion that farmers are not merely end-users of external innovations, but are themselves vital contributors to agricultural advancement, creators of valuable knowledge and rightful holders of intellectual property. There are numerous opportunities for rural women and men that they are able to do. To achieve this, there must be a deliberate effort to reconfigure power dynamics and ensure more equitable representation of diverse stakeholder perspectives in the dialogue around food systems reform and the development of agricultural solutions (Guinto et al. 2024).

Personal ICTs devices, such as smartphones and tablets, are becoming increasingly accessible, and the use of mobile technologies for delivering services and solutions is on the rise (Bolfe et al. 2020). However, there remains a lack of comprehensive understanding regarding the impact and role of digital agriculture in the adoption and expansion of agricultural innovations. This includes identifying critical success factors, addressing challenges specific to implementing digital agriculture in the NENA region, and recognizing the distinctive features of rural environments that influence scaling efforts. Digital agriculture has been identified as a strategic avenue for fostering collaboration between researchers and farmers, enabling them to benefit from agri-food value chains and revitalizing counselling services within the NENA region. Additionally, the potential of disruptive technologies to stimulate rural youth entrepreneurship and drive food system transformation has been highlighted as a significant area for research relevant to this region (van der Burg et al. 2019).

Digital technologies streamline and empowers buyers and sellers to establish agreements, while strengthening their connections and providing guidance to farmer associations on optimal marketing strategies (Kumarathunga et al. 2022). Delivering market intelligence and technical guidance are essential for improving the well-being of smallholder producers, equipping them with the knowledge needed to make sound choices about production and marketing. While digital agriculture offers the capacity to impact vast numbers of individuals, it is equally important to recognize the transformative role these beneficiaries themselves can play. Their active participation can drive the systemic changes necessary to ensure that scaling efforts are contextually appropriate and rooted in local realities.

Currently, smallholder farmers often lack direct access to accurate crop market pricing, leaving them at a disadvantage when dealing with traders, who continue to dominate supply chains (Deichmann et al. 2016). Digital agriculture helps bridge this gap by equipping farmers with real-time information, enhancing their ability to negotiate fairer sales terms. By connecting smallholders directly with market buyers through digital platforms, these tools serve as powerful enablers for farmers to climb the value chain. Instead of relying on second hand or potentially distorted information from intermediaries, farmers receive unfiltered data such as daily wholesale fruit and vegetable prices via SMS, allowing them to make better-informed decisions at the local level (Mulungu et al. 2025). Additionally, SMS-based delivery of technical updates, including weather forecasts and guidance on irrigation and pest management, provides timely, crop-specific advice tailored to each region and season, helping farmers stay on top of essential agricultural tasks.

The purpose of this study is to empower farmers as central contributors and co-creators in the development, oversight, and equitable benefit-sharing of digital agriculture technologies, data ecosystems, and infrastructure. It also seeks to advance supportive policies and promote effective practices that ensure inclusivity and relevance. The anticipated outcome is that the fair and sustainable application of digital agricultural tools will enhance farmers' productivity and earnings, lower exposure to risks, encourage responsible use of natural resources, and bolster both climate adaptation and mitigation efforts. Additionally, this approach is expected to strengthen farmers' participation in the agri-food data economy, improve transparency and efficiency across value chains, and support the tracking of Sustainable Development Goals (SDGs) indicators. This study serves as a pilot, featuring a survey focused on farmers' perspectives, attitudes, and obstacles related to digital technologies, along with research on the current state of digital agriculture as experienced by smallholders. The premise is that this initial, farmer-driven investigation will shed light on the strategic significance of digital agriculture in selected NENA countries namely Jordan, Egypt, and Tunisia. It also aims to support the expansion and integration of agricultural and food security solutions, including scaling promising innovations, transitioning from pilot efforts to broader implementation, addressing institutional and structural barriers, and informing policy development. Therefore, the core objectives of this study are to pinpoint the gaps and barriers faced by smallholder farmers in adopting digital agricultural tools and to determine how these can be most effectively addressed. It also explores the diverse factors that influence farmers' decisions to adopt or reject particular technologies, offering insight into the various pathways through which digital agriculture can help resolve systemic challenges. Furthermore, it highlights the role of digital tools in driving social and behavioural change, and the importance of communication strategies in addressing cultural and social norms that shape local perceptions of agricultural innovations.

Conceptual and analytical framework

The agricultural sector is one of the most important economic sectors in Jordan. Agriculture plays an important role in the development system, especially for rural communities, and contributes a large percentage to achieving food security. Despite the low contribution of agricultural production to the Gross Domestic Product (GDP), it represents, in its economic and social dimensions, one of the most important sectors of the national economy (Ministry of Agriculture 2023). However, agricultural production in Jordan is currently grappling with a host of complex issues. These include scarce surface water availability in the Jordan Valley, the rapid exhaustion of groundwater in highland areas due to excessive extraction, inefficient irrigation practices, declining soil and water quality, fragmented land holdings, and underperforming extension systems that fail to effectively bridge research and practical application at the farm level. In addition, the sector faces significant marketing challenges, characterized by high post-harvest losses, underdeveloped market infrastructure, food safety concerns, and difficulties in aligning production with required quality standards. Beyond its economic role, agriculture in Jordan is a vital driver of employment, rural livelihoods, and national food security. It also presents a strategic platform for addressing pressing environmental and climate-related concerns (Green Growth National Action Plan 2022). While the sector has experienced growth and offers promising investment opportunities, particularly in high-value agriculture, there remains considerable potential to harness technology and inclusive value chain strategies. These approaches could better integrate rural communities into more productive systems and profitable markets, enhancing their roles in the agricultural economy (Jordan Economic Growth Plan 2021).

With over 80% of Jordanian farmers now owning smartphones, ICTs are poised to revolutionize the agricultural landscape. The widespread use of digital tools is narrowing information asymmetries, lowering transaction costs, improving service delivery, generating employment, creating new income opportunities, and supporting resource conservation. Information and Communication Technologies are reshaping how individuals, businesses, and governments operate, connect, and exchange information. For rural populations, particularly youth, digital tools offer powerful means of empowerment, expanding their options, boosting incomes, and fostering greater participation in local development. Moreover, digital innovations enable more productive and sustainable farming by improving yields and quality while reducing the use of critical inputs such as water, energy, fertilizers, and pesticides.

These technologies facilitate precision agriculture, remote operations, and environmentally responsible practices (World Bank 2019; Abiri et al. 2023; Papadopoulos 2024). Controlled-environment agriculture, such as greenhouses, vertical farming, indoor systems, and hydroponics, is increasingly integrating advanced digital solutions including sensors, robotics, and real-time communication technologies to optimize performance and resilience.

Digital technologies are particularly used for improved irrigation and hydroponic production in Jordan. However, the largest uptake of digital technologies on farm is the application of imported irrigation-related technologies such as sensors. The focus on irrigation is reasonable, given the scarcity and relatively high cost of water. Digital technologies that control irrigation, fertilization, temperature and humidity are used in many initiatives to develop soilless agriculture, led by Jordan's Ministry of Agriculture. The application of drone technology and digital imaging in agriculture remains constrained in Jordan, largely due to regulatory restrictions and national security considerations that require official authorization. However, there is growing use of remote sensing tools and digital modelling techniques to evaluate how effectively water is being utilized in agriculture and to assess the effects of climate change on the sector. These remote sensing systems are particularly valuable for estimating evapotranspiration, a key indicator used in tracking water consumption across agricultural areas. On the commercial front, digital solutions are being leveraged to improve market transparency and support agri-food trade. A variety of online platforms have been launched to facilitate the dissemination of market data, including price trends, thereby promoting more efficient and informed agricultural marketing.

Despite its potential, the adoption of digital agriculture in Jordan faces several hurdles. These include a general lack of familiarity with digital tools and their practical uses, limited engagement from both government and private stakeholders, language barriers between the platforms and the end users, and restricted availability of funding and reliable data. For digital solutions to be truly effective, users must first develop a clearer understanding of these tools. Moreover, the technologies themselves need to deliver accessible, tailored, and timely information that speaks directly to the unique challenges farmers face. Despite the justified and declared benefits of digital agriculture, the widespread adoption of digital agriculture in NENA region, and more specifically in Jordan faces significant barriers. One of the main obstacles is lack of infrastructure in rural and remote areas. Access to reliable internet, electricity and mobile networks is limited in many parts of rural areas in NENA region, hindering farmers' ability to use digital tools (Bahn et al. 2021b). Furthermore, the upfront costs of digital agriculture technologies, such as drones, sensors, and artificial intelligence (AI) systems, can be prohibitively expensive for smallholder farmers, who constitute a large portion of the farming population in the region (Subeesh and Mehta 2021; Akhter and Sofi 2022). Digital agriculture in Jordan remains at a nascent stage, yet it holds significant promise to reshape the farming landscape. By leveraging digital innovations, the sector could tackle critical issues confronting farmers, including limited water resources, the impacts of climate variability, and difficulties in connecting to markets.

Agriculture ranks as Egypt's third most significant economic activity, contributing 11.6% to the national GDP and employing 20.5% of the total workforce (Egyptian Center for Economic Studies 2020; World Bank Group 2021). It plays a crucial role in driving employment, fostering economic development, reducing poverty, enhancing food security, and boosting exports. Notably, the sector is a major source of income for women, engaging 45% of all female workers in the country (USAID 2017). In the aftermath of the COVID-19 pandemic, shifts in societal behaviour and perception have influenced how Egyptians engage with, adopt, and adapt to new technologies. Yet, while innovation, especially digital tools and ICTs, offers valuable opportunities, it is not a cure-all for the long-standing structural and socio-economic issues facing the country. The benefits of digital transformation can be substantial, offering improvements in economic productivity and business operations. However, to realize these gains, it is essential to build and sustain foundational elements such as robust digital infrastructure, access to investment and global capital, sound legal and policy frameworks, strong governance, inclusive education, and comprehensive cybersecurity systems. Egypt's Vision 2030 in the Sustainable Development Strategy (Sustainable Development Strategy: Egypt's Vision 2016) points that the efficiency and output of the agricultural sector have seen only modest progress, with overall productivity increasing by merely 1% annually and crop yields remaining largely unchanged for decades. In this context, embracing digital transformation presents a promising opportunity to accelerate productivity by strengthening the connection between farmers and markets. Recognizing the critical role that digital tools can play in modernizing the sector, Egypt's Ministry of Agriculture and Land Reclamation is actively pursuing initiatives to integrate digital solutions into agricultural management and operations.

In 2019, the FAO and the Egyptian government launched a program to boost agricultural productivity through digital agriculture. By leveraging digital technologies, farmers in Egypt gained improved access to vital information on crop and livestock management, enabling them to make more informed and data-driven agricultural decisions. The Agricultural Research Center (ARC) played a key role in implementing this program by converting technical agricultural content into digital formats accessible through mobile applications. Additionally, in 2021, the government of Egypt launched the first online platform called "Digital Agricultural Network". This platform serves the agricultural sector by offering farmers access to support services, financing, trade opportunities, research, extension, marketing, inventory management, mechanization, and supply chain solutions, enhancing the adoption of digital agriculture in Egypt. Digital agricultural platforms in Egypt are playing a key role in shaping targeted strategies across various sub-sectors, including crop production, livestock, poultry, aquaculture, and state-led agricultural initiatives. These platforms emphasize the strategic use of satellite imagery to enhance AI and technology-driven programs, promote data accessibility, encourage information sharing, and establish dynamic, real-time databases. As part of the country's broader digital transformation agenda, national initiatives have been launched to digitize land ownership records and introduce the farmer's card, streamlining administrative processes and incorporating modern tools into agricultural practices. Additionally, Egypt has rolled out a digital application called "Beneficial in Food and Agriculture" to strengthen agricultural extension services and boost productivity, especially among farmers and rural women. The satellite monitoring has been adopted to enhance irrigation efficiency, particularly critical in managing Egypt's limited water supply from the Nile River (Al-Ansari et al. 2022). Another cutting-edge technology that integrates IoT and AI into agricultural production to increase automation and efficiency called "Tomatiki" where this technology leverages big data and analytics for improved decision-making and operational intelligence.

Lastly, Egypt has made significant strides in advancing digital agriculture over the past decade. This progress is reflected in three key areas: (1) increasing adoption of digital tools by farmers and agricultural stakeholders; (2) the growing role of tech-driven start-ups and ICTs-enabled services in transforming agricultural practices; and (3) the initial integration of electronic government services to support the agricultural sector. These developments highlight Egypt's commitment to leveraging digital solutions for a more efficient and sustainable agricultural system (Kamel 2021). Despite ongoing efforts to promote digital agriculture, many initiatives remain fragmented and lack coordination within national agricultural systems. The integration of digital transformation into Egypt's legal and institutional framework is unclear, particularly given persistent structural challenges. These include gaps in the implementation of agricultural laws due to missing regulations, limited incentives for investment in water-saving technologies, institutional conflicts arising from government involvement in professional associations, and insufficient funding for research and development. Addressing these barriers is crucial for the effective and sustainable adoption of digital agriculture (Kassim et al. 2018; Egyptian Center for Economic Studies 2020).

In Tunisia, the shift toward digital agriculture remains slow, even though the potential advantages of these technologies are well recognized and various supportive measures have been introduced. Several efforts have been made, such as deploying drones for crop monitoring, digitally managing water use, and leveraging satellite imagery to assess planted areas and forecast yields. Nonetheless, multiple obstacles continue to impede progress. These include gaps in digital infrastructure across certain regions, limited availability of electronic payment systems, and restrictive data access policies (Ksibi 2019). In Tunisia, while a few innovative start-ups have begun to implement precision farming techniques, their reach remains limited. There have also been significant initiatives aimed at extending digital credit to farmers to support precision agriculture and livestock development. However, Tunisia still lacks technological solutions for risk assessment and screening in agricultural lending, which poses a challenge for scaling up finance in this sector (FAO 2020).

There were agricultural digital solutions that allowed farmers to identify pests and to access necessary information on pests control such as Plantix mobile application (WebManagerCenter 2018; FAO 2020), and Kolfa mobile application that provides farmers with useful information on input prices and services such as seeds, fertilizers, agrochemicals, etc. (Tekiano 2022). The Robot is another mobile platform that allowed farmers to plant specific plots in the fields without intervention (WebManagerCenter 2019). An innovative method of integrating drones was brought into existence in the technical management of orchards in Tunisia. This method allowed farmers and researchers to estimate the leaf area index using low altitude images taken by a drone (Mabrouk et al. 2017). Agritech start-up companies in Tunisia like Ezzayra created a software system that allows regulating salinity of the soil and automating the fertigation process through the agricultural season (Blaise 2020). Similarly, the use of drones in the agricultural sector which allows farmers to make reliable and relevant decisions to better manage their land. For instance, a camera equipped with red, green and blue wavelengths (RGB) technology can detect nitrogen variations across a potato field. This allows the farmer to apply nitrogen more precisely, focusing only on areas where it is lacking thereby enhancing crop yield while reducing unnecessary fertilizer use (African Development Bank Group 2022).

Progress in science, technology, and innovation is unlocking vast potential for generating new insights and practical solutions aimed at improving agricultural productivity (Rijswij et al. 2021). Emerging digital tools are rapidly reshaping the agri-food landscape, revolutionizing the structure of value chains, and creating fresh avenues for decent employment, entrepreneurial ventures, and innovative approaches to longstanding food system challenges. However, there is a growing consensus that the development and application of such technologies must be inclusive and participatory, prioritizing the needs and voices of smallholder producers, particularly rural populations and women. This perspective underscores the need to invest in comprehensive support systems that enhance the capabilities of smallholder producers across multiple dimensions: access to information, skills development, behavioral change, institutional and organizational strengthening, financial services, and more. As digital transformation gains momentum, particularly in countries like Jordan, Egypt, and Tunisia, concerns are mounting over how equitably these innovations are reaching marginalized groups. Ensuring that smallholder producers in the NENA region can access, afford, and benefit from these advancements is essential for achieving inclusive and sustainable agricultural development.

The overarching conceptual and analytical framework inform an argument that the adoption of digital agriculture in NENA region presents a promising avenue for transforming the agrifood system, enhancing productivity and ensuring sustainability. However, the current landscape remains fragmented, with challenges related to policy integration, infrastructure, and farmers' engagement. To fully realize the potential of digital solutions, a more coordinated approach is needed that strengthens governance frameworks, fosters investment in research and extension services, and promotes inclusive access to digital tools. Moving forward, a collaborative effort between governments, private sector actors, research institutions, and farmers will be key to accelerating digital transformation and ensuring its long-term success in the region. The intention is to illuminate how digital innovations can enhance smallholder farming by boosting the value, output, and financial returns of their produce, while also elevating household earnings. Additionally, the role of digital tools in advancing food resilience amid climate shifts was highlighted, emphasizing their contribution to eco-friendly farming practices. These technologies can optimize crop performance, support sustainability, and offer wide-ranging ecological and community-level advantages.

Adoption of digital agriculture in low-resource economies lags behind that of more advanced agricultural economies, despite its significant potential to enhance production efficiency, market inclusion, and rural livelihoods. The slow uptake of digital agriculture limits opportunities for increased productivity, global market participation, and socioeconomic development (Deichmann et al. 2016; Pathak et al. 2019). There is considerable potential for the adoption of small and low-cost digital agriculture, with successful cases of uptake observed in countries such as Jordan, Egypt and Tunisia. However, adoption rates of digital agriculture vary significantly worldwide, with NENA region lagging notably behind North America and Europe in implementation. Given the interplay of social, environmental, political, and production challenges, Jordan, Egypt and Tunisia stand out as countries with substantial potential to benefit from adoption of digital agriculture, making it a relevant and timely case for further exploration.

Materials and methods

The methodology included conducting a thorough and detailed desk-based analysis to explore the current landscape of digital agriculture from the viewpoint of farmers in Jordan, Egypt, and Tunisia, complementing the findings gathered through the field-based survey. Following this, data was collected using a structured and extensive questionnaire designed to capture insights on farmers' perceptions, barriers, and experiences with digital technologies in agriculture across the NENA region. This effort aimed to identify successful models that could support an inclusive transition to digital farming and to supply essential information for comprehensive analysis. The sources reviewed included project proposals, monitoring documents, informational briefs, scientific publications, assessments, and technical documentation. The survey instrument was carefully crafted, modified, and localized for the context of each country, Jordan, Egypt, and Tunisia.

The dissemination of the survey was carried out through multiple channels, including email, Google format, social media platforms, in-person engagement during workshops, networking with farmers' organizations and cooperatives as well as field-level interactions with producers and relevant stakeholders. The main goal was to collect information from both adopting and non-adopting farmers and family-run farms, to understand current practices, digital needs, aspirations, and the factors influencing or hindering the uptake of digital tools in agriculture. Gender representation was purposefully integrated into the design to ensure balanced participation across male and female respondents. A total of 214 responses was collected, 69 responses were from farmers in Jordan of which 8 responses were from women, 74 responses were from farmers in Egypt of which 2 responses were from women, 71 responses were from farmers in Tunisia of which 5 responses were from women. Participants were intentionally chosen to reflect a broad spectrum of farmers across various agricultural regions within each country. It was observed that women's participation in the study was relatively limited, because we relied on existing farmers' networks, organizations, cooperatives, and extension services. These predominantly male-focused, leading to fewer women being reached. Despite the lower number of female respondents, the data revealed minimal differences between male and female participants regarding their access to and use of digital devices, tools, and agricultural applications. This suggests that, once engaged, women utilize digital agriculture similarly to men. Incorporating gender-sensitive approaches in digital agriculture is essential to ensure equitable access and benefits from technological advancements. Therefore, embedding gender analysis into future research will be critical for designing inclusive digital solutions and policies that cater to the needs of both women and men in farming communities.

Initial examination of the data was carried out concurrently with the data gathering phase to identify recurring trends and insights as they emerged, and to assess whether the information being obtained was adequate for analysis. The responses collected through the survey across the three countries were reviewed continuously to inform and guide the ongoing research process and were transferred into an Excel sheet for analysis purposes, and then the final analysis was made immediately after all the required data were completed using IBM SPSS Statistics for Windows, Version 20.0 Armonk, NY: IBM Corp. (IBM Corp 2011). The results were analyzed collectively, combining all participants' responses to ensure a comprehensive overview aligned with the scope of the digital agriculture study. Once the data analysis phase was finalized, both statistical summaries and narrative interpretations were developed to support the formulation of insights, discussions, and overall conclusions.

This regional survey with farmers serves as a foundational reference point for future research and impact assessments.

Furthermore, this study will be as a monitoring and evaluation and build more robust novel evidence. It will contribute to a stronger and more comprehensive understanding of digital agriculture adoption in Jordan, Egypt, and Tunisia, while considering the intricate and evolving nature of scaling such innovations within these national contexts. Collaboration among local and regional research partners played a key role in enabling this study, significantly supporting the data collection process. These partnerships not only enhanced access to diverse farming communities but also sparked increased engagement, leading to a higher number of survey participants and broader interest in the research effort.

Results

General characteristics

Questions were raised about the current use, needs, and expectations for digital agriculture solutions in countries like Jordan, Egypt, and Tunisia. To gather relevant insights, a questionnaire was used and adapted as needed to collect data directly from farmers. The survey explored several key areas, including the use of digital tools in agriculture, the usefulness of online information for family farming, and the challenges farmers face in adopting digital technologies.

The first question focused on the type of irrigation used on the farm, recognizing irrigation as a cornerstone of contemporary agriculture. The selected irrigation approach can greatly influence farm performance in terms of resource efficiency, output levels, and long-term viability. Selecting an appropriate irrigation technique requires thoughtful consideration of various factors, including the type of crops grown, soil characteristics, local climate conditions, and access to water resources. Most of respondents were using either surface irrigation (50%) or drip irrigation (50%) methods as shown below in Fig. 1. These irrigation practices are fundamental to agricultural systems, as they significantly affect water use efficiency, crop productivity, soil preservation, and overall environmental impact.

The majority of respondents 83% identified themselves as family farmers, 15% as members of a family farming unit, 14% as member of farmers' organizations which indicate that the majority of respondents were engaged in family farming. There were only 1 to 8% of respondents who were leaders of trade organization or marketing organization or farmers' organization or farmers' representative in dealing with other types of bodies. Nonetheless, those respondents were also producers and working in the farming system as shown below in Fig. 2.

The majority of respondents were between 40 to 60 years old, accounting for 60% of the total. In comparison, only 20% were aged 20 to 40, while 18% were over 60 years old, as illustrated below in Fig. 3.

An essential factor influencing the use of digital agriculture technologies is the educational background of farmers. To explore this, participants were asked to report their highest level of education. The majority stated that they held a college or university qualification, followed by a significant portion who reported having completed secondary education. Only a small fraction 17% indicated that their education did not go beyond the primary level, as depicted in Fig. 4.

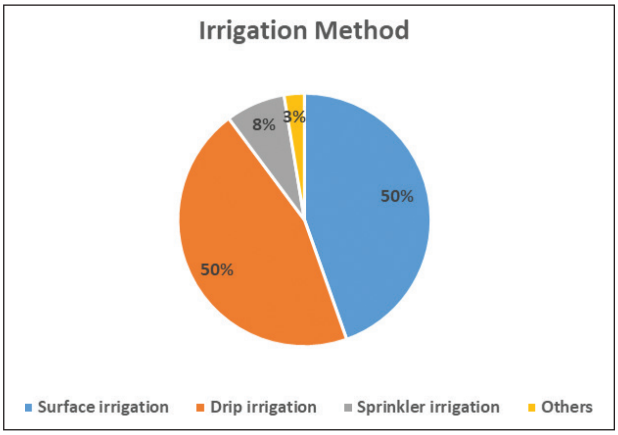

Figure 1. Irrigation techniques employed by farmers.

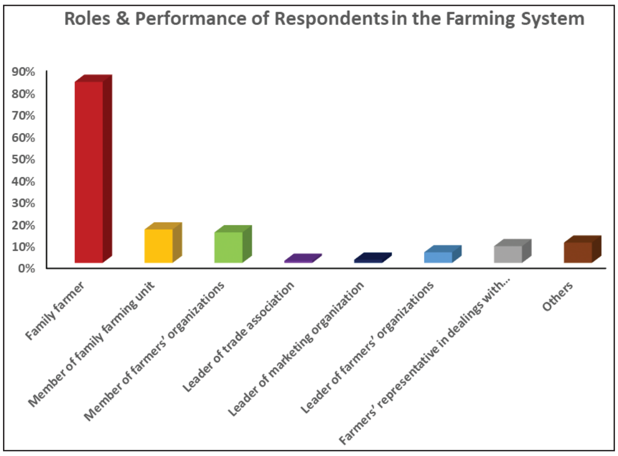

Figure 2. Responsibilities and contributions of participants within the agricultural framework.

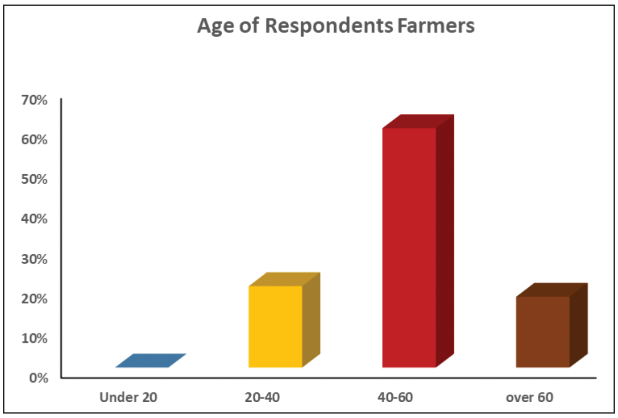

Figure 3. Age distribution of participating farmers.

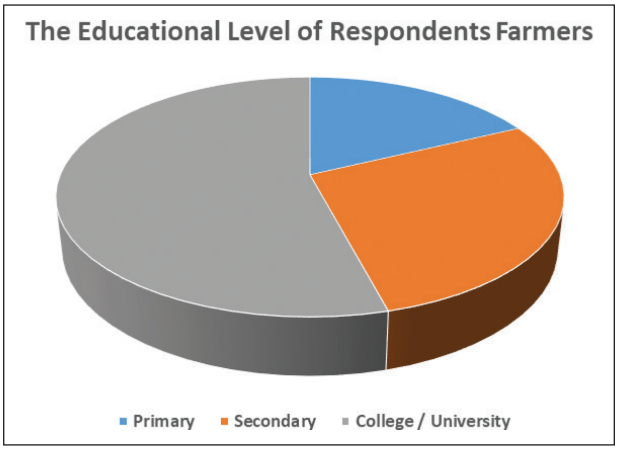

Figure 4. Acquired knowledge background of participating farmers.

Adoption of digital technologies in farming

Concerning the ownership and availability of tech equipment, 84% of participants reported utilizing smartphones. In comparison, 35% made use of computers, and 33% relied on traditional mobile phones. Only a small fraction 6% and 1% indicated they employed alternative technologies such as drones, Global Positioning System (GPS), electronic monitoring devices, or similar tools, as illustrated in Fig. 5.

From the survey results, it is clear that the majority of participating farmers had internet access. Nonetheless, 52% reported experiencing weak connectivity, and 48% noted frequent disruptions in their home internet service. Additionally, 32% of participants mentioned that the cost of internet subscriptions, software, and digital applications was high. A smaller share, 19%, admitted to lacking the skills necessary to navigate digital tools and platforms, while 6% indicated they did not own a smartphone or a modern computing device, as illustrated in Fig. 6. These results highlight a pressing need for improved digital literacy and capacity building to enhance the effective use of digital innovations. Furthermore, unreliable network infrastructure and limited bandwidth remain significant challenges in rural communities. The consistency and strength of internet connections continue to hinder access to digital services, making connectivity a major barrier for rural farmers in fully leveraging digital technologies within the agriculture sector.

It is worth highlighting that a significant portion of respondents 86% depend primarily on domestic network operators and local telecom companies for their internet access, as depicted in Fig. 7. In contrast, only a small fraction reported using alternative sources such as global telecom providers, community-based networks, non-government organizations, or cooperatives. These alternative entities often possess the resources and expertise to implement

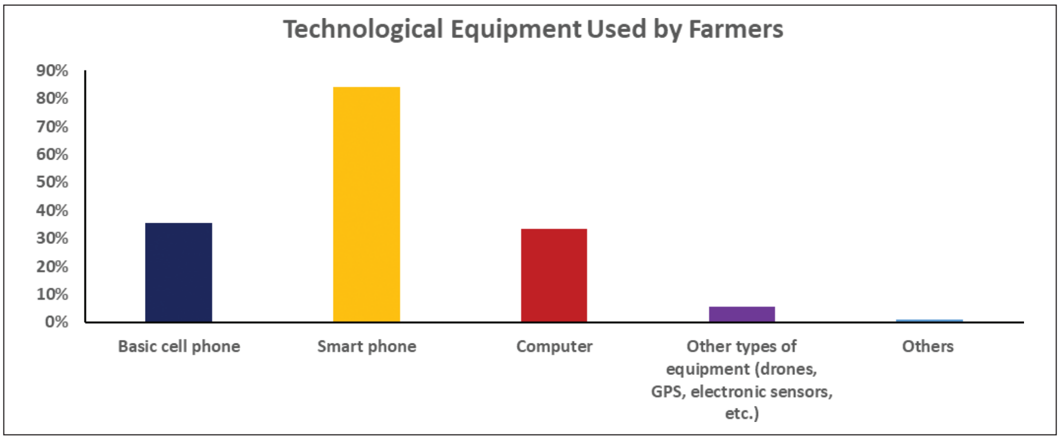

Figure 5. Digital gadgets and tools adopted by agricultural producers.

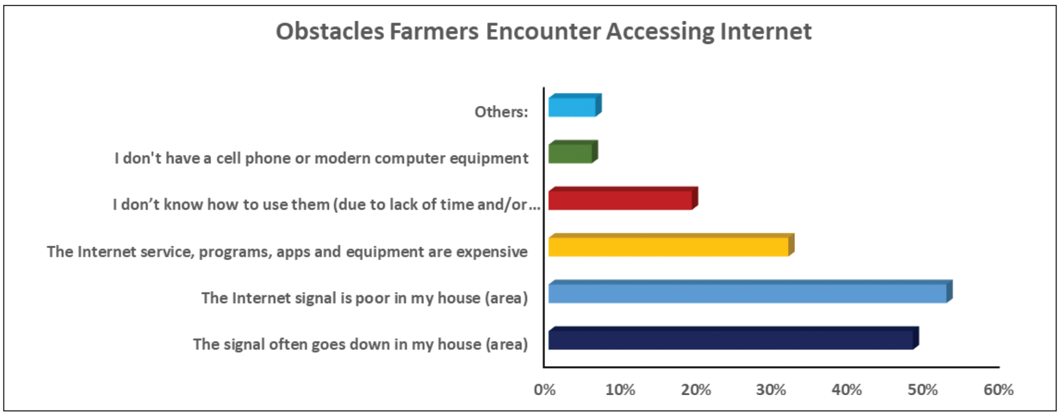

Figure 6. Challenges faced by farmers in obtaining reliable internet connectivity internet.

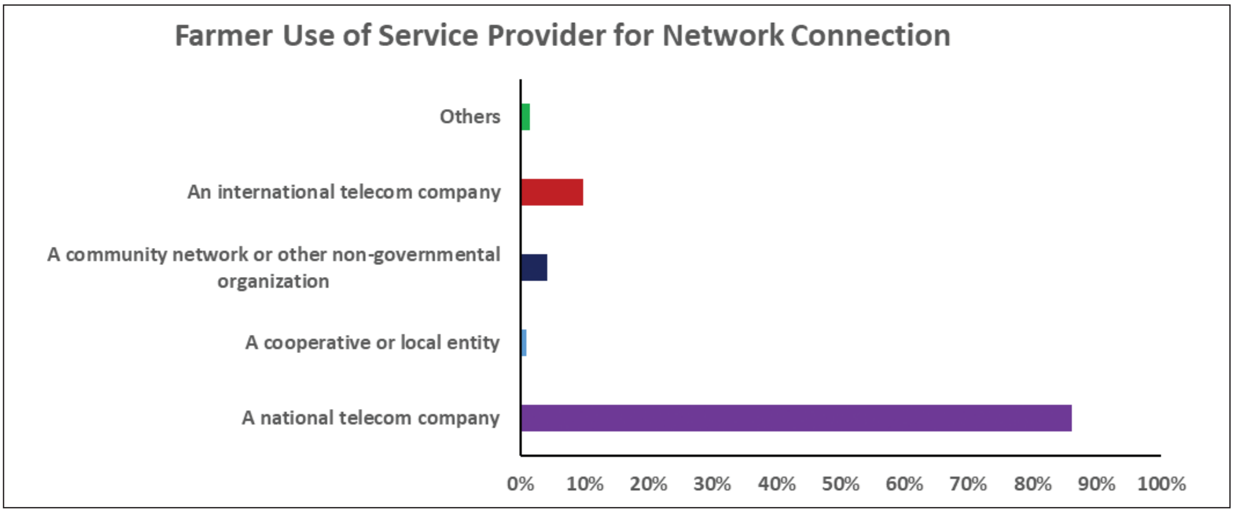

Figure 7. Farmers' preferred network providers for accessing connectivity services.

connectivity initiatives designed to deliver social, economic, and environmental benefits within the regions they serve.

Respondents reported frequent use of various digital platforms and tools. A large portion 84% and 74% noted they regularly used social media platforms like Facebook, YouTube, Instagram, TikTok, and messaging app, respectively, as illustrated in Fig. 8. Additionally, 56% relied on web browsers and search engines. This was followed by 40% who used both email and SMS services, 29% who engaged with agriculture-specific apps, 20% who participated in virtual meetings via platforms like Zoom, 17% who accessed banking, municipal, or government-related applications, and 16% who utilized cloud-based file storage solutions.

When farmers asked about their motivations for using various digital tools and applications, a majority of them 69% and 65% shared that they primarily use them to stay in touch with family, friends, and close contacts, and to keep up with agricultural developments, peer experiences, and announcements about events or training sessions, respectively. Other purposes appeared to be relatively evenly distributed among respondents: 35% mentioned accessing public and financial services, 34% cited marketing and selling their products, another 34% used them for entertainment and general information, 33% for online training and educational programs, and 31% for attending virtual meetings, as illustrated in Fig. 9.

Most respondents 60% indicated that they are utilizing agricultural extension or technical support services in rural areas as illustrated in Fig. 10. In contrast, only 21% stated they do not access any such services. Additionally, 12% mentioned relying on other forms of applications and tools, while a small proportion 9% indicated they use data from technologies such as sensors, satellites, and drones to support farm management and decision-making processes.

When farmers asked about the sources of agricultural applications and services, a majority of respondents (55%) reported utilizing digital tools offered by government agencies for extension and advisory purposes, as shown in Fig. 11. Meanwhile, 20% indicated they accessed services provided by private sector entities, and another 20% stated they did not use any such services at all. Additionally, 11% mentioned receiving agricultural digital services from non-governmental organizations, while 10% referred to other unspecified sources.

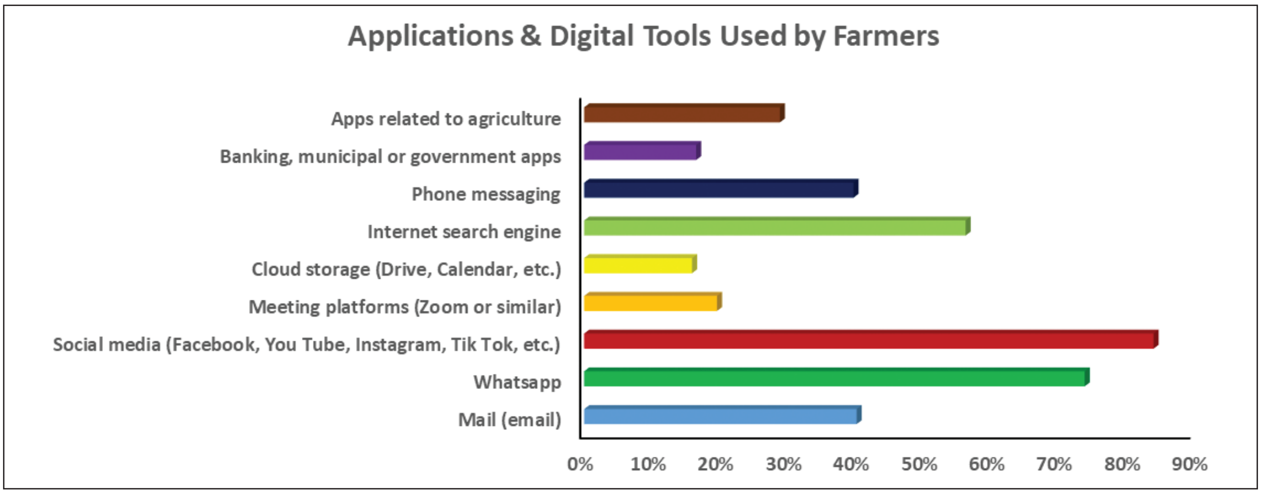

Figure 8. Commonly utilized digital platforms and technologies among farmers.

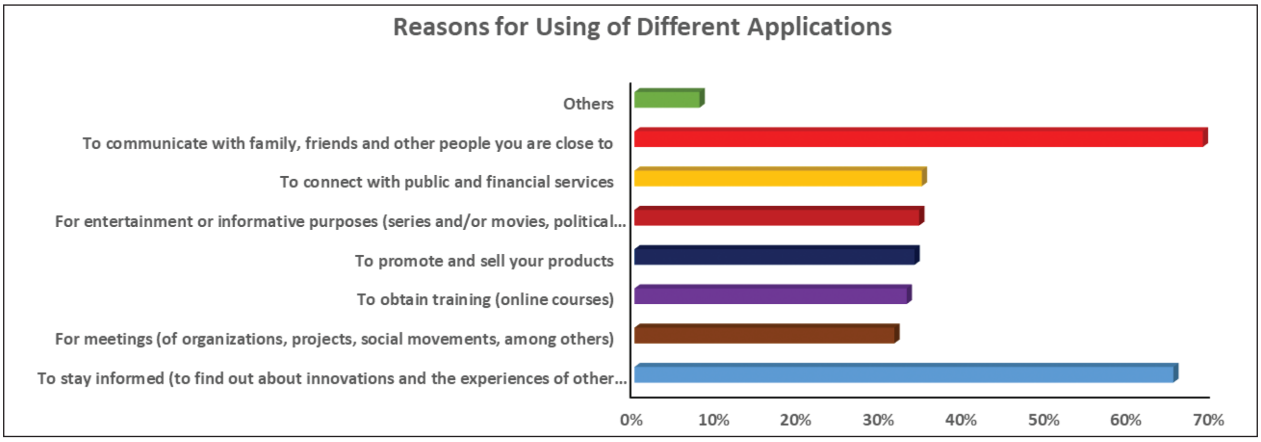

Figure 9. Purposes behind farmers' engagement with digital technologies and platforms.

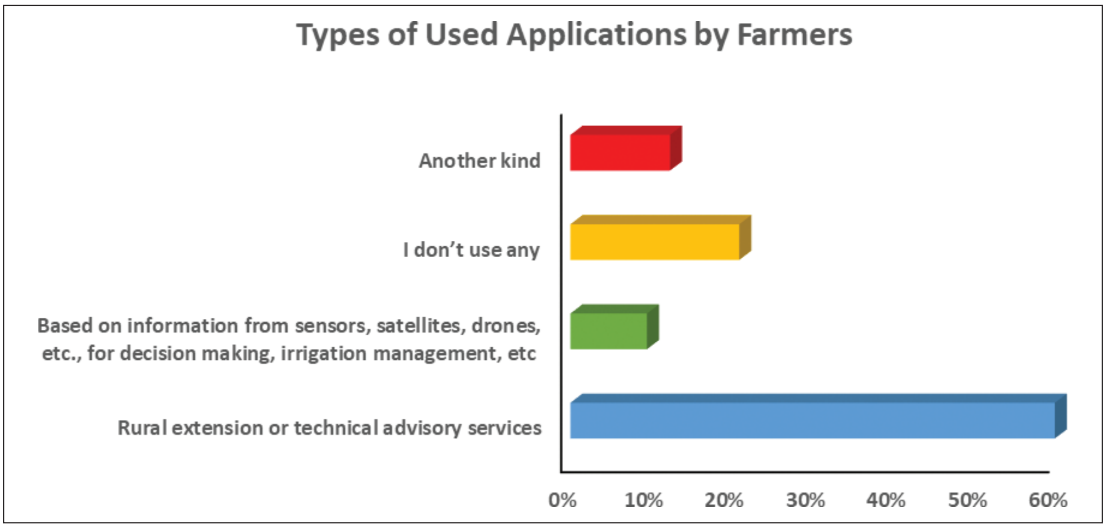

Figure 10. Types of digital tools and support services accessed by farmers.

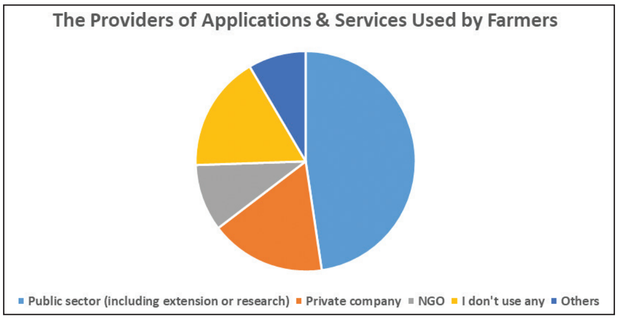

Figure 11. Sources of digital platforms and support services utilized by farmers for agricultural advisory and outreach.

Participants were asked to identify the obstacles they face when accessing digital agricultural information and services. A significant portion 45% reported difficulty in locating relevant or essential services and content. Another 34% noted that while information was available, it was either difficult to comprehend or presented in a foreign language. Additionally, 27% pointed out that some useful resources and tools were only accessible through paid subscriptions, which many farmers could not afford, and were often protected by copyright. Meanwhile, 21% stated that the content or services available did not align with their specific needs. Issues of reliability and credibility were raised by 20% of respondents, while 19% expressed concerns about the handling of farm-related data. A smaller group, 14%, indicated they faced none of the listed problems, 13% mentioned encountering other types of challenges, and 12% highlighted difficulties in understanding contractual terms, often perceiving them as unfair, as depicted in Fig. 12.

Analyzing both the present and future applications of digital agriculture offers valuable insight into its potential influence on the agricultural sector and food systems. Understanding how digital tools are currently used allows us to assess their real-time benefits and identify which practices are already delivering tangible improvements for farmers. This also highlights areas where digital technologies are most effective and could be further scaled up. Conversely, examining anticipated or intended uses of digital agriculture reveals opportunities for innovation and expansion. It provides a vision of how these technologies could evolve to address emerging challenges such as climate change, food insecurity, and the need for sustainable farming practices. By juxtaposing current and future uses, we can identify gaps in adoption, areas requiring more research, and potential new applications, such as integrating

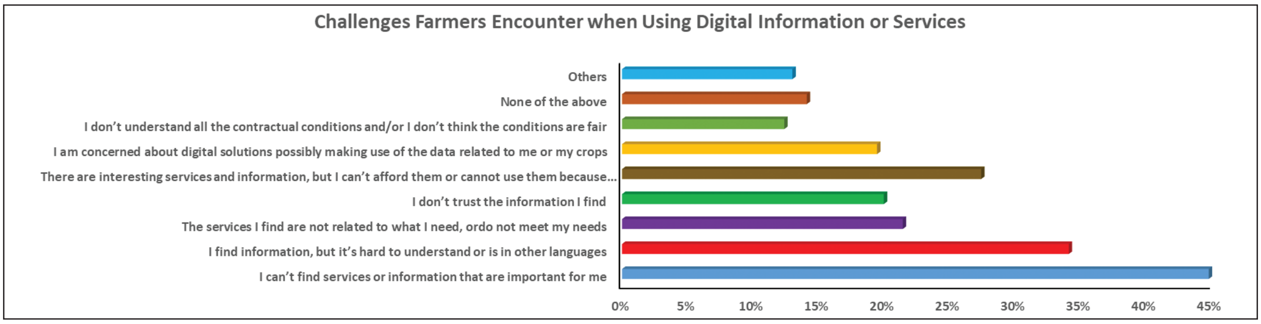

Figure 12. Obstacles farmers face in accessing and utilizing digital resources and support tools.

digital tools into supply chain logistics or enhancing consumer engagement that may currently be underexplored.

When respondents were asked about their present engagement with digital agriculture, the majority (78%) reported using it to monitor weather conditions. Market-related activities followed, with 60% utilizing digital platforms to access information on prices and market availability. Additionally, 55% indicated they used digital tools for guidance on crop production and technical support. Moderate levels of usage were reported for activities such as purchasing inputs, equipment, or service contracts (36%), and for gathering field-related data (34%), including soil condition, rainfall, and temperature. A much smaller segment of respondents noted other specialized applications, including tracking production costs and revenues, managing automated irrigation, regulating environmental controls (such as lighting, heating, and cold storage), accessing credit or making digital payments for transactions, as shown in Fig. 13. Looking ahead, 80% of respondents expressed a strong interest in using digital agriculture to optimize the application of water, fertilizers, and pesticides. Over half (55%) anticipated using these technologies to access services and products from government bodies and research institutions for more efficient production. Similarly, 53% expected to use digital tools for measuring plots, monitoring soil moisture, and detecting pests and plant diseases. Other anticipated uses include: enhancing access to formal credit (47%), receiving expert technical assistance (45%), accessing early climate warnings and weather data (42%), and expanding market reach and securing better selling prices (41%). Additionally, 35% expected to use digital agriculture for training purposes, 34% for reducing input costs, 26% to strengthen cooperatives and farmer organizations, 25% for product certification and traceability, and 24% for automating production decisions using real-time data. Another 34% indicated they would employ these tools to enhance the quality of their agricultural products, as detailed in Fig. 14. In summary, this comparison underscores the current strengths of digital agriculture while pointing to

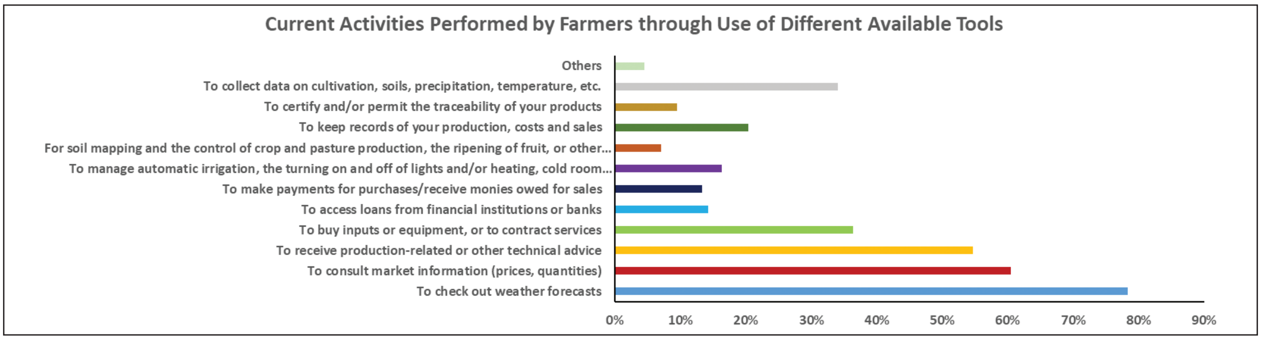

Figure 13. Farmers' present applications and practices utilizing various digital agriculture technologies.

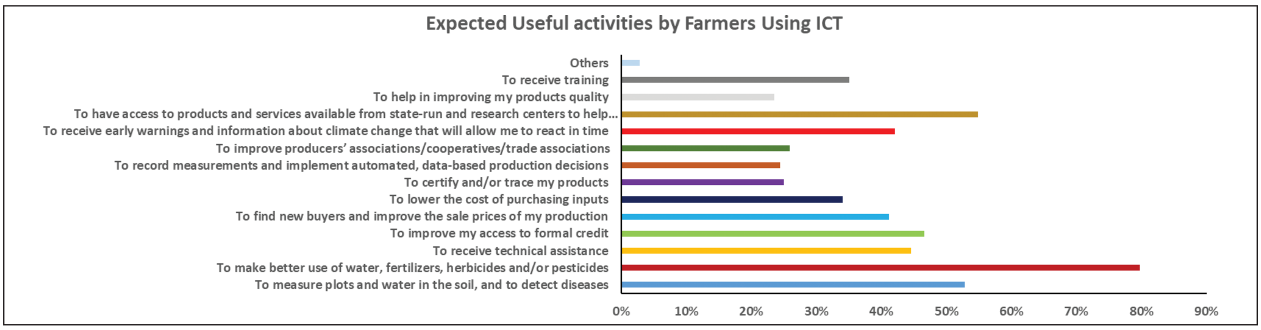

Figure 14. Anticipated applications and engagements by farmers leveraging information and communication technologies.

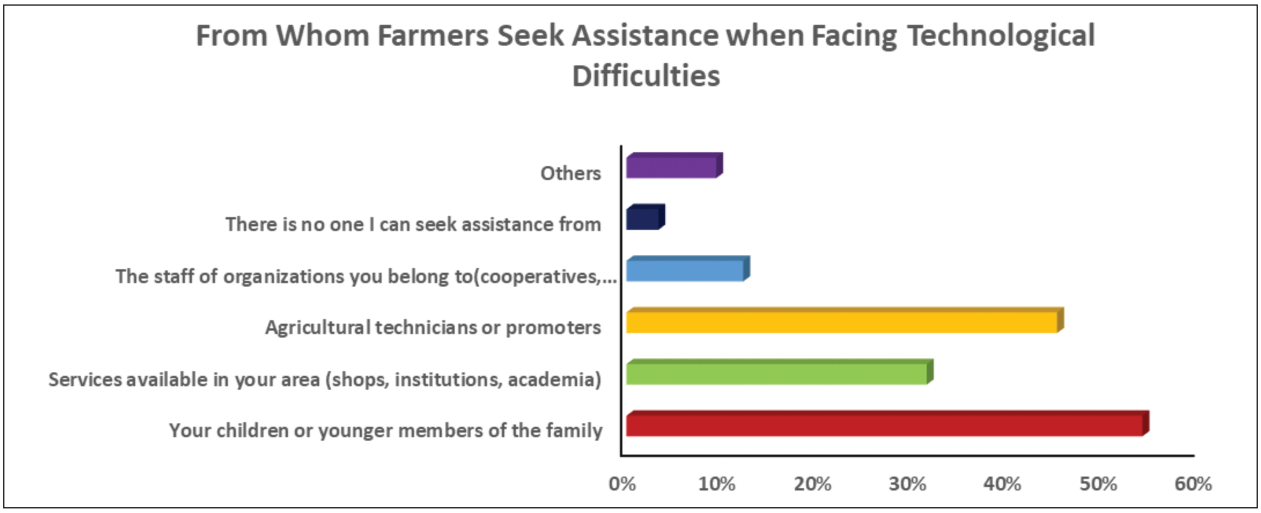

Figure 15. Primary support sources consulted by farmers when encountering technical challenges.

untapped opportunities for its expansion. It also reveals critical areas requiring further development, such as affordability, training, integration into broader services, and infrastructure support, in order to fully realize the transformative potential of digital technologies in agriculture.

As illustrated in Fig. 15, family members, agricultural experts, agronomists, and local service providers play a crucial role in advising farmers and enhancing their understanding of digital technologies. A majority of respondents identified these sources as important, with 54%, 45%, and 31% respectively acknowledging their significance.

Discussion

The choice of irrigation method is a critical decision for farmers in the region, shaping the efficiency, productivity, and sustainability of the agricultural systems. In this study, respondents primarily reported using either surface irrigation or drip irrigation, both of which have distinct advantages and challenges that shape their adoption. Moving forward, efforts to enhance farmer awareness, improve access to irrigation technology, and integrate climate-smart irrigation strategies will be essential in achieving sustainable agricultural development.

The overwhelming presence of family farmers (83%) highlights the prevalence of family-based agriculture, where farming is managed and operated by families who rely primarily on household labor. Family farming plays a crucial role in food security, rural livelihoods, and sustainable agricultural practices. Individuals identified as members of family farming units are often involved in specific tasks such as labor, management, or decision-making but may not be the primary landowners or decision-makers. The 14% membership in farmers' organizations suggests that a considerable portion of farmers engage in collective action to access resources, markets, and support services. However, a small percentage (1–8%) of respondents occupied leadership positions in trade organizations, marketing organizations, or farmers' organizations. The low representation in leadership suggests potential barriers to leadership participation such as lack of leadership training or opportunities for farmers to take on managerial roles. It is important to note that even those who held leadership positions were still actively engaged in farming. This reflects the multi-dimensional nature of farming roles, where individuals not only produce food but also engage in decision-making, advocacy, and market negotiations.

Farmer's age plays a significant role in shaping their willingness to embrace new practices. The results shed light on how different age groups approach farming, revealing important generational trends that influence progress in the agricultural sector. The high percentage of farmers aged 40 to 60 years suggests that middle-aged farmers form the backbone of agricultural activities in the study area and can be the catalyst to drive the integration of digital tools within rural households. This age group is generally characterized by significant farming experience and developing deep-rooted expertise in traditional and modern farming techniques. They are more likely to own land, access credit, and invest in farm inputs, making them key drivers of agricultural productivity. However, this age group may exhibit moderate resistance to digital agriculture solutions due to established traditional practices. The relatively low proportion of young farmers suggests challenges in attracting and retaining youth in agriculture. This age group is crucial for the agriculture sector's future, as they are generally more willing to adopt digital technologies, mechanization, and climate-smart practices. Therefore, younger farmers tend to adopt contemporary technologies more readily due to their educational background, greater willingness to engage with uncertainty, and their longer-term outlook compared to older counterparts (Akudugu et al. 2012). However, it is important to recognize that the age of the head of a farming household does not universally correlate with higher adoption rates. The presence of 18% of respondents above 60 years highlights the continued engagement of older farmers in agriculture. While this group possesses extensive knowledge and experience, there are key challenges such as slower adoption of digital tools due to limited digital literacy, and comfort with traditional practices. Therefore, there is a need for intergenerational knowledge transfer to ensure that younger farmers inherit not only land but also valuable agricultural knowledge.

The findings from this study indicate that most farmers have a college or university degree, followed by those with a high school diploma, while a smaller proportion (17%) reported having only a primary education. These variations in education levels have significant implications for adoption of digital agriculture, productivity, and overall agricultural development. The fact that a majority of farmers hold a college or university degree suggests a strong potential for adoption of digital agriculture. Higher education is typically associated with better understanding of technology, and then, farmers are more likely to grasp the benefits and functionality of digital tools, making them more open to adopting digital agriculture. The prevalence of higher education among farmers also suggests that many farmers are well-positioned to engage with digital tools and leverage innovations for increased agricultural efficiency. The second largest group of farmers reported having a high school diploma, indicating a moderate level of education. While these farmers may not have specialized training in digital technologies, they often possess basic literacy and numeracy skills. These are essential for using mobile-based agricultural applications that provide weather forecasts, market prices, and best agronomic practices. The 17% of farmers with only a primary education highlights a potential barrier to adoption of digital agriculture. Lower education levels can limit farmers' ability to engage with complex technologies, as they may face challenges in understanding digital platforms and software for farm management. Despite these challenges, low-education farmers should not be excluded from digital transformation. Tailored training and extension programs such as farmer field schools can help farmers learn how to use digital tools effectively.

The findings indicate that smartphones are the most widely used technological device among farmers. The high adoption rate suggests that mobile-based digital agriculture solutions, such as weather forecasts, market price updates, and farm management apps, have strong potential for widespread use. This is consistent with the findings of Aker (2010) and Ma et al. (2020) who reported the widespread use of mobile phones that helped bridge information gaps among farmers in developing agricultural economies. With reliable network infrastructure in rural areas, these digital tools provide an opportunity to strengthen communication between researchers, policymakers, extension agents, and farmers. Ultimately, improving knowledge exchange and decision-making in agriculture (Aker 2010; Ma et al. 2020). In contrast, only 35% of farmers use computers, which may indicate limited access to advanced data processing tools or a preference for mobile-friendly solutions that offer greater convenience. Similarly, 33% still rely on basic cell phones, which could limit their ability to engage with internet-based agricultural services but still allow for SMS-based advisory services. The low adoption of advanced technologies such as drones, GPS, and electronic sensors highlights a significant gap in access to high-tech precision agriculture tools. This may be due to cost barriers, lack of technical knowledge, or limited availability of these technologies in local markets. To bridge this gap, targeted interventions, including subsidized technology programs, digital literacy training, and infrastructure improvements, could help farmers leverage advanced digital tools for improved efficiency and productivity.

Access to the internet is a crucial enabler of digital agriculture, allowing farmers to benefit from real-time market information, weather forecasts, online training, and precision farming tools. The findings indicate that all respondents have some level of internet access, suggesting that digital connectivity is becoming increasingly common among farmers. However, several barriers to effective internet usage persist, affecting the potential for widespread adoption of digital agriculture solutions. This underscores the need for skills and knowledge to fully leverage digital technologies effectively. Network connectivity and bandwidth limitations determine the maximum data transfer rate of an internet connection, but remain a significant challenge in rural areas due to inconsistent signal quality, inadequate infrastructure, and limited access to reliable devices. The quality of internet connectivity continues to be a major concern for farmers and rural communities, particularly those in remote agricultural regions, as it directly impacts their ability to access critical digital resources and services. A significant share of small-scale farms in the NENA region is situated in countryside communities, where disparities in digital access and the reliability of internet services remain persistent and unaddressed.

The findings indicate that the vast majority of respondents depend on local service providers and national telecommunication companies for their network connection. This suggests that domestic telecom providers dominate rural connectivity, likely due to greater availability, affordability, and widespread coverage compared to international or alternative service providers. However, only a small percentage of farmers rely on international telecommunication companies, community networks, or non-governmental organizations (NGOs) and cooperatives for their internet access. The heavy reliance on local and national providers highlights the need for improved service quality, investment in rural broadband infrastructure, and expansion of affordable connectivity options. Encouraging greater participation from alternative service providers, such as community-based networks and non-profit organizations, could enhance competition, lower costs, and improve internet access for farmers. Ultimately supporting adoption of digital agriculture and rural development. It is commonly recognized that major telecom providers focus their connectivity services on profitable markets, often overlooking regions with low or scattered populations.

The findings highlight the most commonly used digital tools and applications among farmers, providing insight into how they engage with technology for communication, information access, and agricultural practices.

The overwhelming majority of respondents reported using social media platforms such as Facebook, YouTube, Instagram, and TikTok, while less respondents relied on WhatsApp. These platforms serve as key sources of information sharing, communication, and community engagement. The high adoption of WhatsApp suggests that instant messaging is a preferred method for quick communication with fellow farmers, extension officers, and market stakeholders. However, more than half of the respondents used internet search engines and browsers, indicating a strong reliance on online resources for information gathering. This suggests that farmers actively seek agricultural best practices, weather forecasts, pest control strategies, and market trends from various websites. The moderate usage of email and phone messaging suggests that while traditional digital communication remains relevant, it is not as widely adopted as social media and messaging apps. Email is often used for formal communication with agribusinesses, suppliers, and institutions, whereas phone messaging may be utilized for basic information exchange and alerts. The relatively lower usage of agriculture-specific applications indicating that specialized digital tools for farming have lower adoption compared to general-purpose platforms. These applications often provide precision farming insights, pest and disease management tools, and farm planning solutions. This suggests possible barriers such as lack of awareness or knowledge about agricultural apps, limited availability of locally relevant or user-friendly applications, and challenges in digital literacy or access to smartphones with sufficient capabilities. Furthermore, the use of online platforms such as Zoom for meetings and workshops, highlighting a growing trend in virtual learning and training sessions. This is particularly useful for farmers who may lack physical access to agricultural extension services but can still participate in digital capacity-building initiatives. The use of digital banking and government applications indicates some level of financial and administrative digitalization among farmers. These platforms likely support mobile banking for financial transactions and credit access and government services such as agricultural subsidies, land registration, and licensing. However, this adoption remains relatively low, promoting financial inclusion and e-governance solutions could help farmers streamline transactions and access essential services more efficiently. A smaller proportion of respondents reported using cloud storage services, suggesting that digital file management and data storage are not yet a widespread practice among farmers.

The most common reason for using digital tools cited by respondents is to stay connected with family, friends, and other close contacts. This suggests that social and personal interactions drive digital engagement, with farmers using platforms such as WhatsApp, Facebook, and other messaging apps to maintain relationships, coordinate daily activities, and stay in touch with their communities. Given that rural areas can be geographically isolated, digital communication tools help bridge these distances. A significant number of respondents use digital tools to keep up with agricultural advancements, learn from other farmers, and participate in seminars and meetings. This indicates that farmers value digital platforms as sources of agricultural knowledge and peer learning. This trend reflects the growing role of digital agriculture in knowledge dissemination, making it easier for farmers to adopt best practices and improve productivity. There was a notable number of respondents uses digital tools to connect with public and financial services, indicating an increasing reliance on mobile banking, government portals, and financial management applications. This trend suggests that farmers are gradually adopting digital financial services for transactions, credit access, and subsidies. There was also a notable number of respondents uses digital platforms to market and sell their products, showing a growing interest in digital commerce. These observations align with the results presented by Konfo et al. (2023), who highlighted that digital innovation platforms facilitate improved linkages between farmers and buyers, allowing for more streamlined and effective sales of agricultural products. Nevertheless, the moderate adoption rate suggests that many farmers may still lack knowledge, skills, or confidence in online selling, presenting an opportunity for training programs in digital marketing and e-commerce. The use of digital tools for entertainment and information purposes suggests that farmers engage with digital content beyond agriculture. Platforms such as YouTube, TikTok, and Facebook provide news updates, educational content, and entertainment, making digital technology a multifunctional tool in their daily lives. A significant portion of farmers are using digital tools for training and education, showing that online learning is becoming more accessible and valuable for agricultural communities. This indicates a strong interest in continuous learning and skill development. Finally, respondents reported the use of digital tools for meetings and professional engagements. The adoption of platforms like Zoom and Google Meet suggests that farmers are increasingly participating in virtual events. While this usage rate is lower compared to social interactions and seeking agricultural information, it indicates a growing acceptance of digital engagement in the professional aspects of farming.

The findings reveal important insights into how farmers engage with digital applications and services for agricultural purposes. The responses indicate a strong reliance on rural extension and technical advisory services. This high adoption rate suggests that farmers value professional support and expertise, reinforcing the need to strengthen and expand digital advisory services through mobile applications, online platforms, and AI-driven decision-support tools. However, there was low adoption of advanced digital technologies using data from sensors, satellites, and drones for decision-making and farm management. This suggests that precision agriculture technologies have not yet gained widespread traction among farmers, likely due to high initial investment costs for purchasing and maintaining digital equipment, and technical complexity, requiring specialized knowledge for effective use.

The majority of respondents uses digital technologies to access farming guidance and support services offered by public sector institutions. This indicates that public institutions play a crucial role in supporting farmers through digital platforms, offering guidance on best agricultural practices, market trends, weather updates, and sustainable farming techniques. The high reliance on government services suggests the need for continued investment in digital infrastructure and training programs to further enhance accessibility and effectiveness. However, a smaller percentage of farmers reported using digital agricultural services provided by private companies. Private-sector solutions often include agri-tech applications, precision farming tools, and commercial advisory services. While adoption remains lower compared to government services, private-sector involvement could enhance innovation and efficiency in digital agriculture, particularly through market-driven solutions tailored to specific farmer needs.

Farmers face several obstacles when accessing and utilizing digital agricultural information and services, which can limit their ability to benefit from digital transformation. The most significant challenge reported by farmers is the inability to find important and relevant digital services. This suggests gaps in content availability and customization of digital platforms for agricultural needs. However, many farmers find the available information difficult to comprehend due to technical complexity or language barriers. Simplified content and local language support could improve accessibility. Some farmers encounter useful digital services and data, but these require payment, making them financially inaccessible. More affordable or subsidized digital solutions could enhance adoption. Some farmers also reported that available services do not align with their actual needs, indicating the necessity for user-driven content development and tailored advisory services. A portion of respondents distrust the accuracy and reliability of digital agricultural data. Additionally, concerns over farm and crop data security highlight the need for transparent data policies and farmer protections. Some farmers struggle with understanding digital service contracts and find contractual terms unfair, signalling the need for clearer and farmer-friendly agreements.

Farmers utilize digital agriculture tools for various purposes, with the most common being weather forecasting, which helps them plan farming activities efficiently. Many farmers rely on digital tools to track prices and market demand, aiding in better sales decisions. Over half of farmers use digital platforms to receive expert recommendations on farming practices and crop management. A significant portion of farmers use digital tools to buy seeds, fertilizers, machinery, or other services. Farmers leverage digital tools to monitor cultivation conditions, including soil health, precipitation, and temperature, enhancing decision-making. However, a small percentage utilize digital tools for record-keeping, irrigation management, automation (e.g., lighting, temperature control), accessing loans, and digital payments. However, farmers anticipate leveraging digital agriculture for a range of efficiency, productivity, and market-related benefits. The most significant expected use is improving the efficiency of water, fertilizers, and pesticides, which can enhance sustainability and reduce costs. This is consistent with the findings of Abiri et al. (2023) and Getahun et al. (2024) who reported that the use of digital technology tools can minimize the use of inputs such as fertilizers and pesticides. Many farmers see digital agriculture as a means to connect with public agricultural services and research institutions for better production management. Farmers are interested in using digital tools to measure plots, monitor soil moisture, and detect pests and diseases for improved crop management. Digital tools are expected to facilitate access to credit and technical assistance, helping farmers invest in and improve their operations. Many farmers seek early warnings on climate events and better connections with buyers to secure higher prices. Some farmers foresee digital agriculture helping with training, cost reduction, cooperative strengthening, product certification, automation, and quality improvement.

Farmers rely on various sources for consultation and knowledge enhancement regarding digital technologies. The most frequently cited resource, suggesting that peer learning within households plays a crucial role in digital adoption. Agricultural technicians provide practical guidance and hands-on support, helping farmers integrate digital tools effectively. Farmers also seek advice from specialists and available local services, indicating the importance of expert recommendations for improving digital technology use.

The findings of this research reveal a nuanced interplay between farmers' educational backgrounds and their engagement with digital agriculture. The successful adoption and utilization of digital farming tools often depend on possessing specific knowledge and technical competencies. Farmers with more advanced education tend to be better equipped to navigate digital technologies, benefiting from improved access to information, reliable internet services, and relevant training opportunities. Conversely, those with limited formal education may encounter obstacles in embracing digital tools due to a lack of exposure, insufficient digital literacy, and restricted access to supportive resources. This disparity can deepen the digital gap among farmers, reinforcing pre-existing socioeconomic inequalities (Hennessy et al. 2016). To address this issue, it is essential to invest in inclusive educational and capacity-building initiatives that cater to farmers across all educational levels. Such efforts can help close the digital divide, enabling broader adoption of digital agriculture and contributing to enhanced productivity, environmental sustainability, and better livelihoods in rural communities.

Conclusion

The family farming remains the backbone of the agricultural system, therefore, strengthening farmer organizations, leadership opportunities, and access to modern agricultural technologies could further enhance the efficiency, productivity, and sustainability of farming communities. The middle-aged farmers dominate the agricultural sector, while youth participation remains limited, and older farmers continue to play a role despite physical and technological challenges.

Addressing barriers to youth engagement, promoting digital solutions among middle-aged farmers, and facilitating knowledge transfer from older farmers is essential for building a resilient, productive, and future-ready agricultural sector. The high level of education among farmers in NENA region creates a favourable environment for digital agriculture adoption. However, educational disparities remain a challenge, particularly for those with lower levels of formal education. Bridging this gap through tailored training, simplified digital solutions, and inclusive agricultural policies can ensure that all farmers benefit from digital transformation. Strengthening digital literacy and accessibility will be key to enhancing technology uptake, improving farm productivity, and achieving long-term agricultural sustainability.

Significant challenges were identified such as poor connectivity, high costs, low digital literacy, and lack of access to modern devices. Therefore, addressing these barriers, through improved rural internet infrastructure, affordable digital services, targeted training programs, and greater access to smart devices, will be essential for unlocking the full potential of digital agriculture. Providing farmers with cost-benefit analysis data at the decision-making stage is essential for addressing concerns and minimizing perceived economic risks associated with adopting new technologies. Demonstrating the financial viability of digital agriculture through economic studies can help validate its potential to enhance farm profitability, particularly by improving resource efficiency (Daberkow and McBride 2003; Schimmelpfennig and Ebel 2016). Further research is needed to generate concrete evidence of the economic advantages of digital agriculture adoption, which could strengthen farmer confidence in investing in precision technologies. Social media and messaging apps were identified as the most widely used digital tools, reflecting a preference for interactive, user-friendly platforms. However, there is a need for greater awareness, training, and infrastructure development to support farmers in fully utilizing digital agriculture technologies. The diverse ways farmers use digital tools, with communication and information being the top priorities. But, digital marketing, financial services, and e-learning still have room for growth.

Traditional rural extension services were identified as the primary source of digital agricultural support, while advanced precision agriculture tools were underutilized. Encouraging broader adoption of data-driven decision-making tools could further enhance farm productivity, sustainability, and resilience to climate and market challenges. Government organizations remain the dominant providers of digital agricultural tools, but private-sector engagement and NGO involvement also play a role. Key barriers to digital adoption include lack of relevant content, comprehension issues, affordability, and trust concerns. Addressing these challenges through localized, affordable, and farmer-focused digital solutions can enhance the effectiveness and impact of digital agricultural services. While weather forecasts, market tracking, and technical advisory services are the most widely used digital applications, adoption of advanced digital agriculture functions like automation, financial transactions, and data-driven farming remains limited. Expanding awareness and accessibility to these tools could further enhance productivity and efficiency in farming operations. Farmers expect digital agriculture to boost efficiency, enhance financial and market access, and improve decision-making. However, training, affordability, and infrastructure improvements will be key to realizing these benefits at scale.

This study is unique in its contribution to understanding the profound perceptions, obstacles, motivations, and concerns related to the adoption of digital agriculture tools. It emphasizes the significance of enhancing collaboration and aligning shared goals among regional institutions involved in agricultural research and innovation. Additionally, it lays the groundwork for upcoming investigations and the formulation of informed policies in the realm of digital agriculture.

Conflict of interest

The authors affirm that there are no competing interests. The funding entities were not involved in any aspect of the study's design, data collection, analysis, or interpretation, nor did they influence the writing of the manuscript or the decision to disseminate the findings.

Data availability

All data are securely stored and available.

Ethics approval

The study was conducted in accordance with the Declaration of the Food and Agriculture Organization in Rome, and was approved by the Scientific and Ethics Committee at the FAO in Rome [GCP/GLO/047/EC].

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Material from other sources

No material has been reproduced from other sources.

Authors' contributions

Author Contributions: Conceptualization, N.T., R.S. and V.P.; methodology, N.T., R.S. and V.P.; software, N.T.; validation, N.T., R.S., and A.A.; formal analysis, N.T.; investigation, N.T. and R.S.; resources, N.T., R.S., V.P. and A.A.; data curation, N.T., R.S. and A.A.; writing - original draft preparation, N.T.; writing - review and editing, N.T., R.S., V.P., and A.A.; visualization, N.T.; supervision, N.T., R.S. and V.P.; project administration, N.T. and R.S.; funding acquisition, N.T. and R.S. All authors have read and agreed to the published version of the manuscript.

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