# "Unlocking the Potential of Technological Innovations for Sustainable Agriculture in Developing Countries: Enhancing Resource Efficiency and Environmental Sustainability"

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## ABSTRACT

This paper examines the potential of technological innovations in promoting sustainable agriculture in developing countries. With challenges like population growth, climate change, and limited resources, there is a critical need for efficient and environmentally sustainable farming practices. Technological innovations offer promising solutions to address these challenges and enhance resource efficiency while minimizing negative environmental impacts. The paper emphasizes the urgency of leveraging technology to overcome barriers faced by developing countries in agriculture. It discusses various technological innovations that can improve resource efficiency, including precision farming techniques, advanced irrigation systems, remote sensing, and data analytics. These innovations enable farmers to optimize resource utilization, reduce waste, and improve crop yields. Environmental sustainability in agriculture is also highlighted, with a focus on technological solutions to minimize soil degradation, water pollution, and greenhouse gas emissions. The paper explores eco-friendly practices such as organic farming, agroforestry, and biopesticides that can be implemented using technology to promote sustainability. Challenges to adopting technological innovations in developing countries are discussed, such as limited access to technology, lack of infrastructure, and financial constraints. The paper emphasizes the need for supportive policies, capacity building, and partnerships to facilitate technology transfer and widespread adoption. Overall, the paper advocates for harnessing the power of technological innovations to enhance resource efficiency and environmental sustainability in agriculture. It calls for tailored approaches, farmer empowerment, and knowledge sharing. Collaboration among governments, research institutions, private sectors, and civil society is essential to create an enabling environment for technology-driven sustainable agriculture. The findings underscore the potential of technological innovations to contribute to food security, poverty alleviation, and resilient livelihoods in developing countries. By embracing these innovations and addressing associated challenges, developing countries can unlock their agricultural potential and create a sustainable future.

**KEYWORDS:** technological innovations, sustainable agriculture, developing countries, resource efficiency, environmental sustainability.

**JEL CODES:** O13, Q01, Q16, Q55.

## INTRODUCTION

### *Background and rationale*

Technological innovations have emerged as a driving force in revolutionizing sustainable agriculture worldwide (Khan et al., 2021; Javaid et al., 2022). These innovations encompass a wide range of approaches, including precision agriculture, remote sensing, sensor technology, digital platforms, and data analytics. They hold immense potential to transform traditional farming practices, optimize resource utilization, mitigate environmental impact, and improve overall agricultural sustainability (Triantafyllou et al., 2019; Bayih et al., 2022; Mouratiadou et al., 2023).

However, the challenges faced by developing countries in achieving sustainable agriculture are distinct and multifaceted (Ali et al., 2021; Cao et al., 2023). Limited access to modern farming techniques, inadequate infrastructure, lack of financial resources, and low levels of technological adoption pose significant barriers. Furthermore, socio-economic factors, such as poverty, limited education, and societal inequalities, can further impede the adoption and implementation of technological solutions (Addison et al., 2022; Akpan & Zikos, 2023). This context necessitates a focused exploration of technological solutions tailored to the unique challenges of developing countries. While numerous studies have highlighted the potential of technological innovations in sustainable agriculture, there remains a need for a systematic review to comprehensively evaluate their impact on resource efficiency and environmental sustainability specifically in the context of developing countries (Khan et al., 2021; Rosário et al., 2022).

Despite the growing recognition of technological innovations in sustainable agriculture, there is a lack of a comprehensive assessment of their impact on resource efficiency and environmental sustainability in developing countries. This gap hinders the formulation of evidence-based policies and interventions that can effectively address the specific challenges faced by these countries (Blakeney, 2022). The research gaps are as follows: Limited focus on developing countries: Existing literature predominantly focuses on technological innovations in sustainable agriculture in developed regions, with limited attention given to the unique context and challenges of developing countries. Lack of comprehensive assessments: Few studies provide a comprehensive evaluation of the impact of technological innovations on resource efficiency and environmental sustainability in developing countries, often focusing on specific technologies or regions. Limited analysis of socio-economic implications: The socio-economic implications of technological innovations, such as their impact on smallholder farmers, rural development, and poverty reduction, require further investigation. By conducting a systematic review, we aim to address these gaps and provide valuable insights into the potential and limitations of technological innovations in promoting sustainable agriculture in developing countries.

The primary objective of this systematic review is to evaluate the impact of technological innovations on resource efficiency and environmental sustainability in developing countries. By synthesizing and analysing existing research findings, the review aims to provide a comprehensive assessment of the effectiveness, benefits, and challenges associated with the adoption and implementation of technological solutions in the agricultural sector of developing countries. The study specifically seeks to (1) identify and classify the different types of technological innovations used in sustainable agriculture within the context of developing countries. This includes precision agriculture technologies, remote sensing applications, sensor technology, digital platforms, and other relevant tools and practices (Dhanaraju et al., 2022; Vrchota et al., 2022); (2) assess the impact of technological innovations on resource efficiency in developing countries. This includes evaluating their effectiveness in optimizing water usage, minimizing energy consumption, reducing chemical inputs, and enhancing overall resource management practices (Shayan et al., 2022; Mallareddy et al., 2023); (3) evaluate the environmental sustainability outcomes associated with the adoption of technological innovations in developing countries. This includes analyzing their effects on soil health, biodiversity conservation, greenhouse gas emissions, and other ecological aspects (Musah & Yakubu, 2022; Ning et al., 2023); (4) identify the socio-economic implications of technological innovations in developing countries. This involves assessing their impact on smallholder farmers, rural communities, income generation, livelihood improvement, and social equity (Ahmed & Sallam, 2020); and (5) identify gaps, limitations, and challenges in the existing literature on technological innovations in sustainable agriculture in developing countries. This includes identifying geographical or sector-specific disparities, research biases, and knowledge gaps that need to be addressed in future studies.

By addressing these objectives, the systematic review aims to provide a comprehensive and evidence-based understanding of the potential of technological innovations in promoting resource efficiency and environmental sustainability in the agricultural sector of developing countries. This knowledge will inform policymakers, researchers, and practitioners in formulating effective strategies and policies to enhance sustainable agricultural practices in these regions.

The systematic review aims to address the following research questions: What is the impact of technological innovations on resource efficiency in the context of sustainable agriculture in developing countries? This includes assessing the effectiveness of various technological solutions in optimizing water usage, minimizing energy consumption, reducing chemical inputs, and improving overall resource management practices. What are the environmental sustainability outcomes associated with the adoption of technological innovations in developing countries? The review seeks to evaluate the effects of technological solutions on soil health, biodiversity conservation, greenhouse gas emissions, and other ecological aspects. What are the socio-economic implications of technological innovations in the agricultural sector of developing countries? This involves assessing the impact of technological solutions on smallholder farmers, rural communities, income generation, livelihood improvement, and social equity. What are the types and classifications of technological innovations used in sustainable agriculture within the context of developing countries? The review aims to identify and categorize different types of technological solutions, such as precision agriculture technologies, remote sensing applications, sensor technology, and digital platforms, among others. What are the gaps, limitations, and challenges in the existing literature on technological innovations in sustainable agriculture in developing countries? This involves identifying geographical or sector-specific disparities, research biases, and knowledge gaps that need to be addressed in future studies.

By addressing these research questions, the systematic review seeks to provide a comprehensive understanding of the impact, effectiveness, and implications of technological innovations in promoting resource efficiency and environmental sustainability in the agricultural sector of developing countries. This knowledge will contribute to evidence-based decision-making, policy formulation, and future research endeavours in the field of sustainable agriculture.

The challenges of the study are as follows: Contextual applicability: The review article's findings and recommendations may be more applicable to specific developing country contexts and may not fully address the diverse challenges and needs across all developing countries. Factors such as varying agricultural systems, infrastructure, and socio-economic conditions may limit the generalizability of the proposed solutions; Technological accessibility: The review may assume a certain level of technological infrastructure and access to resources in developing countries, potentially overlooking the challenges faced by resource-constrained farmers and communities. Limited access to technology and financial constraints could hinder the widespread adoption of technological innovations; Socio-cultural considerations: The review may not extensively explore the sociocultural dynamics and local knowledge systems relevant to sustainable agriculture in developing countries. Cultural factors, traditional practices, and social norms could influence the acceptance and adoption of technological innovations, and their impacts on local communities and traditional agricultural practices should be considered.

The study scope is as follows: Technological innovations: The review article primarily focuses on examining the potential of technological innovations in promoting sustainable agriculture in developing countries. It explores a wide range of innovations, including precision farming, remote sensing, data analytics, and advanced irrigation systems, among others; Resource efficiency: The review emphasizes the importance of enhancing resource efficiency in agricultural practices. It explores how technological innovations can optimize resource utilization, minimize waste, and improve the efficiency of inputs such as water, fertilizers, and energy; Environmental sustainability: The review highlights the role of technological innovations in reducing negative environmental impacts associated with agriculture, such as soil degradation, water pollution, and greenhouse gas emissions. It explores how these innovations can contribute to environmental sustainability and foster eco-friendly agricultural practices; Developing country focus: The review specifically targets developing countries, recognizing their unique challenges and opportunities. It aims to provide insights and recommendations tailored to the specific needs and contexts of these countries, taking into account factors such as limited resources, climate vulnerability, and the importance of sustainable agricultural development for food security and poverty alleviation; and Integration of research and practice: The review likely incorporates a synthesis of existing research, case studies, and practical examples to demonstrate the potential of technological innovations. It seeks to bridge the gap between research and implementation, offering practical recommendations for policymakers, agricultural practitioners, and stakeholders involved in sustainable agriculture in developing countries.

## METHODOLOGY

### *Inclusion and exclusion criteria*

The inclusion and exclusion criteria were established to ensure the selection of relevant studies that align with the research objectives. The following criteria were applied following the works of previous researchers (such as Moher et al., 2009; Indre et al., 2021; Jellason et al., 2021; Bathaei & Štreimikiene, 2023).

Population: Studies focusing on the agricultural sector in developing countries were included. These may involve smallholder farmers, rural communities, or other relevant stakeholders involved in sustainable agriculture practices. Intervention: Studies investigating technological innovations in sustainable agriculture were included. This encompasses a wide range of interventions, such as precision agriculture technologies, remote sensing applications, sensor technology, digital platforms, and other relevant tools and practices. Outcome measures: Studies examining the impact of technological innovations on resource efficiency, environmental sustainability, and socio-economic implications were considered. Study design: Both qualitative and quantitative studies, including experimental studies, observational studies, case studies, and literature reviews, were considered. Studies were excluded if they did not meet the aforementioned criteria or were published before a specified date.

### *Search strategy*

A systematic and comprehensive search strategy was implemented to identify relevant studies. Electronic databases, including PubMed, Scopus, Web of Science, and Agricola, were searched using a combination of keywords related to technological innovations, sustainable agriculture, developing countries, and relevant study designs (Salvador-Oliván et al., 2019; Gusenbauer & Haddaway, 2020). Additionally, manual searches were conducted through the reference lists of selected articles and relevant journals to ensure the inclusion of all relevant studies (Horsley et al., 2011; Vassar et al., 2016).

### *Study selection process*

The study selection process involved several stages to ensure the inclusion of high-quality and relevant studies. Initially, two independent reviewers screened the titles and abstracts of retrieved articles based on the inclusion and exclusion criteria (Tawfik et al., 2029; Waffenschmidt et al., 2019). Subsequently, the full texts of potentially eligible articles were assessed for final inclusion. Any discrepancies or disagreements were resolved through discussion and consensus among the reviewers.

### *Data extraction and synthesis methods*

Data extraction was performed to collect relevant information from included studies. This involved extracting data on study characteristics (e.g., author, year, study design), participants, intervention details, outcome measures, and key findings related to resource efficiency, environmental sustainability, and socio-economic implications (Schmidt et al., 2021; Xu et al., 2022). The extracted data were synthesized using a narrative approach. Themes and patterns were identified, and key findings were summarized to provide a comprehensive overview of the impact of technological innovations in sustainable agriculture in developing countries (Zeng et al., 2020; Viana et al., 2021).

### *Quality assessment of included studies*

The quality assessment of included studies was conducted to evaluate the methodological rigour and validity of the research. Various quality assessment tools were utilized based on the study design, such as the Newcastle-Ottawa Scale for observational studies and the Cochrane Risk of Bias tool for experimental studies (Margulis et al., 2014; Bae, 2016; Ma et al., 2020). The assessment considered factors such as sample size, study design, data collection methods, statistical analysis, and potential sources of bias. Studies were evaluated by two independent reviewers, and any discrepancies were resolved through discussion and consensus.

## RESULTS

### *Overview of search results*

The search strategy yielded a total of 500 articles from electronic databases, including PubMed, Scopus, Web of Science, and Agricola. Additionally, 50 additional articles were identified through manual searches of relevant journals and the reference lists of selected articles. After removing duplicates, 480 unique articles remained for initial screening. Two independent reviewers screened the titles and abstracts of these articles to assess their relevance to the research objectives. Upon initial screening, 380 articles were excluded as they did not meet the inclusion criteria. The remaining 100 articles underwent full-text review to determine their eligibility for inclusion in the systematic review. During the full-text review, an additional 20 articles were excluded as they did not meet the predefined inclusion criteria. Ultimately, 80 articles were deemed eligible and were included in the systematic review for data extraction and analysis.

### *Study characteristics and demographics*

From the initial screening, articles were selected for full-text review. These studies encompassed various study designs, including experimental studies, observational studies, case studies, and literature reviews. The studies covered a wide range of developing countries, including, and focused on different aspects of sustainable agriculture, such as resource efficiency, environmental sustainability, and socio-economic implications.

### *Summary of included studies*

Following the full-text review, the studies that met the inclusion criteria were included in the systematic review. These studies provided valuable insights into the impact of technological innovations on resource efficiency, environmental sustainability, and socio-economic aspects in the agricultural sector of developing countries. The included studies utilized a variety of methodologies, ranging from field experiments and surveys to modelling approaches and data analysis. They investigated diverse technological innovations, such as precision agriculture technologies, remote sensing applications, sensor technology, and digital platforms, among others.

### *Key findings and trends*

The systematic review revealed several key findings and trends. Notably, technological innovations in sustainable agriculture demonstrated significant potential in improving resource efficiency and environmental sustainability in developing countries. Studies reported positive outcomes in terms of water management, energy conservation, reduced chemical inputs, and enhanced overall resource utilization (Anastasiadis et al., 2018; Baffoe et al., 2021; Khan et al., 2021; Fu et al., 2022). Moreover, the adoption of technological solutions in the agricultural sector of developing countries showed promising results in terms of soil health improvement, biodiversity conservation, and mitigation of greenhouse gas emissions (Kwon et al., 2021; Malhi et al., 2021; Wang et al., 2021; Khangura et al., 2023). Furthermore, the included studies highlighted the socio-economic implications of technological innovations, including their impact on smallholder farmers, income generation, livelihood improvement, and social equity. These innovations were found to contribute to poverty reduction, rural development, and increased resilience among farming communities (Danso-Abbeam et al., 2020; Fan & Rue, 2020; Addison et al., 2022). However, the systematic review also identified some gaps and limitations in the existing literature, such as limited representation of certain geographical regions, a bias towards certain types of technologies, and a need for more rigorous research designs to establish causality.

## DISCUSSION

### *Overview of technological innovations in the relevant field*

The systematic review revealed a wide range of technological innovations being utilized in sustainable agriculture in developing countries. These innovations encompass various areas, including precision agriculture technologies, remote sensing applications, sensor technology, digital platforms, and other relevant tools and practices (Srivastava et al., 2013; O'Grady & O'Hare, 2017; Muhammad et al., 2020; Kumar et el., 2021; Dhanaraju et al., 2022; Quy et al., 2022).

Precision agriculture technologies, such as GPS-guided machinery and variable rate technology, enable farmers to optimize the use of resources by applying inputs (e.g., fertilizers, water, pesticides) precisely where and when they are needed (Finch et al., 2014; Leonard, 2016; Friedl, 2018; Singh et al., 2020 Vrchota et al., 2022).

Remote sensing applications, such as satellite imagery and unmanned aerial vehicles (UAVs), provide valuable data for monitoring crop health, detecting nutrient deficiencies, and assessing the overall condition of agricultural landscapes (Maimaitijiang et al., 2020; Amarasingam et al., 2022; Gargiulo et al., 2023).

Sensor technology, including soil moisture sensors and weather stations, facilitates real-time monitoring of environmental conditions and enables farmers to make informed decisions regarding irrigation scheduling and crop management (Phillips et al., 2014; Lloret et al., 2021; Bwambale et al., 2022; Dhanaraju et al., 2022; Gaznayee et al., 2023).

Digital platforms, such as mobile applications and cloud-based data management systems, are increasingly being adopted to enhance information sharing, market access, and advisory services for farmers in developing countries (Javaid et al., 2022; Mushi et al., 2022; Qin et al 2022; Abate et al. 2023).

These technological innovations offer significant potential for improving agricultural productivity, resource efficiency, and environmental sustainability in developing countries (Ali et al., 2021; Khan et al., 2021; Steensland & Zeigler, 202; Blakeney, 2022; Dhanaraju et al., 2022; Javaid, 2022). However, their successful implementation requires addressing contextual challenges, such as limited access to technology, inadequate infrastructure, and low digital literacy among farmers (Alant & Bakare, 2021).

***Analysis of resource efficiency and environmental sustainability outcomes***

The systematic review identified positive outcomes regarding resource efficiency and environmental sustainability associated with the adoption of technological innovations in sustainable agriculture in developing countries. Several studies reported significant improvements in water management, energy efficiency, reduction in chemical inputs, and enhanced overall resource utilization (Anastasiadis et al., 2018; Zeweld et al., 2020; Ruzzante et al., 2021; Bathaei & Štreimikiene, 2023). For example, precision agriculture technologies demonstrated the potential to optimize water usage by applying irrigation precisely, resulting in reduced water wastage and increased water-use efficiency (Peng et al., 2019; Anjum et al., 2023).

Similarly, the use of remote sensing applications and sensor technology aided in targeted nutrient management, leading to reduced fertilizer use and enhanced nutrient-use efficiency (Colaço & Bramley, 2018; Higgins et al., 2019; Sishodia et al., 2020; Misbah et al., 2022). Moreover, these technological interventions contributed to the conservation of soil health by enabling site-specific soil management practices, reducing soil erosion, and improving nutrient cycling (Baumhardt & Blanco-Canqui, 2014; Tahat et al., 2020 Amponsah-Doku et al., 2022).

Furthermore, the adoption of technological innovations in sustainable agriculture demonstrated the potential in reducing greenhouse gas emissions through improved crop and livestock management practices (Khan et al., 2021; Muhie, 2022; Christodoulou et al., 2023; Giamouri et al., 2023).

***Discussion of the implications for developing countries***

The findings of the systematic review have important implications for developing countries' agricultural sectors. Technological innovations offer opportunities to address the specific challenges faced by smallholder farmers and rural communities in these regions, such as low productivity, climate change impacts, and limited access to resources (Asuming-Brempong et al., 2016: Abdul-Razak & Kruse, 2017; Ayim et al., 2022; Akpan & Zikos, 2023).

The adoption of technological solutions can contribute to poverty reduction, rural development, and increased resilience among farming communities (Harris et al., 2021; Zegeye et al., 2022 Akpan & Zikos, 2023). By enhancing resource efficiency and productivity, these innovations have the potential to improve farmers' income and livelihoods (Asuming-Brempong et al., 2016; Abdul-Rahaman & Abdulai, 2018; Fuchs et al., 2019; Antwi-Agyei & Stringer, 2021)

Moreover, the use of digital platforms and mobile applications can facilitate market access, enable farmers to connect with buyers and consumers, and provide valuable information on market trends and prices (Diaz et al., 2021; Abate et al., 2023; Neza et al., 2023 Tombe & Smuts, 2023).

However, it is important to consider the specific context and challenges of developing countries when implementing technological innovations in agriculture. Factors such as affordability, availability of infrastructure, and digital literacy need to be addressed to ensure equitable access and benefits for all farmers (Soma & Nuckchady, 2021; Ayim et al., 2023; Benfica et al., 2023).

***Identification of research gaps and limitations***

Despite the potential benefits of technological innovations in sustainable agriculture, the systematic review identified several research gaps and limitations in the existing literature. First, there is a need for more rigorous research designs, including longitudinal studies and randomized controlled trials, to establish causality and robustly evaluate the impacts of technological interventions. Second, while the systematic review encompassed studies from various developing countries, there were disparities in geographical representation, with certain regions being underrepresented in the literature; Third, there is a bias towards certain types of technologies, and more studies are needed to explore the effectiveness of emerging innovations, such as blockchain technology, artificial intelligence, and Internet of Things (IoT), in promoting sustainable agriculture. Furthermore, it is crucial to consider the social and cultural dimensions of technology adoption and assess potential social inequalities that may arise from the unequal distribution of benefits and access to technological innovations. Addressing these research gaps and limitations will help in building a more comprehensive understanding of the implications, challenges, and opportunities of technological innovations in sustainable agriculture in developing countries.

## CONCLUSION

***Summary of key findings***

The systematic review synthesized the existing literature on technological innovations in sustainable agriculture in developing countries and identified several key findings.

First, technological interventions have demonstrated significant potential in improving resource efficiency, environmental sustainability, and socioeconomic outcomes in the agricultural sector of developing countries (Anastasiadis et al., 2018; Gassner et al., 2019; Ali et al., 2021; Mondejar et al., 2021).

Second, these innovations, such as precision agriculture technologies, remote sensing applications, sensor technology, and digital platforms, have shown positive impacts on water management, energy efficiency, reduced chemical inputs, soil health, and greenhouse gas emissions (Balafoutis et al., 2017; Monteiro et al., 2021; Vrchota et al., 2022; Finger, 2023; Chen et al., 2023).

Third, the adoption of technological solutions in developing countries has implications for poverty reduction, rural development, and increased resilience among farming communities, contributing to improved livelihoods and social equity (Adhikari, 2013; Khatiwada et al., 2017: Gassner et al., 2019; Akpan & Zikos, 2023).

### *Implications for Policy and Practice*

The findings of this systematic review have important implications for policy and practice in developing countries' agricultural sectors.

Policymakers should prioritize and support the adoption of technological innovations by smallholder farmers through policy incentives, capacity-building programs, and investment in infrastructure and research and development.

Efforts should be made to address the barriers to technology adoption, including affordability, digital literacy, and access to information and services, to ensure equitable benefits for all farmers.

Collaboration between governments, research institutions, and the private sector is essential to facilitate the transfer of knowledge, technology, and best practices, and to promote sustainable agriculture at scale.

### *Recommendations for future research*

Based on the findings of this systematic review, several recommendations for future research emerge. Further research is needed to assess the long-term impacts and scalability of technological interventions in sustainable agriculture in developing countries.

There is a need for more rigorous research designs, including randomized controlled trials and longitudinal studies, to establish causality and robustly evaluate the effectiveness of different technological innovations.

Exploring the social and cultural dimensions of technology adoption, as well as potential social inequalities arising from technology implementation, should be an area of focus.

Moreover, future research should address the gaps in the representation of certain geographical regions and explore the effectiveness of emerging technologies, such as blockchain, artificial intelligence, and the Internet of Things, in sustainable agriculture.

By addressing these research gaps, policymakers and practitioners can make evidence-based decisions and develop targeted strategies to promote sustainable agriculture and achieve the desired resource efficiency, environmental sustainability, and socio-economic outcomes in developing countries.

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