frontiers | Frontiers in Sustainable Food Systems

TYPE Original Research
PUBLISHED 16 July 2025
DOI 10.3389/fsufs.2025.1605561

Evaluating the impact of adopting conservation agriculture on farm returns of smallholder vegetable farmers in the Eastern Cape Province: implication for extension services

Siphesihle Qange[1], Lelethu Mdoda[1]*, Yanga Nontu[2], Mosima M. Mabitsela[2] and Lungile S. Gidi[3]

[1]Discipline of Agricultural Economics, University of KwaZulu-Natal, Pietermaritzburg, South Africa, [2]Department of Agriculture, University of Zululand, KwaDlangezwa, South Africa, [3]Department of Agricultural Economics and Animal Production, University of Limpopo, Sovenga, South Africa

OPEN ACCESS

EDITED BY
Jelili Yusuff Amuda,
Prince Sultan University, Saudi Arabia

REVIEWED BY
Sujata Shrestha,
Global Institute for Interdisciplinary Studies (GIIS), Nepal
Musa Adamu,
Prince Sultan University, Saudi Arabia
Sadi Haruna,
Prince Sultan University, Saudi Arabia

*CORRESPONDENCE
Lelethu Mdoda
lelethu.mdoda@gmail.com

RECEIVED 03 April 2025
ACCEPTED 20 June 2025
PUBLISHED 16 July 2025

CITATION
Qange S, Mdoda L, Nontu Y, Mabitsela MM and Gidi LS (2025) Evaluating the impact of adopting conservation agriculture on farm returns of smallholder vegetable farmers in the Eastern Cape Province: implication for extension services.
Front. Sustain. Food Syst. 9:1605561.
doi: 10.3389/fsufs.2025.1605561

Introduction: Conservation Agriculture provides sustainable practices for reducing costs of production and enhancing soil health, yet adoption rate among smallholder vegetable farmers in South Africa remains inadequate. This study examines the impact of Conservation Agriculture adoption on farm returns in the Eastern Cape and explores implications for extension services.

Methods: A mixed-methods approach was employed, using structured questionnaires from 200 smallholder vegetable farmers. Logistic regression and Endogeneity Switching Regression (ESR) model were used for analysis.

Results: Logistic regression identified significant factors influencing adoption, including age, family size, and farm size, education, credit access, market distance and extension services. An Endogeneity Switching Regression (ESR) model revealed that CA adopters attained higher vegetable productivity and income compared to non-adopters. Key challenges to adoption included financial constraints, limited knowledge, inadequate access to resources, and socio-cultural factors.

Discussion: The results highlight the economic benefit of CA and the need for targeted extension support, financial provision such as input subsidies and low-interest credit schemes to ease the financial burden on smallholder farmers, additional structured knowledge dissemination. Future research must investigate the intensity of CA practices across regions and long-term environmental implications.

KEYWORDS

adoption barriers, agricultural sustainability, conservation agriculture, farm returns, productivity, smallholder farmers, endogeneity switching regression

Introduction

Agriculture plays a significant role in improving livelihoods and socio-economic development globally. Agricultural sector is known for its significant contribution to the economies of many countries (Reyes et al., 2020; Gina et al., 2023; Pandey and Pandey, 2023). In many African countries, especially Sub-Saharan Africa, agriculture is not only a source of food but also an important contributor to income generation and employment. Most African regions are predominantly composed by small-scale farmers who heavily depend on agriculture for food and livelihoods (Amede et al., 2023). Despite growing urbanization and industrialization, agriculture continues to offer a safety net for many rural communities, playing a pivotal role in combating food insecurity and malnutrition (Abraham and Pingali, 2020; Wangu, 2021).

Several studies assert the positive impact of agriculture on household food security (Pawlak and Kołodziejczak, 2020; Viana et al., 2022; Sekaran et al., 2021; Hlophe-Ginindza and Mpandeli, 2021). Small-scale farmers also contribute significantly toward ensuring household food availability and nutritional diversity (Gomez y Paloma et al., 2020). Various crops, such as green vegetables and livestock grown by smallholder farmers, contribute positively to dietary diversity (Melby et al., 2020; Hlatshwayo et al., 2023). Due to the nature of smallholder farmers, especially in South Africa, subsistence farming is considered more vulnerable to socio-economic, environmental, and institutional constraints that hinder its potential contribution (Bjornlund et al., 2020; Lottering et al., 2021).

In South Africa, Agriculture remains significant as most smallholder farmers reside in rural areas where resource scarcity is prevalent (Fan and Rue, 2020). These farmers are characterized by high levels of unemployment and poverty, making agriculture a main livelihood strategy (Mugejo and Ncube, 2022; Mutengwa et al., 2023). Due to limited access to education, training, technology, water, arable land, and improved adaptation strategies smallholder farmers are considered to be more susceptible to climate change variability (Mdoda et al., 2024). Additionally, poor access to lucrative markets and credit facilities has been highlighted as one of the key factors that have significant implications for commercialization, affecting profitability and household income (Opondo et al., 2020; Nontu and Taruvinga, 2022).

The availability of extension services to rural communities has been identified as a major barrier to effective information dissemination (Norton and Alwang, 2020). The shortage of extension agencies in terms of ratio against the number of communities causes inadequate farmer support (Maake and Antwi, 2022; Namyenya et al., 2022). This shortage restricts the dissemination of agricultural knowledge and innovations (Kassem et al., 2021; Namyenya et al., 2022). As a result, smallholder farmers often lack access to timely advice on best practices and new technologies, an issue that is particularly pressing in regions like the Eastern Cape Province of South Africa, where smallholder vegetable farming plays a crucial role in rural livelihoods, economic development, and food security (Mujuru and Obi, 2020; Nontu and Taruvinga, 2022; Nontu et al., 2024).

Smallholder farmers continue to face persistent issues such as poor soil fertility, erratic rainfall, and limited access to improved inputs, which constrain productivity and profitability (Mathinya et al., 2022). In response to these challenges, several studies have recommended conservation agriculture (CA) as a sustainable farming practice that can improve soil health, enhance water-use efficiency, and lower production costs (Somasundaram et al., 2020; Jayaraman et al., 2021; Cárceles Rodríguez et al., 2022). However, despite these documented benefits, the adoption of CA in the Eastern Cape remains limited, raising concerns about its actual impact on farm returns and its broader economic potential.

Several studies have recommended conservation agriculture (CA) as a sustainable alternative to traditional farming practices that can improve soil health, enhance water-use efficiency, and lower production costs (Somasundaram et al., 2020; Jayaraman et al., 2021; Cárceles Rodríguez et al., 2022). Despite these potential benefits, the adoption of CA remains limited in the Eastern Cape, raising concerns about its actual impact on farm returns and its broader economic potential. A study conducted by Muzangwa et al. (2017) found that only 34.81% of surveyed farmers practiced no-till farming, 25.93% participated in crop rotation, and 22.22% retained crop residues. Challenges to adoption include lack of appropriate equipment, high herbicide costs, lack of knowledge and conflicts with traditional livestock grazing practices. Similarly, Bese et al. (2020) noted that while sustainable agricultural practices such as intercropping and crop rotation are standard, using organic manure as an alternative to chemical fertilizers is not well-known due to information gap and low extension coverage.

Good health and wellbeing can be achieved through a nutritious and well-balanced diet (Morris et al., 2014; James et al., 2022). Poor vegetable consumption in many African households is typical (Uusiku et al., 2010; Webb, 2000; Miller et al., 2016), often contributing to malnutrition at the household level (James and Zikankuba, 2017; Imathiu, 2021). Vegetables are an important food source that provides almost all essential nutrients and vitamins to humans, contributing to good health (Dias, 2012; Ramya and Patel, 2019). However, climate change and population growth are likely to put pressure on global vegetable production (Ayyogari et al., 2014; Ebert, 2017), which might lead to dietary changes.

Traditional farming practices and overreliance on agrochemicals have resulted in severe soil degradation in smallholder farming systems (Chalise et al., 2019). Consequently, vegetable production, natural resource functioning, farm profitability, and food security among smallholder farmers in the Eastern Cape have declined (Phinzi and Ngetar, 2019; Mdoda et al., 2022). Smallholder farmers in the Eastern Cape continue to rely on traditional farming methods despite widespread land degradation (Muzangwa et al., 2017). Transitioning toward sustainable farming practices that can increase crop yields and farm returns is a viable solution for these farmers. Sustainable farming systems such as conservation agriculture, which aim to conserve natural resources while also offering economic and social benefits, should be adopted by smallholder farmers (Andersson and D'Souza, 2014). To overcome food security challenges and poor farm returns, farming practices such as conservation agriculture are being promoted as a solution. The success of vegetable production in smallholder farming systems under CA is often determined by soil type and rainfall availability, as most farmers rely on rainfall for irrigation (Rockström et al., 2002; Mburu et al., 2015).

CA has emerged as a key farming practice that smallholder farmers adopt (Erenstein et al., 2008; Corbeels et al., 2014). In the context of smallholder vegetable farming in the Eastern Cape, CA offers potential benefits such as improved soil health, water retention, and reduced production costs (Indoria et al., 2017; Selvakumar and Sivakumar, 2021; Teng et al., 2024). Despite these advantages, the adoption of CA remains varied among farmers due to socio-economic factors, access to resources, and knowledge gaps in agricultural extension services (Ntshangase et al., 2018; Rodenburg et al., 2021). Therefore, this study aims to evaluate the impact of CA adoption on farm returns among smallholder vegetable farmers and its implications for agricultural extension services in promoting sustainable farming practices among smallholder farmers in the Eastern Cape Province, South Africa.

Theoretical framework

In evaluating the impact of adopting Conservation Agriculture (CA) on farm returns for smallholder vegetable farmers in the Eastern Cape Province, both the Agricultural Innovation System (AIS) and Diffusion of Innovations (DOI) theories provide valuable frameworks for understanding the adoption process and its outcomes. The AIS framework emphasizes the importance of collaboration and knowledge exchange among various stakeholders (such as farmers, extension services, research institutions, and policymakers) in facilitating the uptake of CA practices. By viewing the adoption of CA as part of a broader innovation system, the study can assess how different actors and institutional support mechanisms, including policies, financial resources, and market access, influence the success of CA adoption. The DOI theory complements this by focusing on individual adoption decisions and the factors that determine how innovations like CA are perceived and adopted by farmers. The key DOI elements, such as relative advantage, compatibility, complexity, trialability, and observability, can help evaluate how CA is perceived in terms of its potential to increase farm productivity and income compared to traditional practices. By applying both frameworks, the study can gain insights into how the socio-technical system (through AIS) and individual farmer characteristics (through DOI) interact to shape the adoption of CA, ultimately impacting farm returns and sustainability for smallholder vegetable farmers in the region.

Agricultural innovation systems framework

This study adopted the AIS Framework to understand the impact of adopting conservation agriculture on the farm returns of smallholder vegetable farmers. Figure 1 shows the IAS framework for the study. The AIS framework provides an analytical structure for examining innovation processes (USAID, 2016; Modirwa and Oladele, 2017). AIS is a network comprising organizations, businesses, and individuals dedicated to introducing innovative products, processes, and organizational structures into the economy (World Bank, 2006; Aerni et al., 2015). This network also includes the institutions and policies that shape their actions and overall performance. The AIS consists of farmers, public, and private institutions and applies a systems-thinking approach to drive innovation in the agricultural sector (Gutiérrez-Cano et al., 2023; Hall et al., 2006). The AIS framework offers a comprehensive and dynamic perspective on how agricultural innovations, such as CA, are adopted and diffused among smallholder farmers. By emphasizing the interactions and collaborations among a diverse range of actors (farmers, extension services, researchers, input suppliers, policymakers, NGOs, and agribusinesses), the AIS framework highlights the interconnectedness of the agricultural ecosystem and the complex processes that drive innovation and change.

AIS focuses on how knowledge, resources, and technologies flow between these actors and how their collective actions influence sustainable practices like CA adoption (Markow et al., 2023; Toillier et al., 2018). Achieving higher production requires collaboration among various stakeholders, and the AIS approach bridges the gap. In this context, the AIS framework is particularly valuable for understanding how extension services can act as intermediaries, facilitating knowledge transfer, providing technical support, and connecting farmers with essential resources to enhance the adoption of CA approaches to smallholder vegetable farming. One example of such collaboration is investing in the capacity of extension workers and organizations to adopt value chain approaches, market-oriented extension services, group and organizational development, agribusiness, and effective information-sharing mechanisms. The gap between these organizations poses a challenge in developing effective research systems and mechanisms for sharing information within research and extension efforts (Davis and Heemskerk, 2009). However, various stakeholders in innovation systems play distinct roles, categorized as facilitators, communicators, collaborators, coordinators, knowledge providers, policy formulators, and implementers. Collaboration among these stakeholders helps clarify the relationships between the key players in an innovation system and sheds light on their attitudes toward the network. As a result, the agricultural innovation system approach has gained significant importance among policymakers (Adenkunle and Fatumbi, 2012). The AIS framework is designed to overcome the linear limitations inherent in traditional National Agricultural Research Systems (NARS) and Agricultural Knowledge and Information Systems (AKIS) approaches (Chinseu et al., 2018). It represents a significant shift in the agricultural research and technology development paradigm, highlighting the idea that innovations can emerge from formal research institutions and a wide range of system actors, including agricultural producers. The AIS is promoted as a strategy to enhance the availability and effectiveness of knowledge among key stakeholders and to position agriculture as a primary driver of food security, environmental sustainability, and economic opportunity. The AIS approach emphasizes social learning and knowledge-sharing among diverse actors throughout the research-extension-innovation-utilization continuum. It also aims to create an enabling environment that supports dynamic interactions. Viewed as more systems-oriented, the AIS framework values the importance of multi-directional interactions in technology generation, dissemination, and use. It also highlights institutional learning and change processes, striving to integrate various knowledge and innovation sources (Spielman, 2005; World Bank, 2012).

Spielman and Birner (2008) describe AIS as consisting of three interconnected clusters: 1) agricultural research and education systems, 2) bridging institutions, and 3) agricultural value chain actors and organizations (Figure 1 below). According to Aerni et al. (2015), an AIS is a network of actors, organizations, and individuals supported by institutions and policies in the agricultural and related sectors that facilitate introducing new or existing products, processes, and organizational models into economic and social

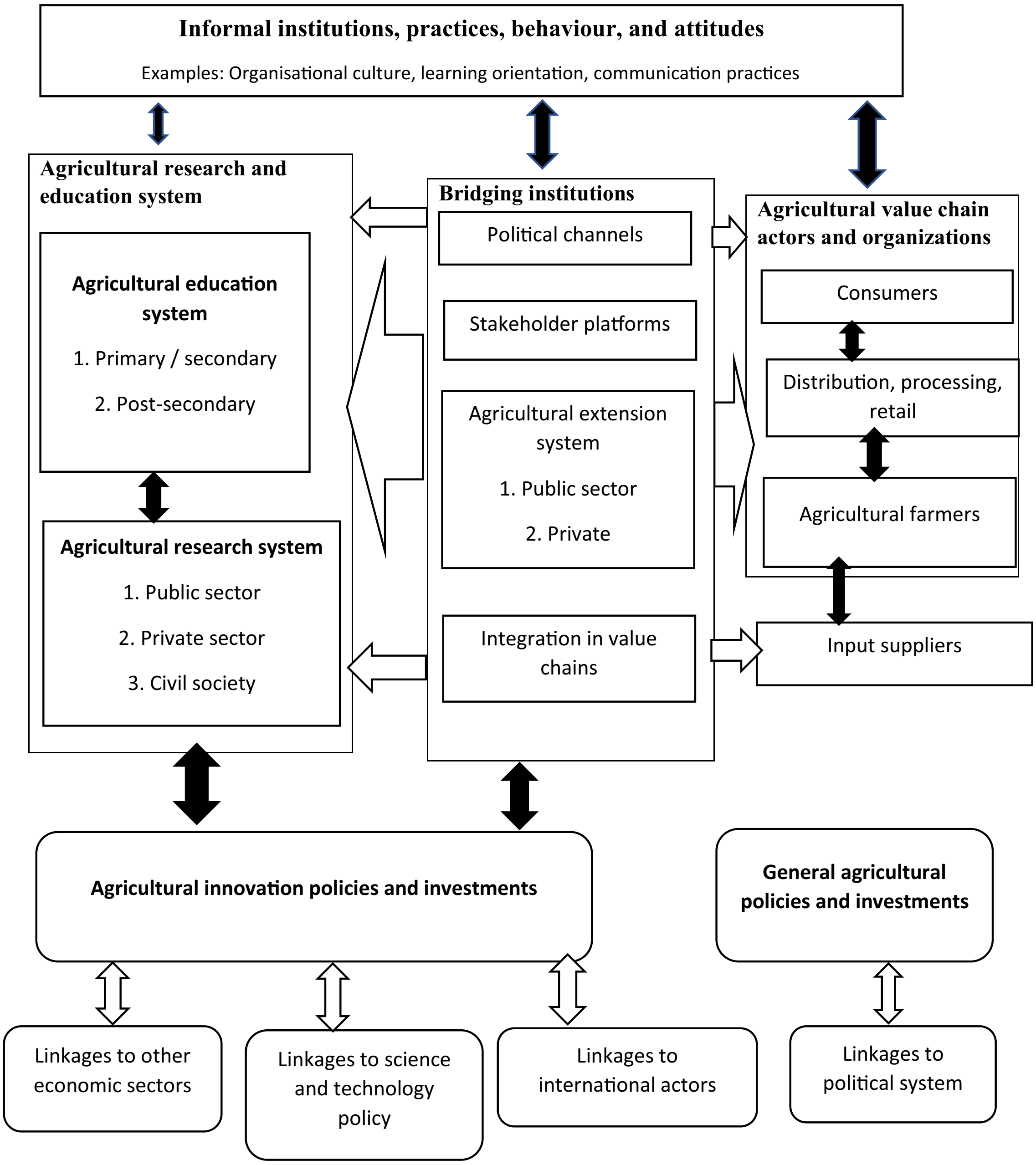

FIGURE 1
Agricultural Innovation System framework adapted from Spielman and Birner (2008).

use. In this approach, various actors collaborate dynamically in an interactive manner, contributing to the production, distribution, processing, value addition, and marketing of agricultural goods and services (Ndah, 2014; Chinseu et al., 2018). Public policies and formal and informal institutions shape the conditions that govern the AIS's operations, such as capacity, procedures, motivations, and attitudes. These factors influence how knowledge is generated and shared and how agricultural innovations are developed and disseminated (Hall et al., 2006). By mapping these interactions, the AIS framework helps identify key leverage points for improving the adoption of CA, offering insights into how the various components of the agricultural system (such as policy, knowledge networks, and resource access) can either promote or hinder the successful uptake of innovative practices among smallholder farmers. This holistic approach underscores the importance of collaboration and coordinated action among all stakeholders in driving the widespread adoption of CA and improving smallholder farmers' productivity and sustainability.

Knowledge networks

Knowledge networks are vital components of the AIS framework, facilitating the exchange of information, technologies, and innovations among various agricultural actors. These networks include formal channels like research institutions and universities, and informal channels like farmer-to-farmer exchanges, community-based groups, and peer networks. They connect farmers, extension services, researchers, input suppliers, and policymakers, enabling collaboration and disseminating agricultural innovations like CA. A key aspect of these networks is the relationship between agricultural research systems and extension services. Research institutions generate scientific knowledge, but for it to be adequate, it must be communicated in a way relevant to local farming contexts. Extension services bridge this gap by tailoring research findings to smallholder farmers' needs and challenges. Extension officers serve as intermediaries, organizing workshops, field visits, and demonstrations to help farmers understand and adopt new practices like CA. They also facilitate two-way knowledge exchange, allowing farmers to share their experiences and challenges, which can inform future research.

Peer-to-peer learning is another critical element of a knowledge network. Farmers who have successfully adopted CA practices can act as local champions, sharing their experiences with others and helping to overcome skepticism. This informal learning, often facilitated through farmer groups or cooperatives, fosters trust and collective problem-solving, accelerating the adoption of new technologies in rural communities. The social learning process builds confidence in CA practices by allowing farmers to learn from one another's successes and failures. Research and development (R&D) play a continuous role in refining and adapting agricultural practices like CA. Collaboration between research institutions, universities, and extension services ensures that innovations are scientifically sound and practically applicable to smallholder farmers. Strengthening knowledge networks through collaboration can significantly enhance the adoption of CA, improving farm productivity, sustainability, and resilience for smallholder farmers.

Bridging institutions

Institutional support and policy frameworks play a crucial role in shaping the adoption of innovations like CA within the AIS framework. As key institutional actors, extension services help translate policies and innovations into actionable knowledge for farmers, fostering the adoption of sustainable practices. The effectiveness of these services depends heavily on the policy environment in which they operate. Extension services can more effectively facilitate adoption in regions where policies support CA through subsidies, tax incentives, or training programs. However, in areas where policies prioritize conventional practices or fail to integrate sustainability goals, extension services face greater challenges in overcoming resistance to change. A supportive policy environment can significantly accelerate the adoption of CA by providing financial incentives such as subsidies for inputs, credit facilities, and research and development support. These policies help reduce the financial barriers that smallholder farmers face when transitioning to CA. For instance, subsidized seeds, equipment, or low-interest loans make CA more affordable, while policies promoting conventional farming can inhibit adoption. Effective policies must be adaptable to local conditions, especially in regions with unique agro-ecological challenges. Decentralized policies that allow local governments to tailor national guidelines to local needs are key to overcoming barriers to adoption.

Political channels and stakeholder platforms are critical in shaping policy development. These platforms bring together government agencies, farmer associations, researchers, NGOs, and agribusinesses, facilitating dialogue and ensuring that policies reflect the needs of all stakeholders. Multi-stakeholder forums can be particularly effective in aligning policy incentives with the capacities and needs of local farmers. These platforms also provide opportunities for sharing knowledge, discussing challenges, and building consensus on promoting CA adoption. Good governance is essential for fostering an environment conducive to innovation adoption. Transparent and accountable governance structures prioritizing sustainable agriculture and smallholder farmers' welfare increase the likelihood of successful CA adoption. By aligning policies, incentives, and stakeholder interests, a well-integrated policy framework can ensure the long-term success of sustainable agricultural practices like CA.

Access to resources (input suppliers and agricultural value chain actors)

Access to physical inputs, financial capital, human capital, and market access is critical for smallholder farmers to successfully adopt CA practices. The AIS framework emphasizes the interdependence of these resources and the role of extension services in facilitating their access. Extension services bridge gaps by providing farmers with knowledge and practical support to access necessary inputs, including seeds, tools, fertilizers, and equipment. They also facilitate links between farmers and input suppliers, ensuring farmers use appropriate resources suited to their specific agroecological conditions. Financial constraints often pose a significant barrier to CA adoption, as smallholder farmers may struggle to afford the initial investment required for CA practices. Extension services can collaborate with financial institutions, such as microfinance banks and agricultural credit schemes, to help farmers access credit, subsidies, or grants. By educating farmers on available financial products and navigating the application processes, extension services improve farmers' ability to invest in CA techniques and tools, thereby enhancing the financial viability of CA practices.

Human capital, in the form of knowledge and skills, is another key factor in adopting CA. Extension services provide training on CA techniques, such as minimum tillage, crop rotation, and residue management, ensuring that farmers understand how these practices work and how to implement them effectively. Peer-to-peer learning, facilitated by extension services, is also vital, as experienced CA adopters share their knowledge with others. Collaboration with research institutions ensures that knowledge generated through agricultural research is disseminated to farmers in a context-specific manner. Market access is essential to incentivize CA adoption. Extension services help farmers access local, regional, and international markets, providing information about market trends and demand for CA-produced goods. By linking farmers to buyers, cooperatives, and value chain networks, extension services help farmers reduce transaction costs, increase bargaining power, and improve the economic returns from CA.

Additionally, by helping farmers access premium markets, such as those for organic or sustainably produced goods, extension services support the long-term sustainability and economic viability of CA adoption.

Agricultural innovation policies and investment

The AIS framework emphasizes that agricultural innovation, such as the adoption of CA, is driven by collaboration among various stakeholders. These interactions are closely linked to agricultural policies and investments, creating an enabling environment for innovation. Effective policies are critical in supporting farmer groups, cooperatives, and community-based organizations, which provide platforms for peer learning and collective action. Policies that offer subsidies for CA inputs, access to credit, and investments in training and extension services enhance the capacity of these groups and facilitate the adoption of CA practices.

Multi-stakeholder partnerships (comprising government agencies, international institutions, research institutions, NGOs, agribusinesses, and financial organizations) are essential for addressing challenges in agricultural innovation. Policies that foster collaboration among these actors and investments in infrastructure, technology, and market access are key to overcoming barriers to CA adoption. By aligning agricultural policies with the needs of smallholder farmers, these partnerships can drive the scaling of CA practices. The agricultural policies and investments form the foundation for collaborative efforts within the AIS framework. When strategically aligned, they enable the adoption of sustainable agricultural practices, like CA, and support long-term innovation and sustainability in agriculture.

Diffusion of innovations theory

The DOI theory, proposed by Everett Rogers, provides a comprehensive framework for understanding how new agricultural practices, such as CA, are adopted by farmers. The theory identifies several key factors that influence the adoption process, including the characteristics of the innovation itself, the adopter's personal attributes, and the broader social system in which adoption occurs. In the context of CA, one critical element is *relative advantage*, which refers to how farmers perceive the benefits of CA compared to conventional farming methods. For CA to gain traction, smallholder farmers need to see it as offering clear advantages regarding improved farm productivity, increased income, or enhanced sustainability. If CA is perceived as more labor-intensive or less profitable than traditional methods, its adoption will be slow. Therefore, extension services must highlight the relative benefits of CA, providing clear evidence of its economic and environmental advantages to overcome initial resistance.

Another crucial DOI element is *compatibility*, which refers to the alignment between innovation and potential adopters' values, needs, and experiences. For smallholder farmers in regions like the Eastern Cape, the degree to which CA practices fit within their existing farming systems, cultural norms, and ecological conditions plays a pivotal role in adoption. Practices such as zero/minimum tillage, crop rotation, and soil conservation might be considered too unfamiliar or disruptive if they do not align with farmers' established knowledge and farming habits. Extension services, therefore, have a vital role in facilitating the adaptation of CA practices to local agroecological conditions and in demonstrating how these practices can complement traditional methods rather than replace them entirely. Compatibility also extends to the social system: if a farmer's community or peer group is adopting CA, it can increase the likelihood of individual adoption through social influence and collective learning.

The *perceived complexity* of CA techniques is another key factor in the DOI framework. Innovations perceived as difficult to understand or implement are less likely to be adopted, particularly among smallholder farmers who may lack technical expertise or resources. Techniques like zero/minimum tillage and crop rotation require new skills and equipment, which can seem daunting to farmers accustomed to conventional methods. *Trialability* (the ability to test new practices on a small scale before fully committing) helps mitigate perceived risks and encourages experimentation. Farmers may be more willing to adopt CA if they can try it out on a limited portion of their land without committing all their resources upfront. Additionally, observability, or the visibility of benefits, is crucial in diffusion. Farmers are more likely to adopt CA if they can see tangible results, such as improved soil quality, better crop yields, or enhanced resilience to climate change. Extension services are critical in making these benefits visible through field demonstrations, farmer-to-farmer learning, and showcasing successful case studies. Extension services can help facilitate the diffusion of CA and accelerate its adoption among smallholder farmers by addressing barriers related to complexity, trialability, and observability.

Methodology

Description of the study area

The study was conducted in South Africa's Eastern Cape Province (ECP), the country's second-largest province, renowned for its remarkable diversity in landscapes and culture. Figure 2 below shows the study sites. Situated in the easternmost part of South Africa, the province spans nearly 170,000 square kilometers, encompassing six district municipalities and two metropolitan municipalities. The Eastern Cape has a rich cultural heritage, primarily driven by the vibrant Xhosa traditions. It boasts a range of natural wonders, from temperate forests in the south to tropical woodlands in the north. The province is also a haven for biodiversity, with its protected areas home to the "Big Five" (elephant, lion, leopard, rhino, and buffalo) and unique marine life, such as dolphins and whales along the coast. Despite these ecological and cultural riches, the province faces significant socio-economic challenges, with ~60% of its 6.6 million inhabitants living in rural areas marked by high levels of poverty and isolation (Mdoda et al., 2023). The economy relies heavily on agriculture, automotive industries, and tourism, yet many remain unemployed

FIGURE 2
Map of the study areas.

or underemployed. Approximately 2.5 million individuals in the region are unemployed, and many rely on subsistence farming, especially in rural areas where the agriculture sector is vital for livelihoods.

Agriculture in the Eastern Cape is diverse, spanning livestock production and crop cultivation, particularly vegetables. However, the region's agricultural potential is hindered by climatic variability, with coastal areas experiencing temperate maritime climates and the interior regions grappling with semi-arid conditions (Mujuru and Obi, 2020). This climatic diversity presents challenges such as droughts, erratic rainfall, and soil degradation, affecting agricultural productivity. Smallholder vegetable farmers, who play a central role in the local economy, struggle with low yields, poor soil health, and high production costs. These factors exacerbate socio-economic hardships and contribute to food insecurity in the province. As traditional farming practices prove increasingly unsustainable, adopting more resilient and environmentally friendly methods, such as CA, has become essential. This study focuses on smallholder vegetable farmers in various districts within the Eastern Cape, examining their farming practices, challenges, and opportunities for adopting CA. By exploring these aspects, the study aims to provide insights into how sustainable farming techniques can improve productivity, enhance soil health, and contribute to the region's long-term economic and environmental resilience. Figure 2 shows the study areas.

Research design

This study employed a robust mixed-methods research design, combining quantitative and qualitative approaches to comprehensively analyze the impact of Conservation Agriculture (CA) adoption on farm returns among smallholder vegetable farmers in the Eastern Cape. A sample of 200 farmers was selected, ensuring diverse representation from various regions and farming conditions, which enhanced the generalizability of the findings. The quantitative component involved structured surveys to capture key data on farm-level economic outcomes, adoption patterns, and socio-economic characteristics. These surveys collected information on farm productivity, income levels, resource access, and the extent of CA adoption. Logistic regression was applied to analyze the data and identify factors influencing the likelihood of adopting CA. At the same time, Endogeneity Switching Regression (ESR) was used to assess the impact of CA adoption on farm returns and income, facilitating a robust comparison between adopters and non-adopters and addressing potential endogeneity issues.

To complement the quantitative analysis, in-depth semi-structured interviews were conducted with a subset of farmers selected from the survey sample. These qualitative interviews provided valuable insights into the personal experiences, challenges, and motivations behind CA adoption. Participants discussed barriers to adoption, perceived benefits, and the role of extension services while highlighting socio-cultural factors such as family traditions, community support, and local knowledge systems that influenced their decisions. By triangulating the quantitative and qualitative findings, the study aimed to provide a nuanced understanding of the relationship between CA adoption and farm returns. The mixed-methods approach allowed for a deeper exploration of the socio-economic and institutional factors shaping adoption decisions, offering both statistical rigor and rich contextual insights. Ultimately, this comprehensive design provided a well-rounded perspective on the potential for CA to improve the sustainability and productivity of smallholder vegetable farming in the Eastern Cape.

Sampling procedure, sample size, and data collection

The study utilized a stratified random sampling technique to select smallholder vegetable farmers from diverse districts within the Eastern Cape Province of South Africa. This method was designed to ensure a balanced representation of farmers from varying socioeconomic and geographic backgrounds, facilitating a comprehensive analysis of the factors influencing the adoption of CA. Each district within the province with a substantial population of vegetable farmers practicing CA or conventional farming was treated as a distinct stratum. From these strata, farmers were randomly selected in proportion to the size of the farming population, ensuring that both CA adopters and non-adopters were adequately represented.

The sample size for the study was set at 200 smallholder vegetable farmers, a figure derived from a power analysis aimed at detecting statistically significant differences in farm returns between CA adopters and non-adopters, as well as understanding the relationship between adoption determinants and various socio-economic characteristics. Given the research objectives and available resources, this sample size was considered optimal, striking a balance between being large enough to provide a representative snapshot of the smallholder farming community in the province and small enough to allow for effective and robust statistical analysis. Ultimately, the sampling strategy ensured that the study's findings would be reliable and relevant to the broader context of smallholder vegetable farming in the Eastern Cape.

Data collection

Data collection for this study employed a robust mixed-methods approach, integrating quantitative and qualitative techniques to comprehensively understand CA adoption and its effects on farm returns. A structured questionnaire was administered to all 200 participating farmers, gathering data on demographic characteristics, farm operations, income levels, and the extent of CA adoption. In addition to these core questions, the survey also explored factors such as access to resources, availability of extension services, market access, financial support, and other key elements influencing farmers' decisions to adopt CA practices. This quantitative data laid the foundation for understanding the broader patterns of CA adoption within the farming community. To complement these findings, semi-structured interviews were conducted with a targeted subset of 20 farmers selected from the larger sample for pre-testing so that the reliability, validity, and training of enumerators would be familiar with the questionnaire. The researchers, together with Department of Agriculture Extension personnel, revised the questionnaire. These interviews provided rich qualitative insights into the personal experiences, challenges, and socio-cultural factors influencing CA adoption, offering a deeper understanding of the nuanced barriers and motivations that the survey alone could not capture. Furthermore, detailed financial and production data were collected from CA adopters and non-adopters, including input costs, crop yields, and revenue figures. This economic data facilitated a comparative analysis of farm returns, enabling the application of descriptive and regression-based methods to assess the financial impact of CA practices. Integrating these diverse data sources allowed for a well-rounded, in-depth assessment of CA's effects on the sustainability and productivity of smallholder farms, ensuring that both statistical trends and personal narratives were considered in evaluating the practice's overall impact.

Data analysis

The analysis is composed of three strands. Firstly, through descriptive statistics, we provide a profile of smallholder vegetable farmers, the challenges, and the impact of CA. This was done through the use of means, percentages, and graphs. Stage 2 involved using logistic regression analysis to estimate the factors influencing the adoption of CA by smallholder vegetable farmers. Stage three involved endogeneity switching regression to estimate the impact of adopting CA on the farm returns of smallholder vegetable farmers.

Adoption of CA practices

According to Aziz et al. (2015), Binary logistic regression is a statistical method used to predict a categorical (usually dichotomous) variable from a set of predictor variables. With this model, one or more independent variables can determine the outcome, where there are only two possibilities. The assumption is that P (Y = 1) is the probability of the occurring event; therefore, the dependent variable must be coded accordingly. The factor level 1 of the dependent variable should represent the desired outcome. Another fundamental assumption is that the binary logistic regression model assumes linearity of the independent variables and the log odds.

The general Binary Logistic Regression Model is expressed as follows:

$$\text{Log (P)} = \text{In}\left(\frac{p_i}{1-p_i}\right) = a + \beta_i X_i \ldots\ldots\ldots \beta_k X_k + \mu_i \quad (1)$$

Where *In* (*pi*/1–*pi*) is the natural log of the odds, *Pi* is the probability that smallholder farmers adopt conservation agriculture, 1 – Pi is the probability that smallholder farmers do not adopt conservation agriculture, β_i is the estimated parameter, X_i is the explanatory variable, and U_i is the disturbance term.

Impact of adopting CA

Endogeneity Switching Regression (ESR) was explored to examine the relationship between the outcome variables and a set of exogenous variables in the context of adopting CA practices. ESR is a sophisticated statistical technique designed to address the issue of endogeneity in treatment effects estimation, which often arises in observational studies.

Endogeneity can occur due to several reasons, including:

Omitted variable bias

When an unobserved variable influences both the treatment (e.g., adoption of CA) and the outcome, leading to a biased estimate.

Measurement error

When the variables used in the model are inaccurately measured, it affects the validity of the results.

Simultaneity

When the treatment and outcome mutually influence each other, creating a feedback loop distorts causal inference.

The ESR methodology is particularly valuable when estimating the impact of a treatment like conservation agriculture adoption, as it accounts for these endogeneity issues. It operates on the concept of latent outcomes and uses switch points to manage the endogenous nature of the treatment variable. It allows for the differentiation between the treatment effect on various groups (e.g., farmers who adopted CA vs. those who did not), addressing potential biases that could skew the findings. Studies like Oduniyi et al. (2022), Toiba et al. (2020), and Okello (2024) have used this model to estimate impact analysis in agriculture. The Endogeneity Switching Regression (ESR) model offers several key benefits, making it a powerful tool for assessing the impact of CA adoption. First, it effectively addresses endogeneity, mitigating issues such as omitted variables, measurement errors, and simultaneity, which are common challenges in treatment-effect studies. By handling these biases, ESR enhances the ability to make more accurate causal inferences about the impact of CA adoption on outcome variables. Additionally, ESR allows for the estimation of heterogeneous treatment effects, meaning it can assess how the impact of adopting CA varies across different groups, such as diverse farmers. The model also incorporates latent outcomes, helping to estimate what would have happened had participants not been exposed to the treatment, providing a more accurate and reliable measure of causal effects. In summary, ESR is a valuable approach for studying the effects of CA adoption, as it addresses endogeneity concerns and enables more precise estimation of treatment effects, mainly when those effects differ across groups.

The subsequent second stage involves the outcome equation, where farm returns, measured in Rands (ZAR) per hectare, are utilized to divide the endogenous model into two distinct components (Lokshin and Sajaia, 2004). This entails implementing separate commands or production functions to analyze small-scale crop farmers' decision-making process regarding the adoption vs. non-adoption of CA practices. The study presumes that the arrays representing these outcome variables adhere to a linear relationship with explanatory factors to assess the influence of adopting CA conditions on farm net returns. This linear specification is articulated as follows:

$$Y_i = X_{i\alpha} + y_i\varphi + \varepsilon_i \tag{2}$$

Where

Y_i is the vector of outcome variables (farm net returns), and X_i is the vector of explanatory variables such as age, education, family size, farm characteristics (e.g., farm size, location of the farm, family size), and institutional and financial variables (e.g., access to extension services, training received on CA, and credit), while y_i is a dummy variable capturing the adoption of CA practices, α and φ are parameters to be estimated, and εi represents the error term.

Estimation and identification

Specific to the research study's reliance on survey data and the non-random nature of selection in CA adoption, it becomes imperative to utilize an approach that addresses selection bias effectively. Hence, this study opted for an Endogenous Switching Regression (ESR) model to mitigate selection bias stemming from both observable and unobservable heterogeneity within the sample, drawing upon the works of Lokshin and Sajaia (2004), Tanimonure and Naziri (2021), and Abdulai and Huffman (2014). This model operates in two stages: firstly, the decision-making process regarding adoption is examined as outlined in the selection Equations 1, 2; secondly, two distinct equations are formulated to represent outcomes for adopters and non-adopters.

$$\text{Command 1 to Adopt } y_{1i} = X_{1i}\beta + \varepsilon_{1i} \ \ if\ A_i = 1 \tag{3}$$

$$\text{Command 2 to Not to adopt } y_{2i} = X_{2i}\beta + \varepsilon_{2i} \ if\ A_i = 0 \tag{4}$$

Where

y_{1i} and y_{2i}, respectively, represent crop yield and farm returns for adopters and non-adopters of CA, measured as ZAR/hectare. X_i is the list of explanatory variables. ε_{1i} and ε_{2i} are the error terms for adopters and non-adopters, respectively.

In the context of this switching regression model, selection bias arises in the error terms ε and η. Assuming the explanatory factors do not account for unobserved variables, there exists a correlation between the error terms of the production and selection equations, denoted as corr (ε, η) ≠ 0. The error terms ηi, ε_{1i} and ε_{2i} adhere to a trivariate normal distribution with a mean of zero, and the

10.3389/fsufs.2025.1605561

covariance matrix is delineated as follows:

$$\mathrm{Cov}\left(\eta\mathrm{i},\ \varepsilon_1 \text{ and } \varepsilon_2\right) = \begin{cases} \delta_\eta^2 & \delta_{1\eta} & \delta_{2\eta} \\ \delta_{1\eta} & \delta_1^2 & . \\ \delta_{2\eta} & . & \delta_2^2 \end{cases} \tag{5}$$

where

The variance of the error terms in the selection equation and the two-production commands 1 and 2 are respectively denoted by δ_η^2 ; δ_1^2; and δ_2^2.

The covariance of the selection equation error term (η_i) and the production regimes 1 (ε_{1i}) and 2 (ε_{2i}) is respectively $\delta_{1\eta}$ and $\delta_{2\eta}$. The dot (.) shows that the commands 1 and 2 outcomes cannot be simultaneously observed for a farmer and hence the covariance is not present (Maddala, 1983). In the presence of selection bias, the expectations of the error terms for the two regime equations are different from zero.

$$E[\varepsilon_{1i} \mid A_i\ =\ 1 = \delta_{1\eta}\,\frac{\varnothing(Z_{i\alpha})}{\Phi(Z_{i\alpha})} = \delta_{1\eta}\,\lambda_{1i}, \tag{6}$$

$$E[\varepsilon_{2i} \mid A_i\ =\ 0 = -\delta_{2\eta}\,\frac{\varnothing(Z_{i\alpha})}{1 -\ \Phi(Z_{i\alpha})} = \delta_{2\eta}\,\lambda_{2i}, \tag{7}$$

where

$\varnothing(.)$ is the standard normal probability distribution.

$\Phi(.)$ is the standard normal cumulative distribution.

λ_{1i} and λ_{2i} are interpreted as inverse Mills ratios (Heckman, 1979) where these were incorporated in the production correct side equations for capturing any selection bias. The correlation coefficients between the error terms of the production and the selection equations are shown.

$$\rho_1\ =\ \frac{\delta_{1\eta}^2}{\delta_\eta \delta_1} \tag{8}$$

$$\rho_2\ =\ \frac{\delta_{2\eta}^2}{\delta_\eta 2} \tag{9}$$

The significance of the estimated covariances and rho sub 2 reflect that the decision to adopt farm returns is correlated, which rejects the null hypothesis of sample selectivity bias. This highlights the importance of the endogenous switching model. In this regard, the complete information maximum likelihood estimate provides an efficient ESR output, simultaneously estimating both the selection and production equations. This is higher than the two-step estimators, which are inefficient for deriving standard errors.

The treatment effect of adaptation strategies

The Endogenous Switching Regression (ESR) model is justified in this context because CA adoption is likely influenced by both observable and unobservable farmer characteristics, leading to selection bias. ESR corrects for this bias by jointly estimating a selection equation (adoption decision) and separate outcome equations (income) for adopters and non-adopters. It accounts for the fact that adopters and non-adopters may systematically differ in ways that also affect income, such as risk preferences, access to information, or motivation. By modeling these differences and estimating counterfactual outcomes, ESR isolates the true effect of CA adoption on income while correcting for endogeneity in the selection process. The study estimates the effect of adopting CA practices on farm returns by employing an endogenous regression model, where adopters are regarded as the treatment group ($A_i =$ 1), and their counterfactual is estimated. The observed outcomes for both adopters and non-adopters are outlined below:

$$\text{Adopter } E[y_{1i} \mid A_i\ =\ 1]\ = X_{1i}\beta_1\ + \delta_{1\eta}\lambda_{1i,} \tag{10}$$

$$\text{Non} - \text{adopter } E[y_{2i} \mid A_i\ =\ 0]\ = X_{2i}\beta_2\ + \delta_{2\eta}\,\lambda_{2i,} \tag{11}$$

Likewise, the equation for the counterfactual farm returns of both adopters and non-adopters is as follows:

$$\text{Adopter counter factual } E[y_{2i} \mid A_i\ =\ 0]\ = X_{1i}\beta_2\ + \delta_{2\eta}\,\lambda_{1i,} \tag{12}$$

$$\text{Non} - \text{adopter counterfactual } E[y \mid A_i\ =\ 0]\ = X_{2i}\beta_1\ + \delta_{1\eta} \tag{13}$$

Then the average treated impact of farm returns for those is computed as:

$$\begin{aligned} \mathrm{ATT}\ &=\ E[y_{1i} \mid A_i\ =\ 1]\ -\ E[y_{2i} \mid A_i\ =\ 1] \\ &= X_{1i}(\beta_1 - \beta_2)\ + (\delta_{1\eta} - \delta_{2\eta}\ )\,\lambda_{1i,} \end{aligned}$$

And the predicted impact of adoption on farm returns for non-adopters (untreated) is:

$$\mathrm{ATU}\ = E[y_{1i} \mid A_i\ =\ 0]\ -\ E[y_{2i} \mid A_i\ =\ 0] \tag{14}$$

$$= X_{2i}(\beta_1 - \beta_2)\ + (\delta_{1\eta} - \delta_{2\eta}\ )\,\lambda_{2i,} \tag{15}$$

Where

ATT—represents the average treatment for the treated (adopters), and ATU—represents the untreated (non-adopters) treatment. The validity of the ESR requires an exclusion restriction that is correlated with adoption, while it does not play a role in the productivity of small-scale crop farmers. Therefore, the study utilizes a set of variables as selection instruments, comprising CA training information and distance to market. These variables are deemed instrumental, as they are crucial factors influencing the decision to adopt to CA, as researchers argue. Nevertheless, variables did not directly dictate farmers' farm income levels. Empirically, the validity of instruments in the Endogenous Switching Regression (ESR) model is assessed. The initial test involves employing a logit model to adopt the CA practices, incorporating both instruments and additional variables. These instruments are collectively confirmed as robust predictors for adoption. A distortion test is also conducted to ascertain whether the instruments significantly influenced return processes. This investigation indirectly verifies whether the instruments exhibit a correlation with unobservable factors. The test affirms that the instruments do not collectively hold statistically significant influence over farm returns among non-adopters.

Cross-sectional data were used in this study because they support causal inference when combined with robust econometric models like Endogenous Switching Regression (ESR), which accounts for selection bias and unobserved heterogeneity. ESR enables estimation of treatment effects (ATT and ATU) by modeling both the decision to adopt conservation agriculture (CA) and the income outcomes for adopters and non-adopters. The results in Table 5 show that CA adoption significantly increases farm income, with both adopters and non-adopters benefiting if they choose CA. However, the absence of a time dimension in cross-sectional data limits the ability to confirm causality, as it cannot establish temporal precedence. Additionally, reliance on strong parametric assumptions and the risk of unmeasured confounders can weaken the reliability and generalizability of causal claims. These were addressed through estimating counterfactual scenarios; the model helps infer causal impacts even in the absence of longitudinal data.

Data

Table 1 below illustrates the data collected from smallholder farmers in the study area.

Results and findings

This analysis of smallholder vegetable farmers' profiles highlights several socio-economic factors significantly associated with adopting CA, as shown in Table 2 below. Key differentiators include access to extension services (68% of adopters vs. 42% of non-adopters), membership in farm organizations, and training on new agricultural techniques, each showing a strong association with CA adoption. The results of this study suggest that several demographic and economic factors play a crucial role in determining the adoption of CA practices among smallholder farmers. The results reveal that female farmers dominate smallholder farmers in the study area, with 60%. It is not surprising that the agricultural landscape has changed throughout the world as more females are investing in and practicing farming. However, these results contradict the findings of Kangogo et al. (2021) and Uddin and Dhar (2016), who found that male farmers dominate smallholder farming as females take care of the household chores. In terms of demographic characteristics, adopters of CA tend to be younger, with a mean average age of 47 years, have slightly larger families (mean average family size of 4 persons in the household), and farm on marginally larger plots of land (mean farm size of 3 Hectares). The age was used as a proxy for farm experience, and this means that these smallholder farmers were at their active age and had farm experience, which guided them to be more open to adopting innovative agricultural practices as they aim to enhance their agricultural productivity and farm returns so that they can take care of their families. These results concur with Oduniyi et al. (2022), Mango et al. (2017), Apeh et al. (2023), and Mdoda et al. (2023) that middle-aged farmers played an important role in adopting innovative technologies aimed at enhancing their agricultural productivity and farm returns, as these farmers are still active, able to read, and access information about new agricultural technologies. Family size was used as a proxy for family labor. The larger family sizes provide more labor, facilitating the additional work required for CA methods. Larger farm sizes can also offer greater scope for implementing practices such as crop rotation and minimal tillage, which are core to CA. This aligns with the notion of Mango et al. (2017) that having a larger family size provides the necessary access to labor and land resources, directly influencing the decision to adopt CA, as it reduces the operational constraints that might discourage adoption due to labor limitations. Furthermore, economic factors such as higher household incomes and greater educational attainment among adopters signal that financial stability and knowledge acquisition are key drivers of adoption. The higher average monthly income (R5,821.20) of adopters compared to non-adopters (R3,567.31) could mean that those with more disposable income are better able to afford the initial investments or input costs required for CA, making them more likely to engage in sustainable agricultural practices (Geffersa et al., 2021). Additionally, the results reveal that farmers were literate (having a mean average of 11 years spent in school) as they spent more years of schooling, suggesting that adopters may better understand agricultural techniques and are more likely to be aware of the long-term benefits of CA. These results agree with Nkonki-Mandleni et al. (2022) that being literate has assisted the majority of smallholder farmers to adopt innovative technologies such as CA, as they have better knowledge and can understand the instructions on operating these innovative technologies on their farms.

The study also underscores the importance of proximity to markets in promoting CA adoption. Adopters are located, on average, 19.26 kilometers from markets, compared to 21.42

TABLE 1 Variable description and expected sign.

Variable	Description and variable measurement	Expected sign
Age	Number of years (Continuous)	+
Gender	Dummy, 1 if the farmer has access to extension services, 0 otherwise	+
Access to extension services	Dummy, 1 if the farmer is male, 0 otherwise	+
Access to credit	Dummy, 1 if the farmer has access to credit, 0 otherwise	+
Access to agricultural input (fertilizer)	Dummy, 1 if the has access to agricultural input, 0 otherwise	-
Member of a farm organization	Dummy, 1 if the farmer is a member of a farm organization, 0 otherwise	+
Full-time farmer	Dummy, 1 if the farmer is full-time, 0 otherwise	+
Family size	Number of people in the household (continuous)	+
Years spent in school	Years spent by the farmer in school (Continuous)	+
Distance to the market input/output	Distance traveled to access the input/output market in Km	-
Farm size	The size of the farm (Continuous) in Ha	+
Access to trainings	Dummy, 1 if the farmer has access to trainings, 0 otherwise	+
Outcome variable		
Household monthly Income	The income per farm output (ZAR)	

TABLE 2 Profile of smallholder vegetable farmers in the study area.

Variable	Adopters of CA (120)	Non-Adopters of CA (80)	Overall (200)	T-test
Sex: female	0.58	0.62	0.60	0.018**
Marital status: married	0.66	0.64	0.65	0.876
Access to extension services: yes	0.68	0.42	0.55	0.042**
Member of farm organization: yes	0.70	0.68	0.69	0.003***
Training on new agricultural techniques: yes	0.66%	0.342	0.50	0.016**
Occupational status: farmer and other	0.54	0.74	0.64	0.752
Variable	**Adopters of CA (120)**	**Non-Adopters of CA (80)**	**Overall (200)**	**Chi-square**
Age	47.68	46.20	46.94	0.008***
Family size	4.26	3.68	3.97	0.028**
Farm size	2.56	2.45	2.51	0.030**
Years spent in school	12.10	10.23	11.17	0.001***
Household monthly income	5 821.20	3 567.31	4 694.26	0.002***
Distance to market output/input	19.26	21.42	20.34	0.012**

Significance at the 5%, and 1% levels are indicated by **, and ***, respectively.

kilometers for non-adopters. This shorter distance to markets facilitates more straightforward access to necessary inputs, such as seeds, fertilizers, and farming equipment, and enables more convenient sales of agricultural products. This logistical advantage suggests that CA adoption is influenced by internal factors like family size and education, and external factors such as market access, which can significantly reduce barriers to adopting new farming methods. Social support networks, such as membership in farm organizations and access to extension services, also emerge as critical components for adoption. These results concur with Nkonki-Mandleni et al. (2022) that having contact with other farmers in the form of farm organizations and contact with extension agents augments the ability of farmers to use innovative technologies such as CA on their farms. Adopters are more likely to have received training on new agricultural techniques and be part of farm organizations providing valuable resources and support. Being a full-time farmer played a crucial role in adopting CA, as you know what is essential for the farm and how to enhance the farm's operation. Most of the farmers were full-time farmers. These factors highlight that adopting CA requires education, financial resources, social networks, and physical resources.

Extent of farmers' knowledge about conservation agriculture practice

The analysis highlights a notable knowledge gap between adopters and non-adopters of CA practices among vegetable farmers, indicating that successful adoption is closely tied to familiarity with these practices. Table 3 below shows Extent of farmers' knowledge about conservation agriculture practice by vegetable farmers. The results reveal that 64%, 26%, and 45% of adopters, non-adopters, and overall farmers had fundamental knowledge about CA practices. These results aligned with Uddin and Dhar (2016) that smallholder farmers know conservation agricultural practices. The substantial differences in awareness, such as 56% of adopters understanding zero/minimum tillage compared to only 18% of non-adopters, suggest that knowledge of CA methods is critical for implementation. This implies that efforts to promote CA should prioritize education and awareness programs targeting non-adopters, particularly practical aspects like zero/minimum tillage, crop residue management, and diversified crop rotation.

TABLE 3 Extent of farmers' knowledge about conservation agriculture practice by vegetable farmers.

Variable	Adopters of CA (120)	Non-Adopters of CA (80)	Overall (200)
Zero/minimum tillage (ripping land preparation)	0.56	0.18	0.37
Crop residue management (Leave crop residues in the field after harvesting, used manure for fertilizer and weed scrapper)	0.63	0.24	0.44
Diversified crop rotation (crop rotation and intercropping)	0.72	0.36	0.54
Total	0.64	0.26	0.45
Training received on crop farming	0.54	0.32	0.43

Moreover, the results indicate that training significantly influences knowledge levels, with 54% of adopters receiving relevant training vs. 32% of non-adopters. Providing targeted training could enhance the knowledge base of non-adopters, potentially leading to increased adoption rates. The findings underscore the importance of integrating training and education into agricultural policies and initiatives, as they can facilitate the transition toward more sustainable farming practices.

Determinants of adopting conservation agriculture by smallholder vegetable farmers

Understanding the factors influencing the adoption of CA is essential for enhancing sustainable farming practices among smallholder vegetable farmers. Table 4 shows the Logistic results of adopting conservation agriculture by smallholder vegetable farmers. This study utilized logistic regression to estimate factors influencing the adoption of conservation agriculture by smallholder vegetable farmers in the study area, as shown in Table 4. The table below depicts the factors influencing the adoption of CA by smallholder vegetable farmers. The logistic regression analysis of the data, comprising 200 observations, reveals significant insights into the relationship between predictors and the binary outcome of CA adoption. The model demonstrates robustness, highlighted by a high likelihood ratio chi-square (LR) value of 172.60, indicating an excellent fit to the data. The associated p-value of 0.0000 firmly rejects the null hypothesis that no predictors influence the outcome, confirming the statistical significance of the model. Furthermore, the Pseudo-R^2 statistic, at 0.6846 (68.46%), indicates that the model explains a substantial portion of the variance in the dependent variable, showcasing its efficacy in capturing the relationship between predictors and the binary outcome. The log-likelihood value of −245.35285 supports the model's adequacy, as a higher value indicates a better fit. These findings demonstrate that the logistic regression model effectively clarifies the influence of predictors on the likelihood of adopting conservation agriculture, making it a reliable tool for policy and decision-making. The next section explores the specific variables that significantly affect adoption, offering insights into how targeted interventions can support greater uptake of CA practices among smallholder farmers. These results support the Logistic and ESR model's appropriateness and confirm that selection bias was present and adequately addressed.

The logistic regression results provide detailed insights into how various factors influence the adoption of CA among smallholder vegetable farmers. The farmer's age is a continuous variable, which was also used as a proxy for farm experience, and emerges as a significant determinant in the adoption of CA among smallholder vegetable farmers, as evidenced by the logistic regression results. The coefficient of age was positive (0.682) with a standard error of 0.239, indicating a positive relationship between age and CA adoption, with a statistical significance of a 5% level ($p = 0.040$). This suggests that every additional year of age by the vegetable farmer induces the log odds of adopting CA to increase by 0.682 units. The marginal effect of age (0.032) further clarifies this impact, showing that each year increases the probability of CA adoption by ∼3.2%. These findings imply that younger and middle-aged farmers are more likely to embrace CA practices, potentially due to entrenched farming methods, resistance to change, or high exposure to new agricultural techniques to enhance productivity and farm returns. These findings align with Nkonki-Mandleni et al. (2022), who observed that younger and middle-aged farmers are more likely to adopt CA compared to older farmers, who tend to have more conservative views and are thus more resistant to change. As a result, there is an inverse relationship between age and long-term conservation investment. These results are in contrast with Ngoma et al. (2021), who found older farmers to be more open to adopting CA as compared to younger farmers.

TABLE 4 Logistic results of adopting conservation agriculture by smallholder vegetable farmers.

Variable	Coef.	Std Err.	P>Z	Marginal effect
Age	0.682	0.239	0.040**	0.032
Years spent in school	1.224	0.294	0.008***	0.051
Access to credit	1.835	0.359	0.007***	0.025
Distance to market input/output	−3.047	0.756	0.001***	0.038
Access to extension services	0.7166	0.328	0.029**	0.014
Family size	1.259	0.126	0.021**	0.023
Farm size	−0.423	0.170	0.015**	0.022
Number of observations: 200	LR Chi-square: 172.60	Prob > chi^2: 0.0000	Pseudo-R^2: 0.6846	Log-likelihood: −245.35285

Significance at the 5%, and 1% levels are indicated by **, and ***, respectively.

The years spent in school by farmers are a continuous variable, and they emerge as an essential factor influencing the adoption of CA among smallholder vegetable farmers. The coefficient of years spent in school was positive (1.224) with a small standard error of 0.294, indicating a robust and statistically significant positive relationship between education level and CA adoption at a 1% level ($p = 0.008$). This implies that each additional year spent in school by the farmers induces the log odds of adopting CA to increase by 1.224 units. The marginal effect of 0.051 further underscores this impact, demonstrating that each additional year of schooling raises the probability of adopting CA by ∼5.1%. These findings highlight the critical role of education in enhancing farmers' awareness, knowledge, and receptivity to sustainable farming practices. These results agree with Mdoda et al. (2023) that educated farmers adopt innovative technology to enhance farm productivity and farm returns of smallholder farmers. Educated farmers may have better access to information on the benefits of CA and the skills necessary to implement these practices effectively.

Access to credit is a categorical variable and arises as a crucial determinant influencing the adoption of CA among smallholder vegetable farmers, as indicated by the logistic regression findings. The coefficient of access to credit was positive (1.835) with a low standard error of 0.359, underscoring a strong and statistically significant positive relationship between access to credit and CA adoption at a 1% level ($p = 0.007$). This suggests that higher credit access levels increase the likelihood of adopting CA by 1.835 units. The marginal effect of 0.025 further elucidates this impact, indicating that improved access to credit enhances the probability of CA adoption by ∼2.5%. This relationship highlights the role of financial resources in facilitating the adoption of sustainable farming practices. Farmers with easier access to credit may have the means to invest in new agricultural techniques, purchase necessary inputs, or mitigate risks associated with adopting unfamiliar methods. These findings are consistent with those of Gebeyehu (2023) and Nkonki-Mandleni et al. (2022), who emphasized that access to credit helps ease farmers' financial limitations, thereby increasing their ability to cover the transaction costs associated with adopting conservation agriculture practices they wish to implement.

The distance to markets for inputs and outputs is a continuous variable and appears to be a significant factor influencing the adoption of CA among smallholder vegetable farmers. The coefficient of distance to market for inputs/output was negative (−3.047), coupled with a standard error of 0.756, indicating a robust and statistically significant negative association between distance to market and CA adoption at a 1% level ($p = 0.001$). This suggests that farmers closer to markets for inputs and outputs are more inclined to adopt CA practices than vegetable farmers far from the central business area. The marginal effect of 0.038 provides further clarity, illustrating that for each unit decrease in distance to the market, the probability of CA adoption increases by ∼3.8%. This finding emphasizes farmers' logistical and economic challenges when accessing essential resources and markets. Proximity to markets facilitates more straightforward access to agricultural inputs, knowledge, and potential markets for produce, all of which are crucial for successfully implementing and sustaining CA practices.

As the logistic regression analysis indicates, access to extension services is a categorical variable and is a fundamental factor influencing the adoption of CA among smallholder vegetable farmers. The coefficient of access to extension services is positive (0.7166), with a standard error of 0.328, revealing a statistically significant positive relationship between access to extension services and CA adoption at a 5% level ($p = 0.029$). This implies that improved access to extension services increases the likelihood of adopting CA by 0.7166 units. These results were in line with Loki and Mdoda (2023), who stated that having access to extension services assists farmers in adopting new technologies to enhance their production. The marginal effect of 0.014 further clarifies this impact, indicating that better access to extension services leads to an approximate 1.4% increase in the probability of CA adoption. Extension services are crucial in disseminating knowledge, providing technical support, and facilitating access to resources necessary for adopting new agricultural practices. Farmers with enhanced access to extension services will likely receive guidance on CA techniques, benefits, and implementation strategies, reducing adoption barriers such as uncertainty and lack of information. Gebeyehu (2023) and Nkhoma and Kalinda (2017) highlighted that having access to agricultural extension services significantly improves the efficiency of adoption decision-making processes.

Family size is a continuous variable and is one of the crucial determinants influencing the adoption of CA among smallholder vegetable farmers. The coefficient of family size was positive (1.259), coupled with a standard error of 0.126, indicating a robust and statistically significant positive relationship between family size and CA adoption at a 5% level ($p = 0.021$). This suggests that larger families are more likely to adopt CA practices, increasing the log odds of adoption by 1.259 units. The marginal effect of 0.023 provides further insight, indicating that each additional family member increases the probability of CA adoption by ∼2.3%. Larger families may have more labor resources, allowing them to effectively implement and manage the additional tasks associated with CA practices. Moreover, larger households might also perceive CA adoption as a strategy to enhance productivity and sustainability, aligning with their economic and food security goals. These results align with the findings of Oscar et al. (2019), who emphasized the importance of family size in smallholder farming. A larger family provides essential labor for the farm, which is particularly vital for conservation agriculture practices, as these families are more likely to have a surplus of labor needed to carry out conservation activities.

Farm size is a continuous variable and plays a crucial role in shaping the adoption of CA among smallholder vegetable farmers, as evidenced by the logistic regression analysis. The coefficient of farm size was negative (−0.423), accompanied by a standard error of 0.170, revealing a statistically significant negative relationship between farm size and CA adoption at a 5% level ($p = 0.015$). This suggests that larger farm sizes decrease the likelihood of adopting CA by 0.423 units. The marginal effect of 0.022 further elucidates this relationship, indicating that each additional unit increase in farm size corresponds to an ∼2.2% decrease in the probability of CA adoption. This finding may stem from several factors: larger farms already have established practices that are less compatible with CA, face higher operational complexities in transitioning to new methods, or perceive lower immediate benefits from changing practices than smaller farms. However, it's essential to note that while larger farms may show lower adoption rates of CA, they could still benefit from tailored support and incentives to overcome barriers and promote sustainable practices. These results contrast with the findings of Ngoma et al. (2021), who discovered that farmers with larger farm sizes can experiment with conservation agriculture on certain portions of their land while continuing to use conventional farming methods that are lower in risk and return.

Impact of the adopted conservation agriculture by smallholder vegetable farmers

In this study, missing data were carefully addressed to maintain the integrity and reliability of the analysis. Table 5 shows the findings from the Endogenous Switching Regression (ESR) model, which evaluates the impact of adopting conservation agriculture (CA) on the farm income of smallholder vegetable farmers. Prior to model estimation, the dataset was examined for incomplete observations. Cases with missing values on key variables [such as farm income, CA adoption status, and instrumental variables (e.g., access to extension services, distance to market)] were excluded using listwise deletion, as the proportion of missing data was relatively low (<5%). This approach ensured that only complete and consistent records were included in the Endogenous Switching Regression (ESR) model. Although listwise deletion may reduce sample size, it avoids introducing potential bias associated with imputation methods when the missing data are minimal and assumed to be missing completely at random. This strategy helped preserve the validity of the estimates while ensuring that the analysis was based on a robust and complete dataset.

Table 5 shows the findings from the Endogenous Switching Regression (ESR) model, which evaluates the impact of adopting conservation agriculture (CA) on the farm income of smallholder vegetable farmers. The analysis considers both the Average Treatment Effect on the Treated (ATT) and the Average Treatment Effect on the Untreated (ATU), offering a detailed comparison of income outcomes between adopters and non-adopters. In this study, the Endogenous Switching Regression (ESR) model assumes joint normality of the error terms in the selection and outcome equations, but this assumption was not formally tested. This was a practical choice due to data limitations, allowing the model to estimate treatment effects and correct for selection bias. While the results suggest a strong positive impact of CA adoption on income, the results were interpreted with caution, and future studies are encouraged to test this assumption or use alternative estimation methods for validation. Results are shown in Table 5 below.

The analysis of the impact of adopting conservation agriculture (CA) on farm income among smallholder vegetable farmers reveals several key insights. Adopters of CA earned an average income of ZAR 7,294, compared to ZAR 6,205 for non-adopters. The Average Treatment Effect on the Treated (ATT) is estimated at ZAR 3,982 ($p < 0.01$) with a standard error of 176, indicating that adopters earned nearly ZAR 4,000 more than they would have if they had not adopted CA. Similarly, the Average Treatment Effect on the Untreated (ATU) is ZAR 1,893 ($p < 0.01$) with a standard error of 43, suggesting that non-adopters could have significantly increased their income had they adopted CA practices. The results clearly demonstrate the positive and significant economic impact of CA adoption among smallholder vegetable farmers. These findings are consistent with previous empirical studies (Khonje et al., 2018; Oduniyi et al., 2022; Sankhulani, 2021), which also documented income gains from CA adoption. Moreover, the greater potential benefit for non-adopters (ATU) suggests a missed economic opportunity and highlights the importance of addressing the barriers to adoption, such as limited awareness, access to resources, or risk aversion. The generated income assisted smallholder vegetable farmers in investing in new and improved agricultural inputs, ultimately enhancing farmers' capacity to accumulate productive assets required for farm operations. Notably, the analysis also reveals significant heterogeneity in treatment effects, with the potential income gain being greater for non-adopters (ZAR 1,759) than for current adopters (ZAR 670). This suggests that while CA benefits all farmers, its impact may vary depending on individual or contextual factors. Therefore, efforts to promote CA should focus not only on expanding adoption but also on tailoring support to farmer-specific needs to maximize its benefits.

Challenges faced by smallholder vegetable farmers in adopting CA

Adopting CA poses several challenges for smallholder vegetable farmers, as highlighted by the statistics detailing the specific constraints they face. Figure 3 below illustrates constraints faced by smallholder vegetable farmers in adopting CA. One of the most significant hurdles is the lack of financial support, which affects 28% of farmers attempting to transition to CA practices. This includes difficulties securing funds for purchasing necessary equipment, seeds, and inputs crucial for implementing CA techniques effectively. Without adequate financial resources or access to credit, farmers struggle to make the initial investments required, hindering adoption efforts. Another critical issue is farmers' insufficient knowledge about CA, affecting 18% of those surveyed. Many smallholders may not be familiar with the principles and benefits of CA, such as soil conservation practices, crop rotation, and integrated pest management. This lack of technical knowledge and training hampers their ability to successfully adopt and adapt CA practices.

Social and cultural factors also play a significant role, impacting 22% of farmers. Traditional farming practices deeply ingrained in local communities may resist changes brought by CA, complicating adoption efforts despite potential benefits. Moreover, the perceived risks and uncertainties associated with transitioning to CA, cited by 10% of farmers, further deter adoption. These uncertainties may include uncertain yield outcomes, market acceptance of CA-produced crops, and climate variability affecting farming conditions. Additionally, the high costs (14%) and inaccessibility (8%) of CA tools and equipment pose considerable barriers. Farmers may find it financially challenging to acquire specialized equipment and may face logistical difficulties in accessing these tools due to limited availability in local markets or inadequate infrastructure Figure 3.

Implications for extension services

The role of extension services in promoting the adoption of CA among smallholder vegetable farmers is critical, as they directly influence key factors such as knowledge dissemination,

TABLE 5 ESR estimating the effect of the adopted conservation agriculture by smallholder vegetable farmers.

Variable	Smallholder vegetable farmers	Adopters of CA Strategies (c1)	Non-adopters of any CA Strategies (c2)	Treatment effect: ATT/ATU (c3)
Farm income	Adopters (r2)	7 294 (175)	3 312 (15)	3 982 (176)***
	Non-adopters (r3)	6 205 (39)	4 642 (16)	1 893 (43)***
	Heterogeneity (r4)	1 089	670	1,759***

***p < 0.01, **p < 0.05, Standard errors in parentheses.

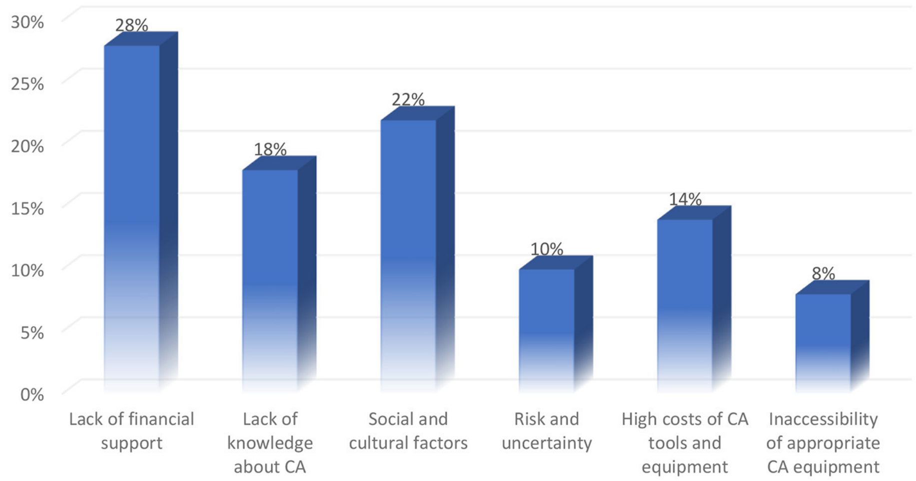

FIGURE 3
Constraints faced by smallholder vegetable farmers in adopting CA.

training, and resource access. The findings of this study demonstrate that adopters of CA exhibit significantly higher awareness levels compared to non-adopters, with 64% of adopters being knowledgeable about CA practices, compared to just 26% of non-adopters. This disparity underscores extension services' pivotal role in bridging the knowledge gap. By offering tailored training, demonstrations, and information on sustainable farming practices like zero/minimum tillage, crop residue management, and diversified crop rotation, extension services can enhance farmers' understanding and encourage the broader adoption of CA.

Training is another critical component that influences adoption rates. The study reveals that 54% of CA adopters received relevant training, compared to 32% of non-adopters. Providing structured, practical training that is closely aligned with local farm conditions and socio-economic contexts equips farmers with the necessary skills to implement CA practices successfully. This highlights the importance of extension services in building farmers' capacities by disseminating knowledge and fostering the confidence needed to adopt innovative agricultural methods. In addition to knowledge and training, access to resources and continuous support are essential for promoting CA adoption. The study finds that 68% of CA adopters had access to extension services, compared to 42% of non-adopters, further emphasizing the importance of extension agents in offering sustained guidance. Extension services can connect farmers to crucial resources such as farm organizations, inputs, and support networks that enhance collaboration, knowledge-sharing, and resource access. These services can also assist in overcoming financial barriers by advising farmers on cost-sharing mechanisms, credit access, and subsidies for adopting CA technologies. Economic support and the long-term financial benefits of CA practices can significantly motivate farmers, especially those with higher disposable incomes.

Furthermore, tailoring extension services to meet the specific needs of diverse demographic groups, such as younger farmers, larger families, and female farmers, can increase CA adoption. An inclusive approach that addresses gender-specific challenges ensures that all farmers have equal opportunities to benefit from CA practices. Extension services can also help farmers overcome logistical challenges, such as improving market access and promoting local input suppliers significantly farther from markets.

The study's findings highlight the critical role that extension services play in facilitating the adoption of CA. With 68% of CA adopters having access to extension services vs. just 42% of non-adopters, it is clear that extension services are a significant factor in enabling the transition to sustainable farming practices. Furthermore, the study reveals that 66% of CA adopters received training on new agricultural techniques, compared to only 34% of non-adopters. These findings emphasize that through practical training and information dissemination on CA practices like zero/minimum tillage and crop residue management, extension services can bridge the knowledge gap and help farmers overcome barriers to adoption. The study also identifies socio-economic factors (such as education, family size, farm size, and income) as significant contributors to CA adoption. Adopters tend to be more educated and have larger families that can provide the labor required for CA practices. These factors suggest that targeted extension services tailored to the socio-economic profiles of farmers can significantly increase CA adoption, thereby promoting sustainable agricultural practices on a wider scale.

Additionally, addressing logistical and economic challenges is crucial in facilitating the adoption of CA. Proximity to markets, for instance, plays a significant role, with adopters living an average of 19.26 kilometers from markets, compared to 21.42 kilometers for non-adopters. Extension services can mitigate such challenges by improving access to resources such as seeds, fertilizers, and equipment, which are necessary to implement CA successfully. Membership in farm organizations also plays a crucial role, as these organizations often serve as platforms for information sharing, problem-solving, and mutual support. These findings align with previous research that emphasizes the importance of extension services in enhancing the capacity of smallholder farmers to adopt sustainable farming practices. Extension services can help smallholder farmers overcome financial constraints, knowledge gaps, and resistance to change by providing technical expertise and logistical support. Therefore, the study advocates for increased investment in extension services and support structures that create an environment conducive to the widespread adoption of Conservation Agriculture among smallholder vegetable farmers.

Conclusion and policy recommendations,

This study assessed the impact of Conservation Agriculture (CA) adoption on farm returns among smallholder vegetable farmers in the Eastern Cape Province. Using a mixed-methods approach, data were collected from 200 smallholder farmers through structured questionnaires, interviews, and farm-level economic analysis. Logistic regression and Endogeneity Switching Regression (ESR) were applied to examine both factors influencing CA adoption and its effect on farm profitability.

The findings reveal vital insights into smallholder dynamics and the effectiveness of CA practices. A key finding is the knowledge gap between adopters and non-adopters of CA practices, with awareness playing a central role in successful implementation. Fifty-six percentage of CA adopters understood zero/minimum tillage, compared to only 18% of non-adopters, highlighting the critical importance of awareness in influencing behavior.

Training is the key factor in influencing adoption. Fifty-four percentage of CA adopters received CA training, while only 32% of non-adopters had similar exposure, highlighting the value of technical support in agricultural transformation. These findings suggest that enhancing training and awareness, particularly on practical aspects such as zero/minimum tillage, crop residue management, and crop rotation, could significantly encourage CA adoption. By incorporating education and training into agricultural policies and initiatives, farmers' knowledge of CA can be improved, fostering the adoption of sustainable practices that contribute to environmental resilience and long-term farm productivity.

The logistic regression analysis identified additional factors influencing CA adoption. Age has a negative effect on CA adoption, suggesting that younger farmers are more likely to adopt innovative practices. Education, access to credit, proximity to markets, and access to extension services positively influence adoption, while larger farm sizes tend to discourage transition to CA among smallholders.

These findings offer valuable insights for policymakers and agricultural stakeholders to implement targeted interventions that promote CA adoption and improve agricultural sustainability in smallholder farming communities. Strengthen the capacity of extension agents to deliver tailored CA training. Outreach efforts could play a key role in disseminating CA techniques and technical support to farmers, especially those with limited resources.

Moreover, policy efforts to enhance financial inclusion for smallholder farmers. Establish microcredit facilities, flexible input financing schemes, and subsidies that make it easier for smallholder farmers to invest in CA practices. This could assist in improving access to agricultural inputs while encouraging the adoption of CA, particularly in rural areas. Addressing barriers to credit access through partnerships with financial institutions, cooperatives and government is critical to ensure sustainable funding mechanism.

Data availability statement

The data used in this paper will be available from the corresponding author upon reasonable request.

Ethics statement

Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

Author contributions

SQ: Visualization, Investigation, Validation, Data curation, Writing – review & editing, Formal analysis, Conceptualization, Writing – original draft, Software, Methodology. LM: Writing – original draft, Methodology, Investigation, Software, Supervision, Conceptualization, Data curation, Resources, Writing – review & editing, Funding acquisition, Validation, Formal analysis, Project administration. YN: Methodology, Formal analysis, Validation, Visualization, Data curation, Software, Writing – review & editing, Writing – original draft, Investigation. MM: Software, Investigation, Writing – review & editing, Writing – original draft, Data curation, Formal analysis, Validation, Methodology. LG: Writing – original draft, Investigation, Writing – review & editing, Formal analysis, Validation, Data curation.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Acknowledgments

The authors would like to thank smallholder farmers for availing themselves to be part of this research, and enumerator's for assisting in collecting data and facilitation.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Abdulai, A., and Huffman, W. (2014). The adoption and impact of soil and water conservation technology: an endogenous switching regression application. *Land Econ.* 90, 26–43. doi: 10.3368/le.90.1.26

Abraham, M., and Pingali, P. (2020). "Transforming smallholder agriculture to achieve the SDGs," in *The Role of Smallholder Farms in Food and Nutrition Security* (Cham: Springer International Publishing), 173–209. doi: 10.1007/978-3-030-42148-9_9

Adenkunle, A. A., and Fatumbi, A. O. (2012). Approaches for setting multi-stakeholder platforms for agricultural research and development. *World Appl. Sci. J.* 16, 981–988.

Aerni, P., Nichterlein, K., Rudgard, S. and Sonnino, A. (2015). Making agricultural innovation systems (AIS) work for development in tropical countries. *Sustainability* 7, 831–850. doi: 10.3390/su7010831

Amede, T., Konde, A. A., Muhinda, J. J., and Bigirwa, G. (2023). Sustainable farming in practice: building resilient and profitable smallholder agricultural systems in Sub-Saharan Africa. *Sustainability* 15:5731. doi: 10.3390/su15075731

Andersson, J. A., and D'Souza, S. (2014). From adoption claims to understanding farmers and contexts: a literature review of Conservation Agriculture (CA) adoption among smallholder farmers in southern Africa. *Agric. Ecosyst. Environ.* 187, 116–132. doi: 10.1016/j.agee.2013.08.008

Apeh, C. C., Agbugba, I. K., and Mdoda, L. (2023). Assessing the determinants of adopting urban tree planting as climate change mitigation strategy in Enugu Metropolis, Nigeria. *Sustainability* 15:12224. doi: 10.3390/su151612224

Ayyogari, K., Sidhya, P., and Pandit, M. K. (2014). Impact of climate change on vegetable cultivation-a review. *Int. J. Agric. Environ. Biotechnol.* 7, 145–155. doi: 10.5958/j.2230-732X.7.1.020

Aziz, S., Wuensch, K. L., and Duffrin, C. (2015). Workaholism, exercise, and stress-related illness. *J. Workplace Behav. Health* 30, 393–406. doi: 10.1080/15555240.2015.1074053

Bese, D., Zwane, E., and Cheteni, P. (2020). The use of sustainable agricultural methods amongst smallholder farmers in the Eastern Cape province, South Africa. *Afr. J. Sci. Technol. Innov. Dev.* 13, 261–271. doi: 10.1080/20421338.2020.1724388

Bjornlund, V., Bjornlund, H., and Van Rooyen, A. F. (2020). Why agricultural production in sub-Saharan Africa remains low compared to the rest of the world–a historical perspective. *Int. J. Water Resour. Dev.* 36, S20–S53. doi: 10.1080/07900627.2020.1739512

Cárceles Rodríguez, B., Durán-Zuazo, V. H., Soriano Rodríguez, M., García-Tejero, I. F., Gálvez Ruiz, B., and Cuadros Tavira, S. (2022). Conservation agriculture as a sustainable system for soil health: a review. *Soil Syst.* 6:87. doi: 10.3390/soilsystems6040087

Chalise, D., Kumar, L., and Kristiansen, P. (2019). Land degradation by soil erosion in Nepal: a review. *Soil Sys.* 3:12. doi: 10.3390/soilsystems3010012

Chinseu, E., Dougill, A., and Stringer, L. (2018). Why do smallholder farmers dis-adopt conservation agriculture? Insights from Malawi. *Land Degrad Dev.* 30, 1–11. doi: 10.1002/ldr.3190

Corbeels, M., De Graaff, J., Ndah, T. H., Penot, E., Baudron, F., Naudin, K., et al. (2014). Understanding the impact and adoption of conservation agriculture in Africa: a multi-scale analysis. *Agric. Ecosyst. Environ.* 187, 155–170. doi: 10.1016/j.agee.2013.10.011

Davis, K. E., and Heemskerk, W. (2009). *Module 3: Investment in extension and advisory services as part of agricultural innovation system.* Avaialable online at: http://siteresources.worldbank.org/INTARD/Resources/335807.1330620492317/9780821386842_ch3.pdf

Dias, J. S. (2012). Nutritional quality and health benefits of vegetables: a review. *Food Nutr. Sci.* 3, 1354–1374. doi: 10.4236/fns.2012.310179

Ebert, A. W. (2017). "Vegetable production, diseases, and climate change," in *World Agricultural Resources and Food Security: International Food Security* (Emerald Publishing Limited), 103–124. doi: 10.1108/S1574-871520170000017008

Erenstein, O., Sayre, K., Wall, P., Dixon, J., and Hellin, J. (2008). "Adapting no-tillage agriculture to the conditions of smallholder maize and wheat farmers in the tropics and sub-tropics," in *No-till Farming Systems*, eds. T. Goddard, M. Zoebisch, Y. Gan, W. Ellis, A. Watson, and S. Sombatpanit (World Association of Soil and Water Conservation (WASWC)), 253–278.

Fan, S., and Rue, C. (2020). "The role of smallholder farms in a changing world," in *The Role of Smallholder Farms in Food and Nutrition Security*, eds. S. Gomez y Paloma, L. Riesgo, K. and Louhichi (Cham: Springer), 13–28. doi: 10.1007/978-3-030-42148-9_2

Gebeyehu, T. A. (2023). Adoption and impacts of conservation agriculture on smallholder farmers' livelihoods in the case of Arba Minch Zuria district of Southern Ethiopia. *Cogent Soc. Sci.* 9:2235782. doi: 10.1080/23311886.2023.2235782

Geffersa, A. G., Agbola, F. W., and Mahmood, A. (2021). Improved maize adoption and impacts on farm household welfare: Evidence from rural Ethiopia. *Aust. J. Agric. Resour. Econ.* 66, 860–886. doi: 10.1111/1467-8489.12489

Gina, G. A., Mariya, A., Natalia, C., Nispuana, S., Wijaya, M. F., and Phalepi, M. Y. (2023). The role of the agricultural sector on economic growth in Indonesia. *Indones. J. Multidiscip. Sci.* 2, 167–179. doi: 10.59066/ijoms.v2i1.325

Gomez y Paloma, S., Riesgo, L., and Louhichi, K. (2020). *The Role of Smallholder Farms in Food and Nutrition Security* (Springer Nature: New York), 251. doi: 10.1007/978-3-030-42148-9

Gutiérrez-Cano, L. F., Zartha-Sossa, J. W., Orozco-Mendoza, G. L., Suárez-Guzmán, L. M., Agudelo-Tapasco, D. A., and Quintero-Saavedra, J. I. (2023). Agricultural innovation system: analysis from the subsystems of R&D, training, extension, and sustainability. *Front. Sustain. Food Syst.* 7:1176366. doi: 10.3389/fsufs.2023.1176366

Hall, M. A., Camacho, F., Lawlor, J. S., DePuy, V., Sugarman, J., and Weinfurt, K. (2006). Measuring trust in medical researchers. *Med. Care* 44, 1048–1053. doi: 10.1097/01.mlr.0000228023.37087.cb

Heckman, J. J. (1979). Sample selection bias as a specification error. *Econometrica* 47, 153–161. doi: 10.2307/1912352

Hlatshwayo, S. I., Slotow, R., and Ngidi, M. S. C. (2023). The role of smallholder farming on rural household dietary diversity. *Agriculture* 13:595. doi: 10.3390/agriculture13030595

Hlophe-Ginindza, S. N., and Mpandeli, N. S. (2021). "Ensuring food security in Africa," in *Food Security in Africa, The Role of Small-Scale Farmers in Ensuring Food Security in Africa* (Intechopen), 63. doi: 10.5772/intechopen.91694

Imathiu, S. (2021). Neglected and underutilized cultivated crops with respect to indigenous African leafy vegetables for food and nutrition security. *J. Food Secur.* 9, 115–125. doi: 10.12691/jfs-9-3-4

Indoria, A. K., Rao, C. S., Sharma, K. L., and Reddy, K. S. (2017). Conservation agriculture–a panacea to improve soil physical health. *Curr. Sci.* 112, 52–61. doi: 10.18520/cs/v112/i01/52-61

James, A., Lawrence, B., and O'Connor, M. (2022). Healthy eating as a new way of life: a qualitative study of successful long-term diet change. *Inquiry* 59:469580221090397. doi: 10.1177/00469580221090397

James, A., and Zikankuba, V. (2017). Postharvest management of fruits and vegetable: a potential for reducing poverty, hidden hunger and malnutrition in sub-Sahara Africa. *Cogent Food Agric.* 3:1312052. doi: 10.1080/23311932.2017.1312052

Jayaraman, S., Dang, Y. P., Naorem, A., Page, K. L., and Dalal, R. C. (2021). Conservation agriculture as a system to enhance ecosystem services. *Agriculture* 11:718. doi: 10.3390/agriculture11080718

Kangogo, D., Dentoni, D., and Bijman, J. (2021). Adoption of climate-smart agriculture among smallholder farmers: does farmer entrepreneurship matter? *Land Use Policy* 109:105666. doi: 10.1016/j.landusepol.2021.105666

Kassem, H. S., Alotaibi, B. A., Muddassir, M., and Herab, A. (2021). Factors influencing farmers' satisfaction with the quality of agricultural extension services. *Eval. Program Plann.* 85:101912. doi: 10.1016/j.evalprogplan.2021.101912

Khonje, M. G., Manda, J., Mkandawire, P. S. K., Tufa, A., and Alene, A. (2018). Adoption and welfare impacts of multiple agricultural technologies: evidence from eastern Zambia. *Agric. Econ.* 49, 599–609. doi: 10.1111/agec.12445

Loki, O., and Mdoda, L. (2023). Assessing the contribution and impact of access to extension services toward sustainable livelihoods and self-reliance in Eastern Cape Province, South Africa. *Afr. J. Food Agric. Nutr. Dev.* 23, 23000–23025. doi: 10.18697/ajfand.119.22990

Lokshin, M., and Sajaia, Z. (2004). Maximum likelihood estimation of endogenous switching regression models. *Stata J.* 4, 282–289. doi: 10.1177/1536867X0400400306

Lottering, S. J., Mafongoya, P., and Lottering, R. T. (2021). Assessing the social vulnerability of small-scale farmer's to drought in uMsinga, KwaZulu-Natal. *Int. J. Disaster Risk Reduct*. 65:102568. doi: 10.1016/j.ijdrr.2021.102568

Maake, M. M. S., and Antwi, M. A. (2022). Farmer's perceptions of effectiveness of public agricultural extension services in South Africa: an exploratory analysis of associated factors. *Agric. Food Secur.* 11:34. doi: 10.1186/s40066-022-00372-7

Maddala, G. S. (1983). *Limited Dependent and Qualitative Variables in Econometrics*. Cambridge University Press, UK: Cambridge, UK. doi: 10.1017/CBO9780511810176

Mango, N., Siziba, S., and Makate, C. (2017). The impact of adoption of conservation agriculture on smallholder farmers' food security in semi-arid zones of southern Africa. *Agric. Food Secur.* 6, 2–8. doi: 10.1186/s40066-017-0109-5

Markow, J., Fieldsend, A. F., von Münchhausen, S., and Häring, A. M. (2023). Building agricultural innovation capacity from the bottom up: Using spillover effects from projects to strengthen agricultural innovation systems. *Agric. Syst.* 209:103670. doi: 10.1016/j.agsy.2023.103670

Mathinya, V. N., Franke, A. C., Van De Ven, G. W. J., and Giller, K. E. (2022). Productivity and constraints of small-scale crop farming in the summer rainfall region of South Africa. *Outlook Agric.* 51, 139–154. doi: 10.1177/00307270221091839

Mburu, B. K., Kung'u, J. B., and Muriuki, J. N. (2015). Climate change adaptation strategies by small-scale farmers in Yatta District, Kenya. *Afr. J. Environ. Sci. Technol.* 9, 712–722. doi: 10.5897/AJEST2015.1926

Mdoda, L., Naidoo, D., Ncoyini-Manciya, Z., Nontu, Y., Govender, L., Tamako, N., et al. (2024). Adaptation measures to drought risk perceived by smallholder crop farmers in the Eastern Cape Province, South Africa: implications for food and nutrition security. *Sustainability* 16:11154. doi: 10.3390/su162411154

Mdoda, L., Obi, A., Christian, M., and Jiba, P. (2022). Profitability of cabbage production by smallholder farmers in the Eastern Cape Province, South Africa. *S. Afr. J. Agric. Ext.* 50, 1–25. doi: 10.17159/2413-3221/2022/v50n2a11214

Mdoda, L., Obi, A., Tamako, N., Naidoo, D., and Baloyi, R. (2023). Resource use efficiency of potato production among smallholder irrigated farmers in the Eastern Cape Province of South Africa. *Sustainability* 15:14457. doi: 10.3390/su151914457

Melby, C. L., Orozco, F., Averett, J., Muñoz, F., Romero, M. J., and Barahona, A. (2020). Agricultural food production diversity and dietary diversity among female small holder farmers in a region of the ecuadorian andes experiencing nutrition transition. *Nutrients* 12:2454. doi: 10.3390/nu12082454

Miller, V., Yusuf, S., Chow, C. K., Dehghan, M., Corsi, D. J., Lock, K., et al. (2016). Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: findings from the Prospective Urban Rural Epidemiology (PURE) study. *Lancet Global Health* 4, e695–e703. doi: 10.1016/S2214-109X(16)30186-3

Modirwa, M. S., and Oladele, O. I. (2017). Linkage activities amongst researchers, extension agents, farmers, input dealers, and marketers towards agricultural innovation systems in the North West Province, South Africa. *S. Afr. J. Agric. Ext.* 45, 20–25. doi: 10.17159/2413-3221/2017/v45n1a403

Morris, M. A., Hulme, C., Clarke, G. P., Edwards, K. L., and Cade, J. E. (2014). What is the cost of a healthy diet? Using diet data from the UK women's cohort study. *J. Epidemiol. Community Health* 68, 1043–1049. doi: 10.1136/jech-2014-204039

Mugejo, K., and Ncube, B. (2022). Determinants of water security in smallholder farming systems in South Africa: a review. *Fund. Appl. Agric.* 7, 235–249. doi: 10.5455/faa.81266

Mujuru, N. M., and Obi, A. (2020). Effects of cultivated area on smallholder farm profits and food security in rural communities of the Eastern Cape Province of South Africa. *Sustainability* 12:3272. doi: 10.3390/su12083272

Mutengwa, C. S., Mnkeni, P., and Kondwakwenda, A. (2023). Climate-smart agriculture and food security in southern Africa: a review of the vulnerability of smallholder agriculture and food security to climate change. *Sustainability* 15:2882. doi: 10.3390/su15042882

Muzangwa, L., Mnkeni, P. N. S., and Chiduza, C. (2017). Assessment of conservation agriculture practices by smallholder farmers in the Eastern Cape Province of South Africa. *Agronomy* 7:46. doi: 10.3390/agronomy7030046

Namyenya, A., Zeller, M., Rwamigisa, P. B., and Birner, R. (2022). Analysing the performance of agricultural extension managers: a case study from Uganda. *J. Agric. Educ. Ext.* 28, 363–389. doi: 10.1080/1389224X.2021.1932539

Ndah, H. T. (2014). *Adoption and Adaptation of Innovations - Assessing the Diffusion of Selected Agricultural Innovations in Africa* (Published PhD Thesis). Humboldt-University of Berlin, Germany.

Ngoma, H., Angelsen, A., Jayne, T. S., and Chapoto, A. (2021). Understanding adoption and impacts of conservation agriculture in eastern and southern Africa: a review. *Front. Agron*. 3, 1–12. doi: 10.3389/fagro.2021.671690

Nkhoma, S., Kalinda, T. and Kuntashula, E. (2017). Adoption and impact of conservation agriculture on smallholder farmers' crop productivity and income in Luapula Province, Zambia. *J. Agric. Sci.* 9. doi: 10.5539/jas.v9n9p168

Nkonki-Mandleni, B., Manenzhe, N. G., and Omotayo, A. O. (2022). Factors influencing the adoption of conservation agriculture by smallholder farmers in KwaZulu-Natal, South Africa. *Open Agric.* 7, 596–604. doi: 10.1515/opag-2022-0098

Nontu, Y., Mdoda, L., Dumisa, B. M., Mujuru, N. M., Ndwandwe, N., Gidi, L. S., et al. (2024). Empowering rural food security in the Eastern Cape Province: exploring the role and determinants of family food gardens. *Sustainability* 16:6780. doi: 10.3390/su16166780

Nontu, Y., and Taruvinga, A. (2022). Welfare implications of home gardens among rural households: evidence from ingquza hill local municipality, South Africa. *S. Afr. J. Agric. Ext.*50, 166–181. doi: 10.17159/2413-3221/2023/v51n1a11554

Norton, G. W., and Alwang, J. (2020). Changes in agricultural extension and implications for farmer adoption of new practices. *Appl. Econ. Perspect. Policy* 42, 8–20. doi: 10.1002/aepp.13008

Ntshangase, N. L., Muroyiwa, B., and Sibanda, M. (2018). Farmers' perceptions and factors influencing the adoption of no-till conservation agriculture by small-scale farmers in Zashuke, KwaZulu-Natal Province. *Sustainability* 10:555. doi: 10.3390/su10020555

Oduniyi, O. S., Chagwiza, C., and Wade, T. (2022). Welfare impacts of conservation agriculture adoption on smallholder maize farmers in South Africa. *Renew. Agric. Food Syst*. 37, 672–682. doi: 10.1017/S1742170522000308

Okello, D. (2024). Evaluating the impact of agribusiness support services on productivity and income among smallholder farmers in rural Kenya: insights from a multinomial endogenous switching regression analysis. *Discov. Agric.* 3, 1–19. doi: 10.1007/s44279-025-00195-7

Opondo, F. A., Owuor, G., Mshenga, P., Louw, A., and Jordan, D. (2020). Estimation of the effect of cassava commercialization on different household income measurements in Kilifi County, Kenya. *J. Sustain. Dev.* 13, 44–58. doi: 10.5539/jsd.v13n1p44

Oscar, C., Pelser, A., van Tol, J., du Preez, C., and Ceronio, G. (2019). Factors influencing the adoption of conservation agriculture practices among smallholder farmers in Mozambique. *Int. J. Agric. Ext.* 7:291. doi: 10.33687/ijae.007.03.3049

Pandey, P. C., and Pandey, M. (2023). Highlighting the role of agriculture and geospatial technology in food security and sustainable development goals. *Sustain. Dev.* 31, 3175–3195. doi: 10.1002/sd.2600

Pawlak, K., and Kołodziejczak, M. (2020). The role of agriculture in ensuring food security in developing countries: considerations in the context of the problem of sustainable food production. *Sustainability* 12:5488. doi: 10.3390/su12135488

Phinzi, K., and Ngetar, N. S. (2019). Land use/land cover dynamics and soil erosion in the umzintlava catchment (T32E), Eastern Cape, South Africa. *Trans. R. Soc. S. Afr.* 74, 223–237. doi: 10.1080/0035919X.2019.1634652

Ramya, V., and Patel, P. (2019). Health benefits of vegetables. *Int. J. Chem. Stud.* 7, 82–87. Available online at: https://www.chemijournal.com/archives/2019/vol7issue2/PartB/7-1-215-320.pdf

Reyes, S. R. C., Miyazaki, A., Yiu, E., and Saito, O. (2020). Enhancing sustainability in traditional agriculture: indicators for monitoring the conservation of globally important agricultural heritage systems (GIAHS) in Japan. *Sustainability* 12:5656. doi: 10.3390/su12145656

Rockström, J., Barron, J., and Fox, P. (2002). Rainwater management for increased productivity among small-holder farmers in drought prone environments. *Phys. Chem. Earth* 27, 949–959. doi: 10.1016/S1474-7065(02)00098-0

Rodenburg, J., Büchi, L., and Haggar, J. (2021). Adoption by adaptation: moving from conservation agriculture to conservation practices. *Int. J. Agric. Sustain.* 19, 437–455. doi: 10.1080/14735903.2020.1785734

Sankhulani, L. (2021). *Impact Evaluation of Conservation Agriculture on Smallholder Farmers' Livelihood in Zambia and Tanzania*. Published MSc Dissertation, University of Pretoria, Pretoria, RSA.

Sekaran, U., Lai, L., Ussiri, D. A., Kumar, S., and Clay, S. (2021). Role of integrated crop-livestock systems in improving agriculture production and addressing food security–a review. *J. Agric. Food Res*. 5:100190. doi: 10.1016/j.jafr.2021.100190

Selvakumar, S., and Sivakumar, K. (2021). Conservation agriculture: a way for soil water conservation. *Agric. Rev.* 42, 474–477. doi: 10.18805/ag.R-2045

Somasundaram, J., Sinha, N. K., Dalal, R. C., Lal, R., Mohanty, M., Naorem, A. K., et al. (2020). No-till farming and conservation agriculture in South Asia–issues, challenges, prospects and benefits. *CRC. Crit. Rev. Plant Sci.* 39, 236–279. doi: 10.1080/07352689.2020.1782069

Spielman, D. J. (2005). "Innovation systems perspectives on developing-country agriculture: A critical review," in *ISNAR Discussion Paper 2* (Washington, DC: International service for National Agricultural Research (ISNAR) Division).

Spielman, D. J., and Birner, R. (2008). "How innovative is your agriculture? using innovation indicators and benchmarks to strengthen national agricultural innovation systems," in *Agriculture and Rural Development Discussion Paper 41* (The World Bank).

Tanimonure, V. A., and Naziri, D. (2021). Impact of climate adaptation strategies on the net farm revenue of underutilised indigenous vegetables' (UIVs) production in Southwest Nigeria. *Resour. Environ. Sustain*. 5:100029. doi: 10.1016/j.resenv.2021.100029

Teng, J., Hou, R., Dungait, J. A., Zhou, G., Kuzyakov, Y., Zhang, J., et al. (2024). Conservation agriculture improves soil health and sustains crop yields after long-term warming. *Nat. Commun.* 15:8785. doi: 10.1038/s41467-024-53169-6

Toiba, H., Nugroho, T. N., Retnoningsih, D., and Rahman, M. S. (2020). Food system transformation and its impact on smallholder farmers' income and food security in Indonesia. *Cogent Econ. Finance* 8:1854412, doi: 10.1080/23322039.2020.1854412

Toillier, A., Faure, G., Audouin, S., Mathé, S., Triomphe, B., and Temple, L. (2018). "Literature review of methodologies for the diagnosis of Agricultural Innovation Systems (AIS)," in *CIRAD Working Paper No. (4)*. Available online at: https://agritrop.cirad.fr/596199/1/Literature%20review%20AIS%20Final%20version.pdf

Uddin, M. T., and Dhar, A. R. (2016). Conservation agriculture practice and its impact on farmer's livelihood status in Bangladesh. *SAARC J. Agri.* 14, 119–140. doi: 10.3329/sja.v14i1.29582

USAID (2016). *Africa Research in Sustainable Intensification for the Next Generation (Africa Rising) Mid-Term Evaluation*.

Uusiku, N. P., Oelofse, A., Duodu, K. G., Bester, M. J., and Faber, M. (2010). Nutritional value of leafy vegetables of sub-Saharan Africa and their potential contribution to human health: a review. *J. Food Compos. Anal.* 23, 499–509. doi: 10.1016/j.jfca.2010.05.002

Viana, C. M., Freire, D., Abrantes, P., Rocha, J., and Pereira, P. (2022). Agricultural land systems importance for supporting food security and sustainable development goals: a systematic review. *Sci. Total Environ.* 806:150718. doi: 10.1016/j.scitotenv.2021.150718

Wangu, J. (2021). The need for a food systems approach in smallholder food and nutrition security initiatives: lessons from inclusive agribusiness in smallholder communities. *Foods* 10:1785. doi: 10.3390/foods10081785

Webb, N. L. (2000). Food-gardens and nutrition: three Southern African case studies. *J. Consum. Sci.* 28:52792. doi: 10.4314/jfecs.v28i1.52792

World Bank (2006). *Information and Communications for Development: Global Trends and Policies.* Washington, DC. Available online at: https://documents1.worldbank.org/curated/en/876661468154168686/pdf/359240PAPER0In101OFFICIAL0USE0ONLY1.pdf

World Bank (2012). *World Development Report 2012: Gender Equality and Development*. Available online at: http://hdl.handle.net/10986/4391