Review Article

A Review on Levering Technology for Sustainable Development in Agricultural Extension Program

Abstract

The transformative potential of technology in agricultural extension programs and its implications for sustainable development. By integrating technologies such as artificial intelligence (AI), machine learning, blockchain, and precision farming tools, agricultural practices can be significantly improved in terms of efficiency, productivity, and sustainability. The discussion is organized into a comprehensive framework that examines successful implementations and outcomes in both developed and developing regions, highlighting case studies that demonstrate the beneficial impacts of technology on farming. Key challenges such as the digital divide, financial constraints, policy and regulatory hurdles, and environmental considerations are critically analyzed to understand the barriers to technology adoption and effective integration. Recommendations are made for policy adjustments, the deployment of inclusive technology strategies, and considerations for long-term sustainability to ensure that these technological advancements contribute effectively to global food security and adhere to Sustainable Development Goals (SDGs). Additionally, future directions are suggested, focusing on emerging technologies like next-generation biotechnologies and their potential impacts. The paper concludes that while the introduction of innovative technologies in agricultural extension holds great promise for transforming agricultural practices, a balanced approach is required. This approach should not only embrace technological innovation but also address the socio-economic and environmental challenges associated with technology adoption. Through strategic policy frameworks, tailored technology solutions, and ongoing support for capacity building, technology can be effectively leveraged to enhance agricultural productivity and sustainability, thereby supporting the broader objectives of economic stability, environmental stewardship, and social equity in rural communities worldwide. The insights provided in this paper are intended to guide policymakers, stakeholders, and practitioners in the agricultural sector towards more effective and sustainable integration of technology in agricultural extension services.

Keywords: *Technology, Sustainability, Biotechnology, Blockchain, GIS, Extension, Innovation*

I. Introduction

A. Agricultural Extension Programs

Agricultural extension programs are designed to enhance the transfer of knowledge and technology from research institutions to farmers to improve agricultural productivity, food security, and livelihoods. The Food and Agriculture Organization (FAO) defines agricultural extension as a "service or system which assists farm people, through educational procedures, in improving farming methods and techniques, increasing production efficiency, and enhancing the quality of life" [1]. These programs typically involve a range of activities, including on-farm demonstrations, training sessions, and the dissemination of research findings to farmers [2].

The core purpose of agricultural extension services is multifaceted. Primarily, it aims to increase agricultural productivity and improve the quality of life for farmers. This is achieved by facilitating access to information on best practices and new technologies, which can substantially enhance crop yields and animal production [3]. Extension services play a crucial role in encouraging sustainable agricultural practices, which are vital for ensuring long-term food security and environmental sustainability [4].

B. Importance of Sustainable Development in Agriculture

Sustainable development in agriculture involves practices that meet current agricultural needs without compromising the ability of future generations to meet their own needs. This concept is critical because agriculture inherently impacts natural resources that are vital not only for current food production but also for the ecological balance necessary for future agricultural productivity [5]. Sustainable agricultural practices, therefore, aim to increase food production efficiency, reduce the environmental impact of farming, and enhance the resilience of agricultural systems against the backdrop of global challenges like climate change [6]. The United Nations' Sustainable Development Goals (SDGs) particularly highlight the importance of sustainable agriculture as a cornerstone for poverty reduction, zero hunger, good health, and environmental sustainability [7]. The integration of sustainable practices in agriculture is seen not only as an environmental or economic issue but as a complex system that encompasses social, economic, and ecological dimensions [8].

C. Role of Technology in Enhancing Agricultural Extension Services

Technology plays a transformative role in modern agricultural extension services. Through the integration of Information and Communication Technology (ICT), Geographic Information Systems (GIS), remote sensing, and mobile technology, extension services have been able to enhance their reach and effectiveness dramatically [9]. For example, mobile phones have been used extensively to provide farmers with timely information on weather forecasts, market prices, and new farming techniques, thereby enabling better decision-making [10]. In addition to mobile technology, the Internet of Things (IoT) and Artificial Intelligence (AI) are increasingly being incorporated into agricultural extension services. IoT devices can collect and transmit data on soil moisture, crop health, and weather conditions, which can be used to provide precise farming advice to farmers [11]. AI, on the other hand, can analyze large datasets to predict agricultural outcomes, thus enhancing the advisories provided by extension services [12].

II. The Need for Technology in Agricultural Extension

A. Challenges Faced by Traditional Extension Services

1. Limited Reach and Accessibility

One of the primary challenges facing traditional agricultural extension services is their limited reach and accessibility. Many rural areas where smallholder farms are most prevalent lack sufficient access to the latest agricultural knowledge and technology due to geographic isolation and poor infrastructure [13]. Extension agents often struggle to visit each farm regularly, leaving many farmers without the necessary guidance for long periods [14].

2. Scalability Issues

Scalability is another significant challenge. Traditional methods rely heavily on face-to-face interactions, which are not only time-consuming but also labor-intensive, limiting the number of farmers an individual agent can support effectively [15]. As a result, the scalability of services is constrained, and expanding these services to a larger number of farmers becomes financially and logistically impractical under the traditional model [16].

3. Resource Constraints

Resource constraints encompass a range of issues, including limited financial, human, and material resources. Funding for extension services is often inadequate, which affects the ability to hire and train enough qualified staff, update educational materials, and utilize new technologies that could improve service delivery [17]. This lack of resources can lead to outdated or irrelevant advice being disseminated to farmers, hampering their ability to improve productivity and sustainability [18].

B. Potential of Technology to Overcome These Challenges

1. Increasing Efficiency

Technology offers numerous tools to increase the efficiency of agricultural extension services. Mobile technology, in particular, has transformed how information is disseminated, allowing for more frequent and cost-effective communication between extension agents and farmers. For instance, mobile apps and SMS-based services enable farmers to receive timely advice on pest management, weather forecasts, and market prices directly on their phones [19]. This method has proven to be highly efficient in reaching a large number of farmers with minimal additional cost [20].

2. Enhancing the Quality of Service Delivery

The quality of service delivery can be significantly enhanced through the use of technology. Geographic Information Systems (GIS) and remote sensing, for example, provide detailed and accurate data about soil health, crop status, and water availability, which can be used to tailor advice to specific conditions at individual farms [21]. This targeted advice ensures that farmers implement the most appropriate practices for their specific circumstances, leading to better outcomes [22]. The integration of Artificial Intelligence (AI) and machine learning in extension services can facilitate the processing of vast amounts of data to generate insights that were previously unattainable [23]. These technologies can predict crop diseases and recommend preventative measures, enhancing the overall effectiveness of agricultural advice [24].

3. Examples from Recent Initiatives

Several recent initiatives illustrate the potential of technology to transform agricultural extension services. In Kenya, the iCow app allows farmers to keep track of their herd's gestation periods and access veterinary advice, which has led to reported increases in productivity and income [25]. Similarly, in India, the e-Choupal initiative by ITC Limited provides computers and Internet access to rural farmers to get up-to-date information on weather and market prices, significantly improving their negotiating power and income [26]. In Latin America, the use of video tutorials and e-learning platforms has enabled extension services to reach more farmers with less reliance on physical travel, which has been particularly beneficial during the COVID-19 pandemic when traditional face-to-face interactions were limited [27].

III. Types of Technologies Leveraged in Agricultural Extension

A. Information and Communication Technology (ICT) Solutions

1. Mobile Applications

Mobile applications are increasingly becoming crucial tools in agricultural extension services, providing farmers with direct access to vital information and resources. Apps such as Plantix, WeFarm, and AgroApp offer functionalities that range from disease diagnosis through image recognition, peer-to-peer advice sharing, and real-time market price information [28]. The convenience and accessibility of mobile applications allow for immediate application of solutions, making them particularly effective in enhancing agricultural productivity. One significant example is the use of the Plantix app, which analyzes photographs taken by farmers of their crops to diagnose potential diseases, nutrient deficiencies, or pest problems. By 2020, it was reported that Plantix had over 500,000 users in India alone, demonstrating substantial user engagement and impact [29]. The application not only provides disease identification but also recommends management practices, contributing significantly to reducing crop losses.

2. SMS and Voice Messaging Services

SMS and voice messaging services are widely used for their simplicity and broad reach, especially in regions with limited internet connectivity. Services like Esoko in Africa disseminate market prices, weather forecasts, and farming tips directly to farmers' mobile phones via SMS, significantly impacting decision-making and income stability [30]. Voice services have also been pivotal, particularly in regions with low literacy rates. Projects like AvaajOtalo in India offer a dial-in service where farmers can ask questions and receive voice-recorded answers from experts. This service reported over 100,000 registered users within a few years of its launch, illustrating its effectiveness and popularity [31].

3. Radio and Television Broadcasts

Radio and television have long been traditional means of reaching broad audiences. In agricultural extension, they are used to broadcast weather updates, agricultural news, and educational programs. These mediums are particularly effective in reaching large numbers of rural farmers who may not have access to the internet or mobile technology [32]. In Nicaragua, for instance, the use of radio programs to broadcast cocoa cultivation techniques led to a noticeable increase in cocoa yields and quality, as reported by local farmers [33]. Similarly, television programs in India like 'KrishiDarshan' on Doordarshan have been broadcasting since the 1960s, providing farming advice to millions of farmers across the country [34].

B. Geographic Information Systems (GIS) and Remote Sensing

GIS technology has revolutionized the way agricultural land is mapped and analyzed. By creating detailed maps of agricultural regions, GIS helps in assessing land use patterns and suitability for different types of crops [35]. This capability is crucial for planning purposes and for assessing changes over time due to factors like climate change or urbanization.

Remote sensing, on the other hand, uses satellite or aerial imagery to gather data on large areas quickly, providing vital information on crop health, water stress, and even soil conditions. This data is invaluable for precision farming applications that aim to optimize resource use and increase crop yields [36].

Accurate weather forecasting and monitoring are essential for effective agricultural planning and management. GIS and remote sensing play critical roles in this area by providing detailed climatic data over broad geographic areas. Advanced weather models integrated with GIS allow for precise weather predictions, which can be used to advise farmers on the best planting and harvesting times and on necessary adjustments for weather events [37]. The use of these technologies has been pivotal in regions prone to extreme weather conditions, where timely information can mean the difference between crop success and failure. For example, the Famine Early Warning Systems Network (FEWS NET) utilizes satellite data to monitor weather patterns and assess drought conditions, providing early warnings to farmers and governments [38]. These technologies, integrated into agricultural extension programs, enable more precise, efficient, and proactive farming practices. By leveraging ICT solutions along with GIS and remote sensing, agricultural extension services can enhance their reach and impact, contributing significantly to agricultural productivity and sustainability.

C. Blockchain and Big Data

Blockchain technology is increasingly recognized for its potential to enhance transparency and traceability in agricultural supply chains. By creating a secure, decentralized, and immutable ledger, blockchain can record transactions in a way that is transparent and accessible to all stakeholders in the supply chain, from farmers to consumers [39]. This transparency helps in reducing fraud, ensuring compliance with safety standards, and boosting consumer confidence in agricultural products. For instance, the use of blockchain in the coffee industry has allowed consumers to trace the product's journey from the farm to the cup. Companies like Starbucks and IBM are collaborating on "Thank My Farmer" app, which uses blockchain to provide consumers with detailed information about where their coffee comes from, the farmer who grew it, and the sustainability of the production practices used [40]. Blockchain can significantly enhance the effectiveness of certifications such as organic or fair-trade labels. By providing a tamper-proof record of the entire supply chain process, blockchain ensures that all certified products adhere to the standards claimed, thereby preventing label fraud and supporting ethical practices in farming [41].

Big Data in agriculture involves the collection, processing, and analysis of vast amounts of data to make informed decisions that enhance the efficiency, productivity, and sustainability of agricultural practices. Big Data can come from various sources, including satellites, sensors, GPS, weather stations, and more, and can be analyzed to uncover patterns and insights that were previously invisible [42]. For example, predictive analytics tools can analyze weather data, crop performance data, and soil health data to forecast future crop yields or identify potential pest outbreaks before they become unmanageable. Such data-driven insights allow farmers to make preemptive decisions that can save both time and resources [43]. Big Data analytics can optimize resource use across the agricultural value chain. For instance, data on crop yields and local weather conditions can be used to fine-tune the amounts of water and fertilizer applied to fields, thus reducing waste and environmental impact [44].

D. Drones and Automated Machinery

Drones, or unmanned aerial vehicles (UAVs), are revolutionizing the way agricultural lands are monitored. Equipped with advanced imaging technologies, drones can provide high-resolution field images that help in identifying crop stress, estimating soil conditions, and even detecting weed or pest infestations [45]. This information is invaluable for maintaining crop health and optimizing yields. Drones offer a unique advantage over traditional ground-based or manned aircraft monitoring methods: they can collect data more frequently and more cheaply while minimizing the disturbance to crops. As such, drones are an excellent tool for precision agriculture—allowing for the monitoring of large areas of farmland efficiently and effectively [46].

Precision farming is a management strategy that uses information technology to ensure that crops and soil receive exactly what they need for optimum health and productivity. The key to precision farming is the application of precise and correct amounts of inputs like water, fertilizer, and pesticides, at the correct time to the crop, thereby increasing efficiencies and reducing costs [47]. Automated machinery plays a critical role in precision farming. For instance, GPS-equipped tractors and implements can be programmed to sow seeds or apply fertilizers at precise locations and rates across a field, minimizing overlaps and reducing wastage. These technologies not only help in reducing the amount of chemicals used but also in increasing yields by ensuring optimal plant growth conditions [48]. Automated irrigation systems can use data from soil moisture sensors to apply water exactly when and where it is needed, avoiding the inefficiencies and resource waste associated with traditional irrigation methods [49].

IV. Impact of Technology on Sustainable Development Goals

The Sustainable Development Goals (SDGs) set by the United Nations aim to address global challenges such as poverty, inequality, climate change, environmental degradation, peace, and justice. The integration of technology in agriculture has significant implications for several of these goals, particularly those related to poverty reduction, zero hunger, decent work, and economic growth, climate action, and life on land. Below we explore the impacts of technology on these aspects in detail.

A. Enhancing Productivity and Sustainability

1. Case Studies Illustrating Successful Outcomes

Numerous case studies demonstrate how technology has successfully enhanced agricultural productivity and sustainability, contributing directly to SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production).

- **Precision Farming in the U.S.:** A study on precision farming techniques in the United States shows that the use of GPS and GIS technologies for crop management has increased yields by up to 15% while reducing the use of water, fertilizer, and pesticides by 20% [50]. This not only boosts food production but also reduces the environmental footprint of farming.
- **Mobile Technology in Kenya:** The M-Pesa mobile payment system has revolutionized financial access for farmers, enabling them to invest more efficiently in their farms and access markets more effectively. This has led to an estimated 10% increase in farm incomes among users [51].

2. Quantitative Improvements (Yield, Resource Use Efficiency, etc.)

Advancements in agricultural technology have resulted in measurable improvements in yield and resource use efficiency:

- **Drip Irrigation:** In India, the implementation of drip irrigation technology has led to an average yield increase of about 50% for various crops, alongside a significant reduction in water usage of approximately 40% [52].

- **Disease Detection Apps:** In Colombia, the use of smartphone apps for detecting plant diseases has decreased pesticide use by 20% and increased yields by 15%, as farmers can treat diseases more effectively and promptly [53].

B. Economic Impacts

1. Cost Reduction

The deployment of technology in agriculture often leads to significant cost reductions through more efficient resource use and improved pest and disease management:

- **Automated Machinery:** In Brazil, the use of automated machinery and equipment has reduced the cost of cultivation by about 20% due to decreased labor costs and enhanced precision in input application, minimizing waste [54].

- **Sensor-Based Irrigation Systems:** Studies have shown that the use of sensor-based irrigation systems can reduce water costs by up to 30% [55].

2. Increased Income for Farmers

Technology increases farm incomes through higher yields and access to markets:

- **E-commerce Platforms in China:** Platforms like Alibaba have allowed Chinese farmers to sell directly to consumers, bypassing the traditional, often costly distribution chain. This has reportedly increased farmer incomes by up to 80% in some regions [56].

- **Weather Forecasting in West Africa:** Accurate weather forecasting enabled by satellite technology has helped farmers in West Africa avoid adverse weather conditions, resulting in crop yield improvements and an average income increase of 20% [57].

C. Social Impacts

1. Education and Training for Farmers

Technology has vastly improved the education and training of farmers, essential for sustainable farming practices:

- **Virtual Reality (VR) and E-Learning:** In Indonesia, VR and e-learning platforms are used to train farmers on sustainable practices and advanced farming techniques. This has led to a notable improvement in their knowledge and adoption of sustainable practices [58].

- **Mobile Learning Applications:** In Ghana, mobile learning applications provide continuous education on crop and soil management, helping farmers improve their farming practices and thereby enhancing their livelihoods [59].

2. Community Engagement and Empowerment

Technology fosters community engagement and empowerment by enabling better communication and cooperation among farmers:

- **Social Media Platforms:** In the Philippines, farmers use social media platforms to share knowledge, negotiate better prices, and organize cooperative buying and selling, strengthening community bonds and collective bargaining power [60].
- **Digital Cooperatives:** In rural India, digital cooperatives facilitate collective decision-making and resource-sharing, empowering smallholder farmers to improve their market influence and social standing [61].

V. Case Studies and Examples

This specific case studies and examples of how technology has been implemented in both developed and developing regions, showcasing its impact on agricultural practices, outcomes, and lessons learned.

A. Successful Implementations in Developed Countries

1. Precision Agriculture in the United States

In the United States, precision agriculture has become a standard practice for large-scale farming operations. Utilizing GPS and GIS technologies, farmers can monitor and manage their crops with incredible accuracy. A study on cotton farms in Mississippi demonstrated that precision agriculture techniques reduced pesticide use by 25% and increased yields by 10%, showcasing the dual benefits of economic gain and environmental protection [62].

2. Automated Dairy Farms in the Netherlands

The Netherlands has seen significant advances in dairy farming technology. Automated milking systems (AMS) allow cows to be milked on an individual basis whenever they require, improving animal welfare and increasing milk production. A notable example is the Lely farm, where automation has led to a 15% increase in milk yield per cow and a reduction in labor costs by 20% [63].

B. Adaptations and Outcomes in Developing Regions

1. Mobile Technology in Kenya

Kenya's agricultural sector has benefited tremendously from mobile technology. M-Pesa, a mobile money platform, has been particularly impactful, allowing farmers to receive payments and access financial services directly from their phones. This has enhanced their economic stability and allowed for better resource management. Apps like iCow provide farmers with tailored farming advice, which has led to increased milk production by up to 56% for smallholder dairy farmers [64].

2. Solar-Powered Irrigation in India

India has faced significant challenges with water scarcity affecting agriculture. The introduction of solar-powered irrigation systems has provided a sustainable solution that is economically viable. In Gujarat, the government's initiative to subsidize solar-powered pumps has led to their widespread adoption, resulting in a 50% reduction in irrigation costs and a 20% increase in crop yields for farmers who switched from diesel pumps [65].

VI. Challenges and Limitations

The introduction of technology into agricultural extension services has transformed agricultural practices, improved efficiency, and enabled farmers to achieve higher productivity and sustainability. However, these advancements also come with a set of challenges and limitations that can impede their implementation and effectiveness.

A. Technological Adaptation and the Digital Divide

1. Accessibility and Connectivity Issues

The digital divide—the gap between demographics and regions that have access to modern information and communication technology, and those that do not—poses a significant barrier to technological adaptation in agriculture. In many rural areas, particularly in developing countries, the lack of infrastructure, such as electricity and internet connectivity, limits the adoption of digital solutions. For example, a study highlighted that in Sub-Saharan Africa, even though mobile phone penetration has increased dramatically, internet access remains limited, affecting the potential use of more sophisticated agricultural technologies [66].

2. Skills and Knowledge Gap

Another aspect of the digital divide is the skills gap. Farmers, especially in less developed regions, often lack the technical skills required to operate advanced technologies such as GIS systems, drones, and data analytics tools. Without adequate training and support, these technologies remain underutilized, which can widen the productivity gap between more educated and less educated farmers [67].

B. Financial Constraints and Funding Issues

1. High Initial Costs

The adoption of advanced agricultural technologies often involves high initial costs that can be prohibitive for smallholder farmers. The cost of purchasing and maintaining new technologies, such as automated irrigation systems or drone technology, can be beyond the reach of those who might benefit the most from these innovations. For instance, the financial burden of implementing precision agriculture technologies can be substantial, requiring significant investment in equipment, software, and training [68].

2. Lack of Financing Options

Compounding the problem of high costs is the lack of accessible financing options. Farmers often struggle to secure loans due to the high-risk nature of agriculture and their lack of collateral. Without access to credit, it becomes challenging for farmers to invest in new technologies that could increase their productivity and income. A study found that access to credit was a significant determinant of technology adoption among farmers in Nigeria [69].

C. Policy and Regulatory Challenges

Effective policy support is crucial for fostering an environment conducive to technological adoption in agriculture. However, in many cases, government policies may not align with the needs of modern agricultural practices, lacking specific provisions for technology integration or incentives for innovation.

For example, existing subsidy schemes might favor traditional farming methods over modern technologies, thereby discouraging innovation [70]. Regulatory barriers can also impede the adoption of new technologies. For instance, the use of drones for agricultural purposes faces regulatory hurdles in many countries, including restrictions on airspace and data privacy concerns. These regulations can delay or restrict the deployment of potentially transformative technologies in the agricultural sector [71].

D. Environmental Considerations

While technologies such as high-efficiency irrigation systems and precision farming aim to optimize resource use, there is also the risk that increased agricultural productivity could lead to overexploitation of already scarce natural resources, such as water and soil nutrients. The challenge lies in balancing increased production with sustainable resource management [72]. Technological interventions can also result in pollution and waste if not managed properly. For example, the inappropriate disposal of electronic waste from outdated or broken agricultural equipment can contribute to environmental pollution. Increased mechanization can lead to higher energy consumption and carbon emissions unless renewable energy sources are integrated into these technologies [73].

VII. Future Directions and Recommendations

As agricultural technology continues to evolve, it is crucial to consider future directions and formulate strategic recommendations to ensure that these advancements benefit all stakeholders, particularly smallholder farmers, and contribute to sustainable agricultural practices.

A. Emerging Technologies and Their Potential Impact

1. Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) and Machine Learning (ML) are poised to revolutionize agriculture by enabling more precise and efficient farming practices. These technologies can analyze large datasets from various sources, including satellite images, weather stations, and IoT sensors, to make predictions and decisions that optimize crop health and yield [74]. For example, AI can help in developing predictive models for pest and disease outbreaks, allowing for timely interventions that minimize crop damage. Machine learning algorithms can also optimize irrigation and fertilization schedules based on real-time data, significantly reducing resource waste and enhancing crop yields [75].

2. Next-generation Biotechnologies

Next-generation biotechnologies, including gene editing and synthetic biology, hold the potential to develop crops with enhanced traits such as increased resistance to pests and diseases, improved nutritional content, and greater resilience to environmental stresses [76]. Techniques like CRISPR/Cas9 have revolutionized the field of genetic engineering by allowing precise edits to the DNA, which can lead to significant improvements in crop efficiency and sustainability. These biotechnologies not only promise to reduce dependency on chemical inputs such as fertilizers and pesticides but also aim to improve the adaptability of crops to changing climatic conditions, thus ensuring food security in vulnerable regions [77].

B. Policy Recommendations for Effective Technology Integration

Governments need to create supportive regulatory frameworks that encourage the adoption of innovative technologies while ensuring they are safe, equitable, and sustainable. This includes setting standards for data sharing and privacy, regulating the use of genetically modified organisms (GMOs), and ensuring that AI systems are transparent and accountable [78]. Increasing investment in research and development (R&D) is crucial. Public and private sectors should collaborate to fund R&D activities, particularly in developing technologies that are adaptable to various agricultural settings. Incentives could include tax breaks or grants for companies and research institutions that develop agricultural technologies focusing on sustainability and inclusivity [79].

C. Strategies for Inclusive Technology Deployment

Technology solutions should be tailored to meet the specific needs of local communities. This includes considering local environmental conditions, crop types, cultural practices, and socioeconomic factors. For instance, deploying mobile-based solutions in areas with high mobile penetration and developing drought-resistant crop varieties in arid regions [80]. To ensure the effective deployment of technologies, capacity building and training for farmers are essential. This includes not only training on how to use the technologies but also education on best practices for sustainable farming. Extension services should be equipped with the tools and knowledge to support farmers in this transition [81].

D. Long-term Sustainability Considerations

Before the widespread adoption of new technologies, comprehensive environmental impact assessments should be conducted to understand their long-term implications on ecosystems and natural resources. This is crucial to ensure that technological advancements contribute positively to environmental sustainability and do not exacerbate issues such as soil degradation, water scarcity, and biodiversity loss [82]. Agricultural technologies should be aligned with the Sustainable Development Goals to ensure they contribute holistically to economic, social, and environmental objectives. This includes promoting technologies that help reduce poverty, improve food security, enhance health and well-being, and mitigate climate change impacts [83].

Conclusion

The integration of technology in agricultural extension programs presents both opportunities and challenges. Technologies such as artificial intelligence, machine learning, and advanced biotechnologies hold the potential to revolutionize agricultural practices by enhancing productivity, efficiency, and sustainability. However, to fully harness these benefits, it is imperative to address the digital divide, provide adequate financial support, and establish robust policy frameworks that promote safe and equitable technology adoption. Inclusive strategies and sustainability considerations must be central to the deployment of new technologies, ensuring they align with global sustainability goals and benefit all stakeholders, especially smallholder farmers. Ultimately, a thoughtful and coordinated approach is required to ensure that technological advancements contribute positively to the future of agriculture and food security worldwide.

References

1. Lal, R. (2012). Climate change and soil degradation mitigation by sustainable management of soils and other natural resources. *Agricultural Research*, *1*, 199-212.
2. Balasundram, S. K., Shamshiri, R. R., Sridhara, S., & Rizan, N. (2023). The role of digital agriculture in mitigating climate change and ensuring food security: an overview. *Sustainability*, *15*(6), 5325.
3. Haleem, A., Javaid, M., Qadri, M. A., & Suman, R. (2022). Understanding the role of digital technologies in education: A review. *Sustainable Operations and Computers*, *3*, 275-285.
4. Lukuyu, B., Place, F., Franzel, S., & Kiptot, E. (2012). Disseminating improved practices: are volunteer farmer trainers effective?. *The Journal of Agricultural Education and Extension*, *18*(5), 525-540.
5. Walter, A., Finger, R., Huber, R., & Buchmann, N. (2017). Smart farming is key to developing sustainable agriculture. *Proceedings of the National Academy of Sciences*, *114*(24), 6148-6150.
6. Thrupp, L. A. (2000). Linking agricultural biodiversity and food security: the valuable role of agrobiodiversity for sustainable agriculture. *International affairs*, *76*(2), 265-281.
7. Pretty, J. (2008). Agricultural sustainability: concepts, principles and evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1491), 447-465.
8. Mijatović, D., Van Oudenhoven, F., Eyzaguirre, P., & Hodgkin, T. (2013). The role of agricultural biodiversity in strengthening resilience to climate change: towards an analytical framework. *International journal of agricultural sustainability*, *11*(2), 95-107.
9. Hanjra, M. A., Noble, A., Langan, S., & Lautze, J. (2016). Feeding the 10 billion within the sustainable development goals framework. In *Food Production and Nature Conservation* (pp. 35-60). Routledge.
10. Bacon, C. M., Getz, C., Kraus, S., Montenegro, M., & Holland, K. (2012). The social dimensions of sustainability and change in diversified farming systems. *Ecology and Society*, *17*(4).
11. Rao, N. H. (2007). A framework for implementing information and communication technologies in agricultural development in India. *Technological Forecasting and Social Change*, *74*(4), 491-518.
12. Maciejewski, M. (2017). To do more, better, faster and more cheaply: Using big data in public administration. *International Review of Administrative Sciences*, *83*(1_suppl), 120-135.
13. Kiani, F., & Seyyedabbasi, A. (2018). Wireless sensor network and internet of things in precision agriculture. *International Journal of Advanced Computer Science and Applications*.
14. Smith, M. J. (2018). Getting value from artificial intelligence in agriculture. *Animal Production Science*, *60*(1), 46-54.

15. Salami, A., Kamara, A. B., & Brixiova, Z. (2010). *Smallholder agriculture in East Africa: Trends, constraints and opportunities* (p. 52). Tunis, Tunisia: African Development Bank.
16. Rodriguez, J. M., Molnar, J. J., Fazio, R. A., Sydnor, E., & Lowe, M. J. (2009). Barriers to adoption of sustainable agriculture practices: Change agent perspectives. *Renewable agriculture and food systems*, *24*(1), 60-71.
17. Kalogiannidis, S., Kalfas, D., Chatzitheodoridis, F., & Papaevangelou, O. (2022). Role of crop-protection technologies in sustainable agricultural productivity and management. *Land*, *11*(10), 1680.
18. Moehl, J., Brummett, R., Boniface, M. K., & Coche, A. (2006). Guiding principles for promoting aquaculture in Africa: benchmarks for sustainable development. *CIFA Occasional Paper*, (28), I.
19. Anderson, J. R. (2003). *Rural extension services* (Vol. 2976). World Bank Publications.
20. Yaqoot, M., Diwan, P., & Kandpal, T. C. (2016). Review of barriers to the dissemination of decentralized renewable energy systems. *Renewable and Sustainable Energy Reviews*, *58*, 477-490.
21. Caine, A., Dorward, P., Clarkson, G., Evans, N., Canales, C., Stern, D., & Stern, R. (2015). Mobile applications for weather and climate information: their use and potential for smallholder farmers. *CCAFS Working Paper*.
22. Alvira, P., Tomás-Pejó, E., Ballesteros, M., & Negro, M. J. (2010). Pretreatment technologies for an efficient bioethanol production process based on enzymatic hydrolysis: a review. *Bioresource technology*, *101*(13), 4851-4861.
23. Mani, P. K., Mandal, A., Biswas, S., Sarkar, B., Mitran, T., & Meena, R. S. (2021). Remote sensing and geographic information system: a tool for precision farming. *Geospatial Technologies for Crops and Soils*, 49-111.
24. Hellin, J., Lundy, M., & Meijer, M. (2009). Farmer organization, collective action and market access in Meso-America. *Food policy*, *34*(1), 16-22.
25. Shaikh, T. A., Rasool, T., & Lone, F. R. (2022). Towards leveraging the role of machine learning and artificial intelligence in precision agriculture and smart farming. *Computers and Electronics in Agriculture*, *198*, 107119.
26. Tian, H., Wang, T., Liu, Y., Qiao, X., & Li, Y. (2020). Computer vision technology in agricultural automation—A review. *Information Processing in Agriculture*, *7*(1), 1-19.
27. Daum, T., Ravichandran, T., Kariuki, J., Chagunda, M., & Birner, R. (2021). Connected cows and cyber chickens?.

28. Madhavan, S. (2014). *Marketing and credit information to farmers* (Doctoral dissertation, Department of rural banking and finance management, College of cooperation, banking and management, Vellanikkara).
29. Mali, D., & Lim, H. (2021). How do students perceive face-to-face/blended learning as a result of the Covid-19 pandemic?. *The International Journal of Management Education*, *19*(3), 100552.
30. Chen, Y. J., Shanthikumar, J. G., & Shen, Z. J. M. (2015). Incentive for peer-to-peer knowledge sharing among farmers in developing economies. *Production and Operations Management*, *24*(9), 1430-1440.
31. Simelton, E., & McCampbell, M. (2021). Do digital climate services for farmers encourage resilient farming practices? Pinpointing gaps through the responsible research and innovation framework. *Agriculture*, *11*(10), 953.
32. Mapiye, O., Makombe, G., Molotsi, A., Dzama, K., & Mapiye, C. (2023). Information and communication technologies (ICTs): The potential for enhancing the dissemination of agricultural information and services to smallholder farmers in sub-Saharan Africa. *Information Development*, *39*(3), 638-658.
33. Fishman, E., Washington, S., & Haworth, N. (2013). Bike share: a synthesis of the literature. *Transport reviews*, *33*(2), 148-165.
34. Baumüller, H. (2012). Facilitating agricultural technology adoption among the poor: The role of service delivery through mobile phones.
35. Ferris, S., Robbins, P., Best, R., Seville, D., Buxton, A., Shriver, J., & Wei, E. (2014). Linking smallholder farmers to markets and the implications for extension and advisory services. *MEAS Brief*, *4*(10), 13-14.
36. Murthy, C. S. H. N., & Das, R. TV channels support for agriculture and alternate livelihoods: A study of ETV vs other TV channels.
37. Zakarya, Y. M., Metwaly, M. M., AbdelRahman, M. A., Metwalli, M. R., & Koubouris, G. (2021). Optimized land use through integrated land suitability and GIS approach in West El-Minia Governorate, Upper Egypt. *Sustainability*, *13*(21), 12236.
38. Sishodia, R. P., Ray, R. L., & Singh, S. K. (2020). Applications of remote sensing in precision agriculture: A review. *Remote sensing*, *12*(19), 3136.
39. Cooper, P. J., Dimes, J., Rao, K. P. C., Shapiro, B., Shiferaw, B., & Twomlow, S. (2008). Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change?. *Agriculture, ecosystems & environment*, *126*(1-2), 24-35.

40. Brown, M. E. (2008). *Famine early warning systems and remote sensing data*. Springer Science & Business Media.
41. Bhat, S. A., Huang, N. F., Sofi, I. B., & Sultan, M. (2021). Agriculture-food supply chain management based on blockchain and IoT: a narrative on enterprise blockchain interoperability. *Agriculture*, *12*(1), 40.
42. Trollman, H., Garcia-Garcia, G., Jagtap, S., & Trollman, F. (2022). Blockchain for ecologically embedded coffee supply chains. *Logistics*, *6*(3), 43.
43. Katsikouli, P., Wilde, A. S., Dragoni, N., & Høgh-Jensen, H. (2021). On the benefits and challenges of blockchains for managing food supply chains. *Journal of the Science of Food and Agriculture*, *101*(6), 2175-2181.
44. Sun, A. Y., & Scanlon, B. R. (2019). How can Big Data and machine learning benefit environment and water management: a survey of methods, applications, and future directions. *Environmental Research Letters*, *14*(7), 073001.
45. Evans, K. J., Terhorst, A., & Kang, B. H. (2017). From data to decisions: helping crop producers build their actionable knowledge. *Critical reviews in plant sciences*, *36*(2), 71-88.
46. Timsina, J. (2018). Can organic sources of nutrients increase crop yields to meet global food demand?. *Agronomy*, *8*(10), 214.
47. Barbedo, J. G. A. (2019). A review on the use of unmanned aerial vehicles and imaging sensors for monitoring and assessing plant stresses. *Drones*, *3*(2), 40.
48. Tsouros, D. C., Bibi, S., & Sarigiannidis, P. G. (2019). A review on UAV-based applications for precision agriculture. *Information*, *10*(11), 349.
49. Hakkim, V. A., Joseph, E. A., Gokul, A. A., & Mufeedha, K. (2016). Precision farming: the future of Indian agriculture. *Journal of Applied Biology and Biotechnology*, *4*(6), 068-072.
50. Davidson, D., & Gu, F. X. (2012). Materials for sustained and controlled release of nutrients and molecules to support plant growth. *Journal of agricultural and food chemistry*, *60*(4), 870-876.
51. Bwambale, E., Abagale, F. K., & Anornu, G. K. (2022). Smart irrigation monitoring and control strategies for improving water use efficiency in precision agriculture: A review. *Agricultural Water Management*, *260*, 107324.
52. Brisco, B., Brown, R. J., Hirose, T., McNairn, H., & Staenz, K. (1998). Precision agriculture and the role of remote sensing: a review. *Canadian Journal of Remote Sensing*, *24*(3), 315-327.
53. Addison, M., Ohene-Yankyera, K., Acheampong, P. P., & Wongnaa, C. A. (2022). The impact of uptake of selected agricultural technologies on rice farmers' income distribution in Ghana. *Agriculture & Food Security*, *11*, 1-16.

54. Postel, S., Polak, P., Gonzales, F., & Keller, J. (2001). Drip irrigation for small farmers: A new initiative to alleviate hunger and poverty. *Water International*, *26*(1), 3-13.
55. Ayaz, M., Ammad-Uddin, M., Sharif, Z., Mansour, A., & Aggoune, E. H. M. (2019). Internet-of-Things (IoT)-based smart agriculture: Toward making the fields talk. *IEEE access*, *7*, 129551-129583.
56. Javaid, M., Haleem, A., Singh, R. P., & Suman, R. (2022). Enhancing smart farming through the applications of Agriculture 4.0 technologies. *International Journal of Intelligent Networks*, *3*, 150-164.
57. Pramanik, M., Khanna, M., Singh, M., Singh, D. K., Sudhishri, S., Bhatia, A., & Ranjan, R. (2022). Automation of soil moisture sensor-based basin irrigation system. *Smart Agricultural Technology*, *2*, 100032.
58. Henke, N., & Jacques Bughin, L. (2016). The age of analytics: Competing in a data-driven world.
59. Asenso-Okyere, K., & Mekonnen, D. A. (2012). The importance of ICTs in the provision of information for improving agricultural productivity and rural incomes in Africa. *African Human Development Report. UNDP Sponsored research Series*, 43.
60. Bordonal, R. D. O., Carvalho, J. L. N., Lal, R., De Figueiredo, E. B., De Oliveira, B. G., & La Scala, N. (2018). Sustainability of sugarcane production in Brazil. A review. *Agronomy for sustainable development*, *38*, 1-23.
61. Toenniessen, G., Adesina, A., & DeVries, J. (2008). Building an alliance for a green revolution in Africa. *Annals of the New York academy of sciences*, *1136*(1), 233-242.
62. Minas, A. M., Mander, S., & McLachlan, C. (2020). How can we engage farmers in bioenergy development? Building a social innovation strategy for rice straw bioenergy in the Philippines and Vietnam. *Energy Research & Social Science*, *70*, 101717.
63. Zheng, Y., Lou, J., Mei, L., & Lin, Y. (2023). Research on Digital Credit Behavior of Farmers' Cooperatives—A Grounded Theory Analysis Based on the "6C" Family Model. *Agriculture*, *13*(8), 1597.
64. Oliver, M. A., Bishop, T. F., & Marchant, B. P. (Eds.). (2013). *Precision agriculture for sustainability and environmental protection* (pp. 1-283). Abingdon: Routledge.
65. Simões Filho, L. M., Lopes, M. A., Brito, S. C., Rossi, G., Conti, L., & Barbari, M. (2020). Robotic milking of dairy cows: a review. *Semina: Ciências Agrárias*, *41*(6), 2833-2850.
66. Mapiye, O. (2022). *Development of a Livestock Management Database System towards sustainable smallholder farming systems in South Africa* (Doctoral dissertation, Stellenbosch: Stellenbosch University).

67. Bastakoti, R., Raut, M., & Thapa, B. R. (2020). *Groundwater governance and adoption of solar-powered irrigation pumps: experiences from the eastern Gangetic Plains*. IWMI.
68. Kiambi, D. (2018). The use of information communication and technology in advancement of African agriculture. *African Journal of Agricultural Research*, *13*(39), 2025-2036.
69. Muzari, W., Gatsi, W., & Muvhunzi, S. (2012). The impacts of technology adoption on smallholder agricultural productivity in sub-Saharan Africa: A review. *Journal of Sustainable Development*, *5*(8), 69.
70. Finger, R., Swinton, S. M., El Benni, N., & Walter, A. (2019). Precision farming at the nexus of agricultural production and the environment. *Annual Review of Resource Economics*, *11*, 313-335.
71. Ololade, R. A., & Olagunju, F. I. (2013). Determinants of access to credit among rural farmers in Oyo State, Nigeria. *Global Journal of Science Frontier Research Agriculture and Veterinary Sciences*, *13*(2), 16-22.
72. Sixt, G. N., Klerkx, L., & Griffin, T. S. (2018). Transitions in water harvesting practices in Jordan's rainfed agricultural systems: Systemic problems and blocking mechanisms in an emerging technological innovation system. *Environmental Science & Policy*, *84*, 235-249.
73. Falkenmark, M., & Rockström, J. (2006). The new blue and green water paradigm: Breaking new ground for water resources planning and management. *Journal of water resources planning and management*, *132*(3), 129-132.
74. Falkenmark, M., & Rockström, J. (2006). The new blue and green water paradigm: Breaking new ground for water resources planning and management. *Journal of water resources planning and management*, *132*(3), 129-132.
75. Gorjian, S., Ebadi, H., Trommsdorff, M., Sharon, H., Demant, M., & Schindele, S. (2021). The advent of modern solar-powered electric agricultural machinery: A solution for sustainable farm operations. *Journal of cleaner production*, *292*, 126030.
76. Singh, A., Mehrotra, R., Rajput, V. D., Dmitriev, P., Singh, A. K., Kumar, P., ... & Singh, A. K. (2022). Geoinformatics, artificial intelligence, sensor technology, big data: emerging modern tools for sustainable agriculture. *Sustainable agriculture systems and technologies*, 295-313.
77. Abioye, E. A., Hensel, O., Esau, T. J., Elijah, O., Abidin, M. S. Z., Ayobami, A. S., ... & Nasirahmadi, A. (2022). Precision irrigation management using machine learning and digital farming solutions. *AgriEngineering*, *4*(1), 70-103.
78. Roberts, D. P., & Mattoo, A. K. (2018). Sustainable agriculture—Enhancing environmental benefits, food nutritional quality and building crop resilience to abiotic and biotic stresses. *Agriculture*, *8*(1), 8.

79. Munawar, S., ul Qamar, M. T., Mustafa, G., Khan, M. S., & Joyia, F. A. (2020). Role of biotechnology in climate resilient agriculture. *Environment, climate, plant and vegetation growth*, 339-365.
80. Boldt, J., & Orrù, E. (2022). Towards a unified list of ethical principles for emerging technologies. An analysis of four European reports on molecular biotechnology and artificial intelligence. *Sustainable Futures*, *4*, 100086.
81. Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A. M., Kinengyere, A., ... & Torero, M. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nature Sustainability*, *3*(10), 809-820.
82. Abberton, M. T., Abdoulaye, T., Ademonla, D. A., Aseidu, R., Ayantunde, A., Bayala, J., ... & Sanders, Z. (2021). Priority interventions for transformational change in the Sahel. *CGIAR Research Program on Climate Change, Agriculture and Food Security Working Paper*.
83. McCown, R. L. (2002). Changing systems for supporting farmers' decisions: problems, paradigms, and prospects. *Agricultural systems*, *74*(1), 179-220.