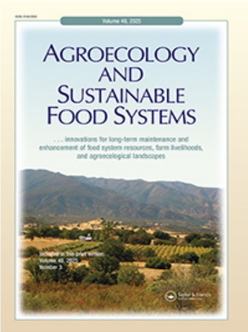

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Farmers' decision processes about biocontrol innovation adoption: dynamics surrounding push-pull technology in Western Kenya

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ABSTRACT

Smallholder farmers in sub-Saharan Africa (SSA) face increasing challenges from pests and climate change, among other issues. In response to these challenges, international agricultural research for development (R4D) investment is often focused on developing and scaling up techniques and technologies that bolster resilience. However, such approaches are often technocentric and follow linear assumptions of innovation diffusion and adoption, which overlook the complex realities that influence smallholder farmers' dynamic decisions and engagement with novel techniques. This study used qualitative ethnographic methods to explore the experiences, knowledge construction, motivations, and decision-making of farmers in Western Kenya regarding the extensively researched push-pull technology (PPT). Findings reveal that motives for practicing PPT evolve as farmers respond to emerging realities. Farmers' practices were motivated by factors such as food culture, resource availability, market demand, social networks, and risk management. Farmers often modify and adapt PPT components rather than simply adopting the practice as taught or shown. Contextual factors such as health, livestock ownership, land tenure, access to information and inputs, cost/benefit trade-offs, and social dynamics interact in complex ways. Ultimately, innovation unfolds as a dynamic process requiring inclusive participation, flexibility for local adaptation, and long-term collaboration with farmers as partners in finding solutions.

KEYWORDS
Agricultural innovation; biocontrol; push-pull technology; smallholder farmers decision making; sub-Saharan Africa

SUSTAINABLE DEVELOPMENT GOALS
SDG 2: Zero hunger

Introduction

In the context of sub-Saharan Africa (SSA), biocontrol technology has emerged as a promising approach to enhance crop production through the use of natural methods, including introduction, inoculation, and inundation of natural enemies such as parasitoids, intercropping systems, and

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biopesticides (Hulot and Hiller 2021; Ratto et al. 2022). Globally, pest outbreaks and infestations reportedly cause crop losses valued at about $220 billion annually (FAO 2021), contributing to economic instability and food insecurity. Smallholder farmers in SSA are not exempted; they have been challenged by pests such as stemborer and fall armyworm (FAW), whereas cereal grain losses linked to parasitic Striga weed alone have been estimated at 4.1 million metric tonnes (Benjamin et al. 2024) Biocontrol technologies have been developed as a sustainable alternative to conventional pest management strategies (e.g., chemical pesticides and herbicides), which have harmful impacts on non-target organisms, human health, and the environment (Barratt et al. 2018; Ratto et al. 2022). Although some biocontrol technologies have been successful in controlled field conditions, their widespread adoption at scale remains limited (Ratto et al. 2022). The challenges biocontrol technologies face go beyond practical implementation (e.g., inadequate access to resources). Innovation and farmer decision-making processes, which are often not well understood, may explain the difficulties in scaling these types of agricultural practices (Hermans et al. 2020; Whitfield et al. 2015). However, the conventional models of innovation and theory of change (ToC) used by international agricultural research agencies and developmental organizations often oversimplify this complexity by focusing primarily on adoption rates (Douthwaite and Hoffecker 2017; Williams et al. 2022).

These conventional approaches to research and innovation emphasize the transfer of technology, known as Technology Supply Push (TSP), position scientists as innovators while casting farmers as passive recipients who must follow prescribed guidelines through agricultural extension workers or “lead” farmers (Balew et al. 2023; Hounkonnou et al. 2012). This model exhibits a supply-driven and top-down style where research objectives are pre-defined based on projects and agendas (Douthwaite and Hoffecker 2017). Empirical studies that follow the conventional approach tend to reduce technological change to binary adoption metrics, overlooking the complex reality of farming decisions (Douthwaite and Hoffecker 2017; Douthwaite, Keatinge, and Park 2001; Klerkx, van Mierlo, and Leeuwis 2012).

Despite the growing recognition of the shortcomings of this seemingly linear and reductionist model, the practice of using the adoption and technical performance of technology as a yardstick for success remains prevalent in contemporary agricultural development programs (Crivits et al. 2014; Glover et al. 2019). Several authors have underscored the inadequacy of the conventional concept of adoption metrics for evaluating technological change and measuring success in research investments because it does not capture the complexity, flexibility, and dynamics embedded within agricultural innovation processes and decision-making (Glover et al. 2019; Glover, Sumberg, and Andersson 2016; Hermans et al. 2020). Other scholars have emphasized that adoption within agriculture should be considered a dynamic process that transcends the confines of a binary choice (Andersson and D'Souza 2014; Pannell and Claassen 2020). Wilkinson (2011) further describes adoption as a non-rigid process that frequently manifests as incomplete or partial across various geographical settings and even within individual farms.

Push-pull technology (PPT) in SSA provides an excellent case study for understanding these innovation dynamics. PPT biocontrol farming system combines the pest-repelling forage legume (*Desmodium* spp.) with attractant fodder, such as Napier grass (*Pennisetum purpureum*) or *Brachiaria* spp., to manage pests such as Stemborers *(Chilo partellus* or *Busseola fusca*) and Fall armyworm (*Spodoptera frugiperda*) while controlling parasitic Striga weeds (*Striga hermonthica*) through the allelochemical mechanism of root exudates secreted by *Desmodium* spp (Hooper et al. 2010; ICIPE 2022; Khan et al. 2014).

PPT has been used on a limited scale, mostly in maize and sorghum-based farming systems across SSA (Buleti et al. 2023; Kopper and Ruelle 2022) Previous PPT studies in SSA that focused on adoption relied on quantitative research approaches, such as cross-sectional and pre-set questionnaires, and examined the role of socioeconomic variables as determinants of PPT adoption (Adesina et al. 2023; Kopper and Ruelle 2022). Socioeconomic variables, such as age (Amudavi et al. 2009), gender (Murage et al. 2015), education level (Chepchirchir et al. 2017), and farm characteristics, such as plot distance to market or administrative center (Mwangi, Obare, and Murage 2014), influenced PPT adoption. Attendance at PPT field days (Kassie et al. 2018) and group memberships (Muriithi et al. 2018) were reported to affect the likelihood of PPT adoption among farmers. However, these studies often overlook the complexities of innovation and decision-making processes at the farm level, which downplay the importance of social knowledge construction and farmers' changing contexts and changing needs (Adesina et al. 2023; Hermans et al. 2020; Whitfield et al. 2015).

In contrast, our study employs qualitative ethnographic methods to explore the social-economic, cultural, environmental and individual subjective experiences underlying motivations and innovation decisions within smallholder farming households. Qualitative ethnographic methods have been selected for their ability to better capture lived experiences, dynamics, and contexts (Malterud 2001) which extends our understanding of the "how" and "why" behind survey findings and provides valuable insights into innovation-decision processes. We use PPT to comprehend innovation processes in SSA and Western Kenya as a lens into on-farm contexts, which are typically associated with diverse social and ecological conditions, complex decision-making, and resource constraints. The Western region of Kenya is renowned for food production, contributing substantially to the nation's agricultural output (Diiro et al. 2018; Muriithi et al. 2018). Approximately 77% of the population in this region engages in crop-livestock farming practices (D'Annolfo et al. 2021; Kassie et al. 2018). Several agricultural research interventions and practices have been introduced and diffused among farmers in the region. Examples of such practices and technologies include imazapyr-coated herbicide-resistant maize (IR-maize) developed by the International Maize and Wheat Improvement Center (CIMMYT) (De Groote et al. 2008). Another example is the Kichawi Kill bio-herbicide developed by the Toothpick Company using the fungus *Fusarium oxysporum* to combat Striga weed (Baker, Sands, and Nzioki 2023; Nzioki et al. 2016). This research aims to understand the experiences, contexts, practices, motivations, knowledge sources, power dynamics, social networks, and interactions that previous PPT survey research/data did not fully capture. We examine how smallholder farmers in Western Kenya adopt, adapt, and experience PPT, the decision-making processes involved, and the role of social dynamics with the goal of improving agricultural innovation practices to better support smallholder farmers in SSA. Therefore, we seek to address two pivotal questions in this study:

- How is innovation adopted/adapted or experienced, and in what ways do farmers engage with and make decisions regarding PPT practices in different and changing contexts?
- What implications do social interactions, relationships, and group dynamics, as well as the insights generated from this study, have for agricultural research and development in SSA?

The insights generated in this study will serve as guiding principles for future agricultural research aimed at advancing sustainable farming practices, food security, and improving rural livelihoods in Africa.

Materials and methods

Description of the study area

A qualitative and ethnographic study was conducted in two counties in Western Kenya where prior survey research on PPT had been conducted, namely Kisumu in Nyanza Province and Vihiga in Western Province (Figure 1). These sites were selected because of their long-standing history of ICIPE's PPT research and extension activities, which include trials, demonstration sites, farmer group training, and farmer field schools (Gatsby Charitable Foundation 2014; Hassanali et al. 2008). Kisumu spans an area of 2085.9 km^2, situated between longitudes 33° 20“–35° 20” East and latitudes 0° 20“–0° 50” South (CGoK 2018; MoALF 2017). Vihiga County covers an area of 536.8 km^2, located between longitudes 34°30’–35°0’ East and latitudes 0°–0° 15’ North, with hills and valleys forming the dominant landscape (CGoV 2018; MoALFC 2021). Both counties usually experience a bimodal rainfall pattern,

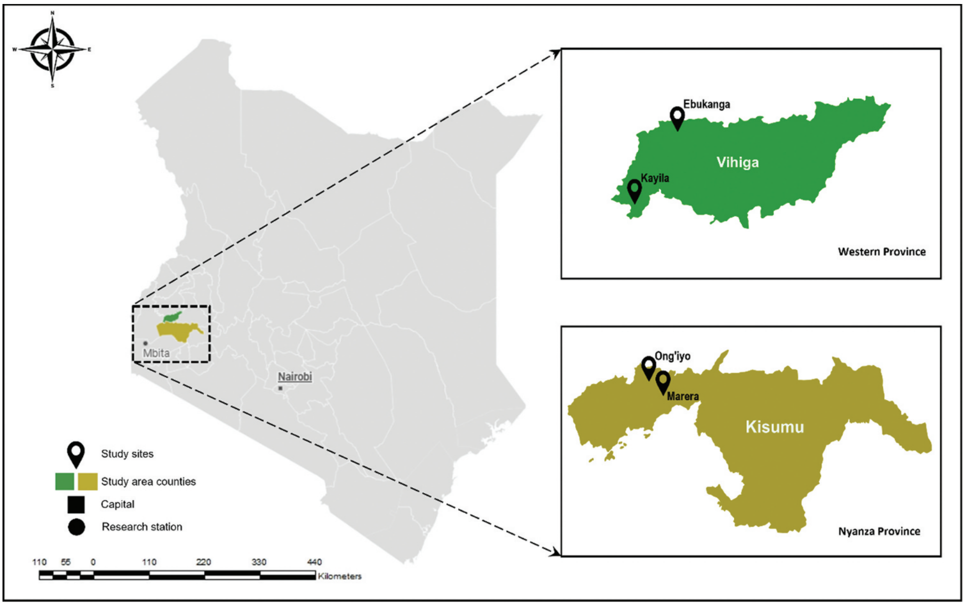

Figure 1. Map of the study area in Western Kenya.

Table 1. Specific information on the study area and sites.

Study sites	County and Province	Land area of the County	Mean annual temperature (°C)	Mean annual rainfall (mm)	Elevation (masl)	Main AEZ	Rainfall regime
Marera and Ong'iyo	Kisumu *Nyanza Province*	2085.9 km^2	21–24	1200–1500	1144 –1525	Upper and Lower Midlands	Short and long rains
Ebukanga and Kayila	Vihiga *Western Province*	536.8 km^2	24–26	1700–2200	1217 – 1923	Upper Midlands	Short and long rains

enabling two distinct cropping seasons: a long season from March to August and a short season from October to January (Cheruiyot et al. 2020; Khan and Pickett 2008). Other essential information about the study area and sites is presented in Table 1.

Agriculture plays a pivotal role in the economic landscape of both counties, with recent government assessments showing significant contributions to household income (approximately 47% in Kisumu and 64% in Vihiga) and overall economic growth (MoALF 2017; MoALFC 2021). Smallholder farmers play a crucial role in driving agricultural production for household consumption and sale through mixed farming practices on small plots (often less than 3 ha) of land in the study area (CGoK 2018). Field observations and local records indicate that land used for agriculture is often obtained through inheritance, with only a few people purchasing or renting land for farming purposes (CGoK 2018; MoALF 2017). Maize, sorghum, beans, bananas, and cash crops such as sugarcane, rice, and cotton are staple crops that contribute to both household cash flow and food security (MoALF 2017). Since crop production in the region is mainly rain-fed, these counties are vulnerable to the effects of climate change, such as heat stress, droughts, and floods (Cheruiyot et al. 2021). Livestock farming, which includes poultry, dairy cattle, goats, and sheep, alongside fodder production, is also essential to the livelihoods of most households (MoALF 2017; MoALFC 2021). Female farmers actively cultivate valuable crops such as legumes, fruits, vegetables (Indigenous and exotic), cereals, oil crops, trees, and shrubs (Buleti et al. 2023). These crops are often sold in local markets or to larger agricultural companies. By participating in the cultivation of high-value crops, female farmers contribute to household income and improve their standard of living (Buleti et al. 2023). This can, in turn, benefit their families and communities by providing greater access to food and other resources. Moreover, small-scale trading is the primary informal non-agricultural activity in the area (MoALFC 2021). Kisumu's proximity to Lake Victoria fosters a thriving fishing industry, and the County is characterized by medium-sized farms averaging 1.0 ha per household. Vihiga, on the other hand, is densely populated with small but intensively cultivated farmlands averaging 0.41 ha per household (Buleti et al. 2023). Both counties allow for diversity in ecological and social contexts while offering comparative insights. Specifically, the Ongiyo and Marera communities (Kisumu County) and the Kayila and Ebukanga communities (Vihiga County) (Figure 1) were selected as the ethnographic research sites where there is an ongoing PPT intensification effort. These communities have experienced challenges such as stemborer, Fall armyworm, and Striga weed infestations affecting cereal crop production (Cheruiyot et al. 2021). Overall, agricultural practices in the study area are challenged by increasing input costs, climate change impacts, land tenure complexities, and resource overuse due to population growth and land fragmentation (Diiro et al. 2018; Kassie et al. 2018; Muriithi et al. 2018).

Data collection methods

The study employed a multiple data collection approach structured in different phases. In the initial phase, 10 farmers in the study area were selected during a Scoping Field Trip in 2022 using an opportunistic sampling method. Farmers were then asked to talk about their farming activities, pest management techniques, access to extension activities, support received, and farming challenges (Scoping Field Trip in 2022). Following this preliminary phase, a list of farmers and households who have engaged with ICIPE's PPT in the study area was compiled with the help of an ICIPE field agent during fieldwork in 2023. From the generated list, research participants were selected based on their experiences with PPT and involvement in farmers groups, including lead farmers, trial farmers, and those with varied relationships and encounters with PPT (e.g., partial users, adapters, and discontinued ex-users). We also considered the farmers' age, gender, educational level, years of farming experience, and community role during participant selection. To ensure comprehensive representation, a snowball sampling method was employed to further augment the participant pool, identifying additional participants who had not yet engaged with PPT or were not involved in farmers groups.

Semi-structured interviews

A total of 25 participants were interviewed using a semi-structured interview guide, and a follow-up visit was conducted during the fieldwork in 2023 to enrich the data collected. The interviewer gathered general demographic information before delving into their farming activities, experiences, challenges, coping mechanisms, and practices. In addition, the participants were asked about their involvement and decisions made regarding PPT over the past years. Visits to the farmers' fields provided a hands-on understanding of the discussion points.

Focus group discussions (FGDs) and participatory research (PAR)

Furthermore, we conducted four FGDs and PAR sessions across the selected study sites (FGD 1 and 2 in Kisumu; FGD 3 and 4 in Vihiga, 2023). Each group consisted of 6–8 smallholder farmers, with a total of 28 participants. These farmers were engaged in diverse farming activities and enterprises. During these sessions, multiple participatory tools were employed:

- Participants collaborated to construct a timeline of key events over recent years (Figure 3), including pest outbreaks, droughts, and agricultural intervention programs that occurred before and after PPT was introduced.
- Farmers worked together to create a farming activity calendar for each month between the short rainy season of 2022 and the long rainy season of 2023 (Table 2).

Fieldnotes and observations

In addition to information gathered from interviewed participants (IP), FGD, and PAR, the researcher attended local (baraza) group meetings and field days to observe and gain deeper insights into social interactions and information flow within the communities (Table 3).

Data analysis

The interviews and FGDs were transcribed and imported into NVivo software version 14.0 [QSR International Inc.] for qualitative analysis using thematic

Table 2. Farming activities and decisions made during 2022 short and 2023 long-cropping calendar.

	Short (Rains) growing season 2022					Long (Rains) growing season 2023						
Months	August	September	October	November	December	January	February	March	April	May	June	July
Main activities	– Land preparation – Planting maize – Harvesting maize – Farmyard manure preparation	– Land preparation – Planting maize, beans, cowpeas, millet, groundnuts & potatoes – Thinning & gapping – Bird scaring – Transporting compost manure to the farm	–1st Weeding – Top dressing - Scouting pests & diseases – Planting potatoes - Thinning & gapping	–2nd Weeding – Top dressing – Scouting pests & diseases – Thinning & gapping – Harvesting groundnut & beans	– Harvesting of beans, cowpeas, groundnuts, potatoes & maize – Threshing & drying harvested produce – Storing & preserving produce – Selling harvested produce	– Harvesting maize – Land preparation – Farmyard compost preparation	– Land preparation Farmyard compost preparation – Transporting compost manure to the farm	– Planting beans, cowpeas, millet, sorghum groundnuts & vegetables – Bird scaring –1st weeding – Transporting compost manure to the farm – Thinning & gapping	–1st or 2nd Weeding –Top dressing – Scouting pests & diseases – Thinning &gapping	– Top dressing –2nd weeding – Harvesting groundnuts, vegetables, millet & beans –Thinning & gapping	– Harvesting maize, beans, cowpeas, sorghum	– Harvesting Maize, sorghum
Decision with inputs, including labour	Purchasing seeds & DAP fertilizer, Hired & or family labour	Applying DAP & farmyard compost manure, Hired & or family labour	Purchasing & applying CAN, Urea fertiliser, Hired & or family labour	Purchasing & applying CAN, liquid foliar fertiliser, Mostly family labour	Hired & or family labour	Purchasing seeds & DAP fertiliser, Mostly family labour	Purchasing seeds & DAP fertiliser, Hired & or family labour	Applying DAP & Farmyard compost manure, Hired & or family labour	Purchasing & applying CAN, Urea, liquid foliar fertiliser, Hired & or family labour	Purchasing & applying CAN, Urea fertiliser, Mostly family labour	Mostly family labour	Mostly family labour
Experimentation and adaptation decisions	Attempting new intercrop combinations or planting arrangements and crop density. Modifying the timing, type, and blend of fertilisers.		Trying different pest control methods. Modifying the timing, type, and blend of fertilisers.		Evaluating results and planning adjustments for the next season.		Attempting new intercrop combinations or planting arrangements and crop density. Modifying the timing, type, and blend of fertilisers.		Trying different pest control methods. Modifying the timing, type, and blend of fertilisers.		Evaluating results and planning adjustments for the next season.	

*The calendar captured decisions and activities carried out on plots where PPT is practiced and plots with no PPT.
*Decisions to hire labor usually depend on the size of the farmland and affordability.
*The gestation period and maturity of crops depend on the variety planted, assuming optimal agronomic conditions.

Table 3. Information flow, social interactions, and settings of occurrence in the study area.

Channel of Information	Organisations and Sources of Information	Settings Where Interaction Occurs	Type of Interaction	Frequency of Interaction	Type of Support Received
Farmer-to-farmer	Peers (e.g., relatives, friends, and neighbours), lead or model farmers	Residences and farms, field days, barazas, religious houses	Knowledge exchange and experience sharing	Regular	Information, awareness, social and emotional support
R&D workers-to-farmer	Research institutions, input companies, developmental NGOs, local industries	Field days, barazas, religious houses, public spaces, and events	Research dissemination, technology trials and demonstration	Occasional	Technical support and training, capacity building, inputs-subsidies, and incentives
Mass media	Local industries, government, and developmental NGOs	Mass media platforms (e.g., Radio, TV)	Usually, one-way communication and broadcasting	Daily/weekly	Information and awareness
Posters and brochures	Local industries, research institutions, and developmental NGOs	Roadshows, public spaces, and events	one-way communication	Occasional	Information and awareness
Farmer groups and associations	Community leaders, Research institutions, developmental NGOs, and local government	Usually at leaders' residence	Group discussion, collaboration, resource sharing	Regular	Mutual support, knowledge sharing, access to inputs, and loans
Farmer field schools	Research institutions, government, and developmental NGOs	Farms, communities, and research stations	Structured and group learning	Occasional	Knowledge and skill development, and hands-on training

analysis principles and inductive coding techniques (Nowell et al. 2017). The analysis proceeded in sequential stages: (1) Initially, open coding was conducted by assigning codes that captured key concepts, experiences, practices, motivations, and decision patterns. (2) Focused coding was then performed to synthesize and categorize these initial codes into overarching themes. (3) The main themes were developed and refined on the basis of dominant trends, similarities, and differences observed across the codes and data. The themes generated include farmers' experimentation, adaptation to changing contexts, and group dynamics, providing nuanced insights into the complexity and dynamics underpinning smallholder innovation experiences, knowledge construction, motivations, and decision-making processes. Cross-comparisons between data sources were made to ensure a rich, contextualized understanding of the themes (Malterud 2001). For instance, information gathered during key informant interviews was compared with FGD insights to validate findings.

Results

This section explored the three main themes that emerged from the analysis of data collected from smallholder farmers in four study sites across two Western Kenya counties Figure 2. To gain a deeper understanding of these themes, the experiences of six individuals in the study sites were narrated in relation to their contexts, farm practices, social engagements, and decisions regarding PPT (Figure 2).

Theme 1: adaptation through experimentation and evolving motivation

Broader observations across the study sites revealed that farmers actively engage with and use the knowledge acquired from diverse sources. These sources of knowledge include farmer-to-farmer learning through social networks, field days organized by agri-input producing companies and agriculture research institutes, community groups and associations, mass media platforms, and direct interaction with R&D organizations such as KALRO, ICIPE, Send-a-Cow, and One-acre fund (FGD 1–4). Farmers combine the

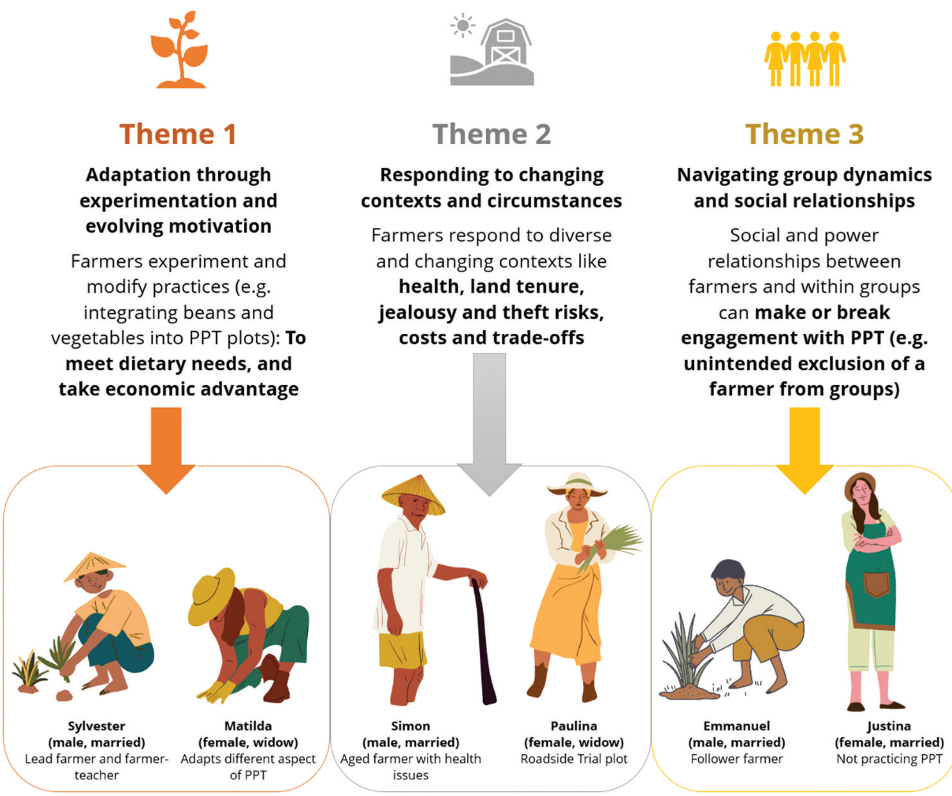

Figure 2. Three main themes from the research capture innovation processes and smallholder farmers' decision patterns around PPT.

knowledge acquired from these sources as they experiment on their farms and adapt the practices to suit their unique contexts and needs. For example, several farmers (IP 3, 5, 7, 8, 12 and 15) modified the original PPT designs by intercropping additional crops such as vegetables (especially *B. oleracea var. acephala* – a leafy green vegetable used to prepare a dish called *sukuma wiki*, usually eaten with *ugali* – cornmeal), or local bean varieties (e.g., *Phaseolus vulgaris L. and Vigna radiata L.*), against initial recommendations by experts.

This modification was later validated by ICIPE after conducting research on the performance of PPT with an additional intercrop of common beans, *Phaseolus vulgaris L.* (Midega et al. 2014), as farmers continually recounted the benefits, such as nutritional security, short-term income generation, and diversification against crop failure (FGD 1 and 3; IP 3, 7 and 15). Findings from multiple data sources (FGD 1 and 4; IP 2, 9, 11, 16, and 17) showed that farmers' initial motives surrounding new practices such as PPT evolved. While higher yields from maize, pest control, and access to livestock fodder were repeatedly mentioned as the initial reasons for trying PPT, these motivations changed with time and season as farmers adapted their practices to emerging events, priorities, and interests (e.g., new projects, incentives, cost of inputs, and climate change), while managing risks strategically. For example, Sylvester [male, married], an active promoter of PPT in the early 2000s within his community, shares his farming practices and research experiences with PPT. His choice of farming is carefully timed to seize economic opportunities while also considering biophysical factors in his decisions and practices.

Sylvester has been invited several times to ICIPE's Mbita research station to learn about PPT research. His involvement in PPT has boosted his social status as a lead farmer in the community, as he has been featured in ICIPE brochures and agricultural programs broadcast by Kenya's Citizen TV station, showcasing his success stories with PPT. He described who was selected to visit the research station: " *. . . They [ICIPE R&D workers] picked key farmers, role models, those who are very serious for the training at Mbita.*" He is currently not an active farmer-teacher because ICIPE is not supporting him to perform the role. However, he is a member of several groups where he has gained knowledge of planting vegetables for seed production and tree planting for sale. He explained: " *. . . I'm a member of another group. We normally focus on planting vegetables to get seeds for sale.*" He is one of the farmers who plant vegetables in their PPT plots. Sylvester avoids planting vegetables during long rains but usually takes the risk during short rains when many farmers shy away due to erratic rainfall, leading to scarcity and increased demand. He described the rationale behind his style of vegetable farming and his motivations for including it in his PPT plot:

> . . . You know this long range [season], many people plant vegetables, and there's no market. So, when it comes to shorter range, that time there's a challenge in planting the vegetables because there is not enough rain. That is when I take the risk of planting, the prices go up and I earn more . . . . So, I also put sukuma wiki [B. oleracea var. acephala] in the push-pull and told ICIPE to allow it because other farmers want vegetables and beans too.

In comparison to the story of Sylvester, Matilda's [female, widow] decisions to modify and experiment with PPT further provide unique evidence that reinforces the value of farm-level knowledge for meaningful research and development impact. She started active farming in the early 2000s after her husband passed. She believed that planting maize and beans together is a more recognized way to effectively improve family nutritional status when eaten and household income when sold. This food culture and perspective were shared by several other farmers in the study area (FGD 2 and 3; IP 1, 3, 16, and 19). She sometimes gifts a few cups of beans to her relatives because many of them already grow maize. Matilda is also one of the farmers who periodically reverted to local maize varieties when hybrid seeds from Agrovets became unaffordable or failed to germinate (IP 5, 8, 11, 12, and 15 have also made similar decisions).

Matilda heard about PPT benefits from one of the farmers invited to the ICIPEs Mbita campus, who gave her *Desmodium* seeds while she sourced Napier by herself. She decided to try PPT on a half-acre plot and started seeing encouraging yield in the second year of practicing the technology. Matilda was told to share her success stories with another farmer, which she did. However, her co-farmers complained about the inability to grow different crops, particularly beans, in the PPT plot. To this end, she experimented with maize and beans on her PPT plot. At first, she made a single row of maize, then beans, and *Desmodium*. To manage her plot space effectively and save time, she planted maize and beans in the same hole at once, and it was easier to drop maize and beans together. The result was good, as her maize and beans could share the fertilizer. She explained the process of her experimentation with bean integration in PPT:

> . . . I wanted to try if the beans would do better in the push-pull . . . We used to put maize and beans in different holes, but nowadays we put in the same hole . . . I find that if you intercrop like that, the beans do very good, it shares the same fertiliser, so the yield is very good and also, it's easier for you to do the weeding . . . dropping the maize and beans together makes the work easier . . .

She was excited to point out that the ICIPE field workers initially disagreed with the technique, but after a long time, they learned and later allowed the inclusion of beans in the PPT plot. In her words: " . . . *They [ICIPE] learned it [bean integration] from us.*" She noted that certified hybrid maize was recommended for planting in the PPT plot so that the technology could work effectively. However, seeds are now costly (Up to 600ksh per 2 kg). In response, she sometimes plants local maize varieties in her PPT plot because her friend who used to help her with Western hybrid seeds stopped.

This theme and the stories of Sylvester and Matilda specifically exemplify a constantly evolving landscape of practices observed through ongoing adaptation to suit their preferences and individual situations, as they depend on agriculture for their livelihoods and subsistence. Farmers often experiment with new techniques on a small land area, typically measuring 15 × 15–20 m or 0.2 acres in size (FGD 1–4; UPSCALE Consortium 2021). In addition, farmers may use the less fertile parts of their plots to experiment with new farming practices to see how they perform. Sometimes, they may ignore experts' recommendations to plant a double or triple line of border plants in PPT plots to make room for other farming practices (FGD 2; IP 2, 3, 8 and 11).

Table 2 summarizes the common farming activities and decisions made throughout the farming timeline, highlighting the points at which farmers made certain experimentation and adaptation decisions (Complied from FGDs and Interviews, 2023). During land preparation, farmers may choose to experiment with local crop varieties rather than using certified seeds, and they may also try new intercropping combinations and planting arrangements (FGD 1–4). They may also modify the timing or blend of chemical and organic fertilizers during planting and top dressing. Regarding weeding and pest management, farmers may try different control methods, such as biopesticides. During the harvesting and post-harvest stages, farmers can evaluate their results and plan adjustments based on changing conditions and priorities for the next season (FGD 1–4). The position represented under this theme aligns with studies by Glover et al. (2019), Hermans et al. (2020), and Whitfield (2015), establishing that farmers actively seek ways to innovate around and optimize technologies for their specific needs rather than passively adopting a practice.

Theme 2: responding to changing contexts and circumstances

Farmers in Western Kenya grow various crops on their plots and use technologies that work best for their specific needs and changing realities. They have been exposed to several agroforestry and tree-planting practices for food, fuel, soil fertility improvement, windbreaks, and pest control (IP 1, 3, 4, 10–16). Therefore, different varieties of established trees are found on many farms, with which the introduction of PPT has to contend or co-exist. Beyond existing practices, farmers respond to social circumstances, including family structure and dynamics, health status, security concerns, social networks, and land tenure issues. For instance, many older farmers discontinued practices like PPT due to declining health status and the labor-intensive nature of the practice (FGD 1–4; IP 18, 22, 23 and 25). As Hermans et al. (2020) found in similar African contexts, the health status of farmers is an essential but often overlooked factor influencing farmers' decisions regarding conservation agriculture (CA) practices in Malawi.

A typical example is the case of Simon [male, married], a 75-year-old farmer who stopped practicing PPT in response to his health condition. Simon was once a farmer-teacher and an active promoter of PPT in his community in the early 2000s. In recent years, he felt that managing PPT takes much time and labor. In addition, he transitioned from being actively involved in farming to supervisory roles, as agreed upon by his family, while his wife and children handled most of the farming work. He commented:

> . . . I decided to stop practising push-pull because I found the management was difficult for me . . . My health didn't allow me to continue the farming, I left farming for my wife and children to handle . . . Just doing monitoring and supervision as my wife and children insist. Since I was the one that was trained on the push-pull management, everybody [family] agreed with my decision to stop practising push-pull because I brought it to the family.

Simon and his family now rotate crops that were previously impossible because of the presence of *Desmodium* intercrop in the PPT plots. He planted *Tithonia* spp. around the hedge of his plots and sometimes sprays a mixture of crushed *Tithonia* leaves and water, including wood ash, to control pests. He instructs his family to use agrochemicals purchased from the Agrovet to control pests in case of a severe outbreak. In addition, he combines aspects of different agricultural practices, such as incorporating elements of PPT with conventional practices. For example, he spaces his maize rows 75 cm apart, then plants groundnuts or beans between them, and finally plants two maize seeds per hole before thinning.

Some participants also highlighted theft and jealousy concerns due to the visibility and prestige given to "model farmers" chosen to showcase interventions through demo plots (IP 10, 12 and 14 had similar experiences). These social pressures sometimes led farmers to avoid planting certain commodity crops encouraged by projects. Paulina's [female, widow] story is one where her demo plot garnered attention, but that came with unintended consequences, and she had to respond by discontinuing maize and PPT practices. Paulina learned about PPT in 2022 from ICIPE field agents, who introduced it to a self-help group where she is the secretary. In the same year, she volunteered 0.25 acres of her land for a trial, which was later used for demonstration during field day. She articulated how her encounters with PPT occurred:

> . . . They [ICIPE field worker] talked to us about push-pull in our self-help group. They helped us to plant it, they can plant for two people in one day. My push-pull did very

well, last year the Field Day was at my place. When they [other farmers] saw my maize, they were very interested this time.

However, she could not harvest anything from the trial plot due to theft despite how promising the PPT maize looked. In her view, her closeness to the road and the structure of the maize plant made it easy for her crops to be stolen. Paulina and her daughter reported the case to the village chief, but the perpetrators were not found. The theft experience on her farm compelled her to shift focus to alternative crops such as beans, groundnuts, and sweet potatoes, which are difficult to steal, unlike maize.

The cases of Simon and Paulina mentioned in this theme demonstrate how farmers' innovation decisions are shaped by their unique, changing contexts and experiences over time. Farmers in this study area have encountered and responded to various events, shocks, and interventions impacting their agricultural practices and decisions. For instance, some farmers responded to periodic pest outbreaks such as Stemborer between 2010 and 2012 in Vihiga and Fall armyworm outbreaks in Kisumu during 2016–2017 (see historical timeline of key events in Figure 3) by spraying a mix of paper, wood ash, and rabbit urine (IP 3, 5, 20, and 22), whereas others utilized chemical pesticides and planting-resistant crop varieties

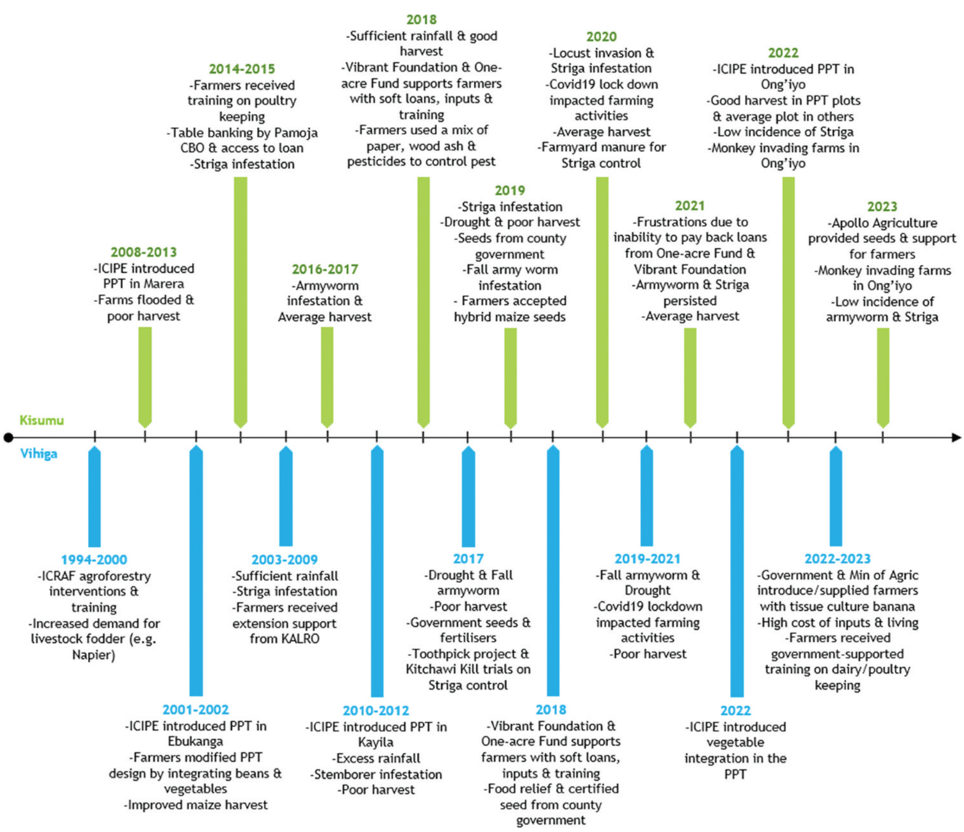

Figure 3. Historical trends of notable occurrences that influenced farmers' innovation decisions over several decades.

recommended by Agrovets and extension workers (IP 1, 4, 23 and 24). Farmers with medium-sized plots (often between 1.2 and 2.0 ha per household), particularly in Kisumu County, were observed to prefer that livestock graze the leftover crop residues and use animals/tractors for plowing – a practice that does not accommodate the perennial *Desmodium* intercrop in the PPT plot (FGD 1 and 2). A similar pattern was observed in Muzangwa, Mnkeni, and Chiduza (2017), which examined conservation agriculture practices among smallholder farmers in South Africa. Recurring drought conditions from 2017 to 2019 to 2021 prompted some farmers to plant early maturing crops (IP 1, 4, 5 and 21), grow hybrid maize and drought-resistant crops (e.g., cassava, sorghum, and sweet potatoes) and continually wet crops during establishment (IP 3, 7 and 19) or rely on faith "God's mercy" in extreme events (IP 6, 8, and 15). Others sought off-farm income sources, reduced planted acreage, and relied more on livestock farming (IP 2, 9, 22 and 23). In Vihiga, farmers have continually planted trees introduced through agroforestry intervention programs between 1994 and 2000 as resilience strategies (FGD 3 and 4). Additionally, they sought help from the government and NGOs, including soft loans from the Vibrant Foundation and One-acre Funds in Vihiga (2018) and Kisumu in 2021 (FGD 1–4). Notably, the COVID-19 pandemic presented unprecedented challenges in 2020, disrupting access to the market, which was further complicated by the rising cost of synthetic fertilizers and poor harvest (FGD1–4). In response, farmers coping mechanisms include planting more subsistence crops for household consumption, using more farmyard manure, and increasing reliance on credit, which could potentially lead to debt burdens. They also utilized government-provided support aids to improve resilience and productivity. Some farmers also expressed interest in trying out tissue culture bananas introduced in 2022–2023 by the Ministry of Agriculture, as they can be more productive than traditional varieties (IP 1, 3, 20, and 24; FGD 3 and 4). These experiences over time have played a crucial role in shaping the realities of farmers, evolving agricultural practices, and informed innovation decisions.

Farmers often weigh the cost of a novel practice against their own practice, and there were cases where farmers only wanted to respond to the problems whenever there was an outbreak. For instance, when a farmer uses a certain technology to manage an outbreak, and the pest is no longer an issue, farmers return to their preferred way of doing things (IP 3, 10, 18 and 22). The position represented under this theme corroborates studies by Hermans et al. (2020) and Glover et al. (2019), which recognize the importance of context and that technology adoption cannot be seen as a binary decision. Hence, understanding farmers' realities can inform more targeted, context-specific innovation promotion efforts.

Theme 3: navigating group dynamics and social relationships

Local farmer groups and associations are crucial in providing farmers with access to training workshops, farm inputs, and information about new agricultural practices (IP 8, 18, 19, 24, and 25). Some of these groups have even shared plots of land, and the produce was usually shared among members (FGD 2 and 4; IP 16, 18, 24, and 25). If sold, proceeds from the plot could be used to support members' immediate financial needs (e.g., medical treatment, travel, school fees, and home improvement). Field days, demonstrations, and training were usually organized through previously established farmer groups and lead farmers, facilitating knowledge and information diffusion (see Table 3 for common information sources and interactions) (FGD 1–4). However, relying on "model" farmers and influential local opinion leaders to drive uptake within their networks can have both positive and negative effects. Although they don't necessarily prevent other farmers from joining groups or accessing technologies, their influence often sways group behavior and dynamics, setting local trends (Buleti et al. 2023; Hermans et al. 2020). Other lesser-endowed farmers in or out of their group strive to copy them as a means to hedge against risk (as the model farmers are thought to be more educated and informed). Meanwhile, nonmembers of these groups sometimes feel deprived of the support needed to try practices like PPT on their own (FGD 1 and 4). In addition, unequal access to inputs such as seeds and fertilizers, among other incentives provided by projects, occasionally exacerbated inequalities within communities. For instance, few farmers like IP 20, 24, and 25 in the study area perceived that model/lead farmers unfairly monopolized resources that should be jointly managed. A typical example is Emmanuel, who began farming after his father's passing in the late 1990s.

Emmanuel [male, married] was introduced to an ICIPE field officer by one of the field staff at the International Centre for Research in Agroforestry (ICRAF), now known as World Agroforestry. The field officer encouraged Emmanuel to try PPT and advised him to join an existing PPT group formed by the first set of farmers who started practicing the technology. Emmanuel gave out the low-yielding and infertile part of his plot to be used to test the technology while the field agents helped him establish the PPT plot. He later became a follow-farmer under Sylvester's tutelage. However, after some time, Sylvester stopped giving him seeds, fertilizers, and incentives meant for those practicing the technology. He believed that Sylvester was hoarding them for his personal use. He narrated his concerns:

> . . . They [ICIPE R&D worker] gave us machines [motorcycle] and fertiliser to our group . . . . Sylvester and those people in charge of maintaining it took those things. . . It was used for their own business, and they neglected others. It was not circulating any

> longer. We are trying to tell the ICIPE people . . . . But they fear these guys. You are doing something only beneficiary for some people only.

Emmanuel later decided to replace *Desmodium* with beans to properly use his plot and ensure that his family of eight was more secure with food. Again, removing *Desmodium* allowed him to rotate crops on his plot. After removing *Desmodium* from his plot, which had previously functioned as a cover crop, he decided to divide the land into two sections. He then dug a trench at the dividing point and planted cassava and cocoyam. This practice helped retain leached topsoil and manage erosion, an idea he got from the government extension agent. However, he retained Napier grass as a border plant because he believed that Napier fodder would continue to help capture harmful pests while serving as a high-quality feed for his livestock. In addition, he noticed that the *Napier* spp. from ICIPE increases livestock milk production compared to others and helps prevent soil erosion. The case of Emmanuel contributes to explaining the issues surrounding model farmers and the associated leveraging of resources that could be counterproductive.

Justina's [female, married] experience further adds insights into the unspoken issues surrounding groups and social relations within farming communities. She started farming after getting married in the mid-1990s, primarily for household consumption. Due to unintentional exclusion from the PPT group and subsequent activities, she felt deprived of access to the technology, which strained her engagement with the practice. In the early 2000s, Justina attended a monthly meeting at the chief's house, commonly called the chief's baraza, a forum for communicating with the local public and an avenue for agricultural experts to introduce interventions and technologies to farming communities. She stated, *"... I attended their meeting once every month. They [ICIPE field worker] came to the chiefs' place, and I decided to go there."* At this meeting, an ICIPE field extension officer spoke to them. According to her, the extension officer talked about the benefits of *Desmodium* and Napier grass. "*We were discussing about the push-pull and how to use it . . . and if you want to plant how to plant it.*" After the meeting, she noticed that some farmers had already formed a group, positioned themselves, and established close contact with the extension officer. She was not part of the group, and there was no follow-up regarding the practice. Justina described her reason for not engaging with the PPT:

> . . . But the problem is I didn't continue with push-pull . . . I was not informed to continue since I was not in that group. I only went there that day, but I was not in that group . . . . the person I know in the group came out of that group.

Nonetheless, she cleared a small portion of her land to plant Napier grass for her livestock. Her livestock grew healthier when feeding on Napier rather than weeds or grazing. She continued to use the knowledge and farming techniques learned from her parents while growing maize, beans, and sweet potatoes for sale and household consumption.

The stories of Emmanuel and Justina described in this theme shed light on some of the complexities within social and group dynamics, reflecting broader patterns around contextual barriers and enablers (inclusion and exclusion) that shape innovation experiences. As shown in Table 3, information is often exchanged through "farmer-to-farmer" interactions and "social networks" (FGD 1–4), which can significantly shape access to resources, awareness, engagement with, and co-creation of practices like PPT when compared to the linear, one-way communication and top-down knowledge transfer approaches. However, it is essential to acknowledge that social inequalities already exist in the farming communities, and these may impact individual power relations, ultimately affecting innovation experiences on the ground (Whitfield et al. 2015). Social relationships significantly affect how farmers perceive and utilize agricultural information. The narratives under this theme agree with studies emphasizing that inclusion and power relations are crucial and should be addressed for a just, effective intervention design and implementation (Kiptot et al. 2006; Spielman et al. 2008; Spielman, Ekboir, and Davis 2009).

Overall, the three themes presented in our results showcase the diversity and interactions of contexts, motivations, and experiences underlying farmers' innovation decisions. The stories highlight the situational and fluid nature of innovation and decision-making processes. While individual narratives provide insights, clear patterns emerged across cases that recognized the interconnected and non-independence of the themes. This perspective of innovation experiences can inform more holistic and tailored support for the sustained uptake of new agricultural practices.

Discussion

Re-framing innovation beyond technology and transfer

The conventional assumptions that underlie many agricultural development programs are based on a narrow view of innovation as merely a "technology" or a "new technique" that is essential to address agricultural challenges (Balew et al. 2023; Hounkonnou et al. 2012). This framing has long dominated the research and development space alongside simple and linear conceptions of technology transfer, which assume that if a technology works, it will lead to widespread adoption (Rogers 1962). Such technocentric perspectives portray innovations as fixed packages of solutions that are transferred to passive recipients, accompanied by usage guides (Klerkx, van Mierlo, and Leeuwis 2012). This conventional framing also overlooks the active role of farmers as innovators. However, our study aligns with the recent literature arguing that the conventional framing of innovation does not capture the interplay between technical and social innovation processes (Adesina et al. 2023; Hermans et al. 2020). Compared with technology in other sectors, a total replacement of an existing practice by a new one is rarely seen in agriculture (Glover, Sumberg, and Andersson 2016).

Farmers draw on diverse sources of information, local networks, personal experiences, and history to actively experiment and modify shared practices (Dietze and Feindt 2023; Glover et al. 2019; Whitfield 2015). For instance, farmers like Simon grow *Tithonia spp*., another biocontrol measure planted as hedgerows on his farm, yet he also turns to pesticides during severe pest outbreaks, suggesting different coping strategies on the same plot. In addition, the Kuper et al. (2017) study in North Africa described how smallholders engaged and adapted a foreign technology (drip irrigation package) to suit their needs and context using readily available and locally manufactured components. These narratives challenge linear "transfer of technology" models where knowledge and technology move from experts to farmers as mere recipients, calling for a rethink among agricultural research and development organizations (e.g., ICIPE, CABI, and the CGIAR partners), policymakers at all levels of government, donors (e.g., Biovision Foundation and One-acre Fund), and other practitioners (Douthwaite and Hoffecker 2017; Whitfield et al. 2015; Williams et al. 2022). To develop more effective approaches to innovation and scaling biocontrol technologies in SSA, there is a need to recognize farmers as innovators and important sources of knowledge while focusing on strengthening enabling conditions and innovation capacities, fostering collaboration among diverse actors, and adopting systemic, long-term perspectives oriented to transforming conditions and relationships rather than short-term projects (Hounkonnou et al. 2012; Spielman et al. 2008). The experiences of farmers like Matilda and Sylvester illustrate how farmers' experiential knowledge enabled them to adapt and personalize PPT, sometimes countering or improving upon extension officers' recommendations.

Another important aspect highlighted in this study is the social embeddedness of innovation enabled by knowledge exchange within social networks (Smith et al. 2021). The exchange of information, ideas, and resources between farmers and groups was dominant among smallholders in Western Kenya. For example, a common practice among farmers is planting certified maize seeds, which goes with the application of mineral fertilizers such as Diammonium phosphate (DAP) and top dressing with Calcium ammonium nitrate (CAN) for improved productivity (Table 2; Buleti et al. 2023). However, several farmers have acknowledged the adverse effects of overdependency on these fertilizers, including increased soil acidity levels (IP 1, 4, 5, 12 and 14). Farmers have responded to the challenge in different ways, including rotating crops and raising concerns with fellow farmers during field days, barazas, meetings with experts, where a return to farmyard manure or a blend of the practice was recognized as a more cost-effective solution (FGD 1–4; Buleti et al. 2023). These actions attest to the socially constructed nature of agronomic knowledge (Whitfield 2015) and show that solely relying on top-down approaches in the effort to scale technologies will not produce the expected results. Instead, innovation should be supported through complex interactions among farmers, extension workers, NGOs, and government programs (Dietze and Feindt 2023; Spielman et al. 2008). Innovation is broader than technology and should be regarded as an ongoing process of change brought about by multi-stakeholder exchange of ideas and social learning. Sustained participatory research approaches can stimulate innovations, policies, and support responsive to farmers' feedback and needs (Hounkonnou et al. 2012; Klerkx, van Mierlo, and Leeuwis 2012).

Furthermore, it is essential for donor agencies, as well as R&D organizations, to acknowledge that innovation in agriculture requires the integration of social, economic, ecological, institutional, and organizational processes within a specific context (Whitfield et al. 2015). This recognition is crucial if sustainable transformation of the sector is to be achieved. Efforts to evaluate success could be based on farmers' learning, experimentation, and incremental changes over time. For example, research projects can incorporate long-term accomplishment and outcome monitoring to understand how farmers' use of biocontrol techniques such as PPT evolves across seasons and in response to changing conditions. Engaging farmers as partners in collaborative design and co-creation processes cannot be overemphasized. However, facilitating multi-directional knowledge flows between scientists, extension workers, and farmers supports context-specific adaptation and leverages complementarities between scientific and local knowledge systems.

According to Glover, Sumberg, and Andersson (2016), innovation consists of technical and social components that can change over space and time. Glover, Venot, and Maat (2017) emphasized the importance of context specificity and detaching a technology or practice depending on where it is developed. The Glover PEDR and innovation systems framework presents a more comprehensive and user-centric way of understanding innovation processes, rethinking technological change, and diverging from common linear and technocentric concepts suited for SSA farming systems (Glover et al. 2019; Spielman, Ekboir, and Davis 2009). While there has been considerable effort to recognize farmers as key stakeholders in agricultural development initiatives (Dietze and Feindt 2023; Klerkx, van Mierlo, and Leeuwis 2012), involving them from the onset through farmer-led identification of problems, existing practices and technology refinement through feedback cycles is expected to help achieve meaningful and sustainable impacts in SSA (Andersson and D'Souza 2014; Hounkonnou et al. 2012; Schut et al. 2016). Innovation platforms connecting diverse stakeholders across knowledge systems could stimulate more holistic solutions tailored to the realities of smallholders. Currently, ICIPE is trying this approach in the UPSCALE project to enhance the effectiveness of PPT interventions (https://upscale-h2020.eu).

Moreover, there needs to be more emphasis among R&D organizations on focusing agricultural training and support on core concepts and principles while allowing flexibility for farmers to adapt technologies such as PPT to their specific contexts and realities (Andersson and D'Souza 2014; Glover et al. 2019). For example, PPT biocontrol practice, integrated pest management (IPM), or climate-smart agriculture (CSA) projects could prioritize building farmers' understanding of key agroecological and biocontrol principles while allowing flexibility in the specific components used and how the practices are implemented in farmers' heterogeneous conditions. This might involve using locally available materials, adjusting crop varieties and arrangements, or blending new and traditional techniques on their farms. The ethics of R&D organizations can sometimes restrict farmer participation and transparency, affecting the outcomes of research projects. To address this, donor agencies providing support and funding for agricultural research, education, and training in SSA (e.g., One Acre Fund, International Fund for Agricultural Development (IFAD) should consider funding agricultural research proposals and projects that prioritize farmer feedback and engagement throughout the entire program cycle to capture their social and environmental concerns while ensuring that interventions are well tailored and relevant. This will lead to more effective and impactful research in the agricultural sector rather than a maximum focus on scaling up. At that point, sustained investments should go into capacity building of farmers and frontline staff (e.g., extension workers and field agents (Isgren et al. 2023) while embracing principles of participation, inclusiveness, and responsiveness in program design and implementation. Our research supports calls for a paradigm shift in agricultural innovation research toward more participatory, flexible, and responsive approaches to diverse farmers' local contexts and needs, making technology like PPT biocontrol more relevant in SSA. The study also emphasizes supporting farmers by collaborating with them on developing innovative ideas and agricultural research from the outset of development programs.

Understanding farmers' decisions beyond simplistic adoption metrics

The literature on PPT in SSA has identified various factors influencing technology adoption, including sociodemographic factors and farm characteristics (Adesina et al. 2023; Kopper and Ruelle 2022). We have also observed some of these determinants and adoption factors through our field data. Farming households with diversified income sources tend to be more confident in investing in new practices and agricultural technologies such as PPT (Adesina et al. 2023; Mwangi, Obare, and Murage 2014). Many farmers engage in other enterprises like poultry farming, selling small items in kiosks, tailoring, community health care, and other off-farm income-generating activities to meet household needs (Buleti et al. 2023). These diversified income sources make it easier for them to invest in farming and PPT. We also found further evidence suggesting that group membership had a positive impact on technology adoption (Amudavi et al. 2009; Muriithi et al. 2018). Participation in different community groups helped them learn about new practices and improved their ability to implement them. Farmers want to take advantage of and participate in many initiatives introduced to the community. Livestock ownership is another crucial factor that cannot be overlooked in the data gathered, as PPT's fodder component meets the dietary needs of livestock (Kopper and Ruelle 2022; Mwangi, Obare, and Murage 2014). Livestock serves as a financial safety net for smallholders while providing a reliable source of dairy milk for family consumption and sale. Additionally, livestock dung is used as fertilizer to improve soil and crop yields (Buleti et al. 2023). Thus, PPT practice becomes more attractive to livestock owners as they can obtain quality fodder from their PPT plots compared with those without livestock and needing animal feed. However, there are cases where farmers complained about being unable to sell excess fodder in their PPT plots, especially when they do not have livestock to feed (FGD 1 and 3). For instance, farmers with no livestock units are sometimes perceived by their colleagues as wasting their land space if they engage in growing Napier, *Brachiaria*, or *Desmodium*. Land fragmentation and ownership issues drive farmers away from long-term investment (FGD 1–4) and establishing PPT on rented land aligns with research in SSA, which shows that tenure systems influence farmers' decisions to an extent.

While our study acknowledges some of these previously mentioned adoption determinants, there is also counter-evidence that suggests these factors may overlap, contradict, or undermine each other. The theories of change underpinned by Rogers's (1962) pioneering work, which forms the basis of research and donor organizations' efforts to objectively measure change, overlook farmers' heterogeneous and interacting contexts in reality. Evaluation of technology adoption determinants as simply a decision of whether or not to implement a technology underestimates smallholders' risk management and experiential abilities, as well as changing contexts and motivations (Hermans et al. 2020; Whitfield et al. 2015; Williams et al. 2022). Farmers captured in this study made decisions regarding a practice based on several dynamic rationales, including weighing the cost/benefits and possible trade-offs associated with their decisions. Farmers like Sylvester strategically integrate vegetables in their PPT plots during short rains when market conditions are favorable. Farmers like Matilda modify the spacing and crop combinations in their PPT to maximize the use of their plots. Others adapted PPT components that suited their context, such as retaining Napier grass for animal feed but removing *Desmodium* intercrop (Cheruiyot et al. 2021; Kopper and Ruelle 2022).

Furthermore, the individual stories reveal how personal and social circumstances, such as health situations, intra-household relations, land tenure systems, and group politics, which are not captured in prior survey studies, influence farmers' decisions regarding PPT. For instance, Simon opted out of PPT based on declining health and family consensus. Paulina discontinued maize farming on her land following theft, encouraged by the visibility of her demo plot. Justina felt excluded from engaging with PPT because she was not followed up after attending an initial community meeting. These experiences demonstrate that personalized and social dynamics contexts shape decisions beyond socioeconomic characteristics and assumed motivations such as profit or technical efficacy of the technology (Whitfield et al. 2015). Therefore, recognizing diversity in farmers' decision-making patterns would enable interventions that are better aligned with local realities.

Our research underscores the need to carefully consider social dynamics and relationships to avoid exacerbating inequalities through agricultural development initiatives (Adesina et al. 2023; Hermans et al. 2020). The experiences of Paulina and Emmanuel reveal unintended social consequences that quantitative adoption studies rarely highlight. Providing inputs in the form of starter packs or incentives is common among organizations trying to scale technology. However, farmers sometimes only see a reason to try a new practice if they receive inputs as a form of support. Contrary to assumptions that groups stimulate adoption, we found that group dynamics and power relations sometimes shape decisions and limit access to knowledge about technology and practices such as PPT, thus constraining some farmers from opportunities to benefit from the practices and incentives attached to promoting the technology. For example, PPT literature recognizes leveraging lead farmers' social influence, and networks could enhance access to information and new techniques within the communities (Adesina et al. 2023; Buleti et al. 2023). However, the expected spontaneous spread of a new practice might be challenged by power relations, differences in social positions, and inequities if the implementation is not inclusive and transparent (Hermans et al. 2020; Whitfield et al. 2015). People without direct contact with R&D workers may develop a mind-set that attempting the change on their own would not be worthwhile, thus limiting engagement with such practice or technology. In addition, the experiences of farmers like Emmanuel and Justina suggest that exclusion from farmer groups and networks meant missing out on crucial training, inputs, and incentives needed to experiment with the technology long-term. They believe that some farmers with influence receive special extension attention and that similar support is required if anyone can successfully implement PPT. This emphasizes the importance of taking cognizance of social dynamics and raises concerns about the equity of resource allocation and distribution within farming communities and farmer groups, calling for adequate funding for research projects and increasing the capacity of R&D

institutions to cover many farmers for sustainable development (Whitfield 2015; Adesina et al. 2023). In addition, conscious efforts are required to ensure inclusive participation and equitable access to training programs and resource allocation (e.g., ensuring underrepresented groups are actively involved) rather than relying primarily on lead farmers to ensure that no one is left behind (Doss et al. 2018). Overall, ICIPE and other agricultural research for development programs should consider shifting away from a narrow focus on adoption metrics and innovation outcomes to more inclusive, participatory, quality innovation processes as objectives/measures of success. Relying solely on quantifiable indicators risks concealing the complex dynamics influencing farmers' decisions.

Conclusion

Our findings reinforce the notion that innovation operates as a dynamic social process, whereby farmers continuously experiment and adjust techniques to cater to diverse motivations and evolving priorities that are specific to their context. Farmers decision-making process is not straightforward but rather reflects ongoing engagement with multiple influencing factors. Their actions and decision patterns are influenced by a combination of factors, including social networks, group dynamics, changing circumstances, risk management, and available resources. Farmers navigate through these dynamics while adapting to both social-economic and environmental change. By uncovering the heterogeneity and intricacies surrounding smallholder innovation decisions, we support theoretical arguments against oversimplified adoption metrics in agricultural development programs. Findings from this study indicate the need to recognize farmers' sovereignty, ingenuity, heterogeneity, and embeddedness within social systems to develop policies and interventions that effectively support their learning capabilities and gradual practice change. Again, this research stresses the importance of inclusive participation, assessing success based on farmers' innovation journeys over time, and collaborating with farmers as partners in knowledge creation from the onset of problem identification and solution finding. Furthermore, our analysis of key informant interviews, FGDs and field observations demonstrates the value of qualitative research methods to elucidate the realities surrounding smallholders' agricultural innovation practices that reductionist adoption metrics overlook. By tracing the experiences of individuals and subgroups, we can identify uneven access and social exclusion, aspects that aggregated survey data may not capture. Ultimately, scaling biocontrol technology such as PPT in SSA requires placing farmers' diverse realities at the center of innovation processes, rather than striving for universally applicable technological fixes. We hope that these perspectives will stimulate projects, programs, policies, and initiatives that embrace farmers' diversity and unique contexts to strengthen African food systems.

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Statements and declarations

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Ethics and consent statement

Approval for this study was obtained from the Faculty of Environment Research Ethics Committee at the University of Leeds [AREA FREC 2023-0457-401]. The research participants provided their consent and were assured anonymity by using pseudocodes. Furthermore, the National Commission for Science, Technology and Innovation (NACOSTI) granted clearance for this research to be conducted in Kenya [NACOSTI/P/22/18845].

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