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Farmers' perceived pathways for further intensification of push-pull systems in Western Kenya

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Push-pull technology provides farmers in East Africa with an eco-friendly strategy that increases crop yield and household income in smallholder cereal systems by controlling pests and improving soil health. Though promising for a sustainably intensified production, push-pull has been used at limited scale, primarily in maize- and sorghum-based production systems. Expanding the scope, applicability and acceptance of the practice in smallholder farming systems, will leverage the full potential of push-pull as a widely applicable sustainable farming practice. Using key informant interviews and focus group discussions, we explored farmers' needs and perceived pathways for integrating push-pull and other sustainable intensification practices in synergy with existing cropping systems in Kisumu, Vihiga and Siaya Counties in Western Kenya. We found that farmers in the region typically grow and intercrop a variety of crops, with maize being the most common crop. Farmers commonly practice crop-livestock farming, intercropping, crop rotation, manure and fertilizer use, and use improved varieties to increase maize production. Across the counties, integration of food legumes, agroforestry and crop-livestock farming, were identified as fundamental pathways for stretching the benefits of push-pull. Limitations to farmers' aspirations and key enablers for facilitating spontaneous adoption of identified sustainable intensification practices for push-pull farming systems are discussed.

KEYWORDS

push-pull technology, crop-livestock farming, legume integration, agroforestry, sustainable intensification, eco-friendly farming, smallholder cereal system

1. Introduction

Smallholder agriculture is the mainstay of agricultural production and food security for millions of rural populations across the world (Poole, 2017). In Sub-Saharan Africa (SSA), almost 80% of farms are under 2 hectares (Lowder et al., 2016). Of these, about 12.85 million household farms are classified in the subsistence production domain (*ibid*). However, smallholder agriculture is gradually being transformed into more productive and profitable enterprises that can increase food security and household income (Gassner et al., 2019). Much effort has been invested in increasing agricultural productivity in SSA, for example, through implementation of innovative sustainable agronomic practices (Kuyah et al., 2021). Despite decades of these efforts, yield gaps persist in the region. Thus, most smallholder farmers remain poor and food insecure (Droppelmann et al., 2017). Yet, sustainable agriculture is expected to provide food, fodder, fiber, fuel, and feedstock, and assist people escape poverty (Gassner et al., 2019). Agriculture in Africa is expected to meet the dual objectives of providing food and helping people to escape poverty. African agriculture is dominated by smallholdings and donors generally target their agricultural support at the smallholder sector. The expectation is that if the gap between actual and potential yields can be closed, smallholders will grow sufficient crops to feed their families, with a surplus to sell, thus meeting food security needs and bringing in an income to move them out of poverty. While technologies already exist that can raise smallholder farmers' yields 3 or 4 times, even under rainfed conditions, the small size of land available to them limits how much can be grown and the *per capita* income from agriculture is insufficient to allow people to move above the current World Bank-defined poverty line of US$1.90 per day. We link this finding with farmer typologies to further explain that there are large differences between individual farming households themselves in terms of their investment incentives and capability to benefit from field-level technologies that are aimed at increasing farm productivity. We argue for more differentiated policies for agricultural development in Africa and suggest that policymakers should be much more aware of the heterogeneity of farms and target interventions accordingly. It is important to understand where and for whom agriculture will have the main purpose of ensuring food and nutritional security and where and for whom there is the potential for significant increases in incomes and a contribution to wider economic growth. Researchers and policy makers should recognize the distinctiveness of these targets and underlying target groups and work towards solutions that address the underlying needs.

Cereals, particularly maize (*Zea mays*) and sorghum (*Sorghum bicolor*), are among essential staples grown by millions of smallholder farmers throughout SSA; others include rice, wheat and millets such as pearl millet (*Penissetum galucum*) or finger millet (*Eleusine coracana*). Their efficient production in the region is however constrained by many factors, including pests and diseases, soil infertility and climate change. Lepidopterous insects comprising stemborers (*Busseola fusca*) and the invasive fall armyworm (*Spodoptera frugiperda*) are the most damaging maize insect pests. They cause yield losses of 8.3–20.6 million tons annually (De Groote et al., 2020). Parasitic weeds in the genus Striga (e.g., *Striga hermonthica*) also constrain cereal production in the region, causing up to 100% maize yield losses. The severity of these constraints is aggravated by poor soil fertility and the effects of climate change (Midega et al., 2018; De Groote et al., 2020).

Several technologies have been deployed to address the problems of agricultural pests and soil infertility. These technologies include application of biological control methods like the push-pull technology (Hooper et al., 2015), insect-resistant maize for the management of pre- and post-harvest pests (De Groote et al., 2010), use of fertilizers and manures to improve soil fertility, and herbicide-resistant maize for managing parasitic striga weeds (Tefera et al., 2016; Tambo et al., 2020). While the practices can increase crop productivity when pest control and soil fertility are enhanced, some are limited by yield trade-offs and environmental regulations. For example, many chemical pesticides are discouraged as they are harmful to human health and other beneficial organisms such as pollinators (Biondi et al., 2012). The development of pest control strategies, including integrated pest management, that provide additional ecosystem services represents an important component of efforts to sustainably improve food security in SSA (Snapp et al., 2021). Another limitation relates to the prevalent application of inorganic fertilizers, which are known to boost crop yields in the short term, but lose their effect over time. This is partly due to the non-responsive nature of soils in western Kenya (Njoroge et al., 2017), caused by low soil organic carbon. Hence, improving crop production while reversing environmental degradation and restoring ecosystem services are becoming the focus of poverty alleviation efforts in SSA (Droppelmann et al., 2017).

One of the eco-friendly approaches to managing the constraints of cereal production in eastern Africa is the push-pull technology. Originally developed and introduced by the International Centre of Insect Physiology and Ecology (ICIPE) and partners more than 20 years ago in western Kenya, Push-Pull Technology (PPT) is an agroecological management strategy rooted in the "Stimulo-deterrent Diversion" concept of (Miller and Cowles, 1990). In PPT, behavior-modifying stimuli from bioactive volatiles produced by companion plants regulate the abundance and distribution of pests and other beneficial insects (Khan et al., 1997; Sobhy et al., 2022). This companion cropping system intercrops cereal crops with forage legumes in the genus *Desmodium* (commonly called desmodium) and a forage grass, e.g., *Brachiaria mulato* II (commonly called brachiaria) as a border crop. Repellant plants like desmodium emit volatile organic compounds that drives away gravid moths ('push'), while the grass border emits compounds that attracts the moths ("pull"), providing an alternative oviposition substrate that inhibits larval development (Chidawanyika et al., 2014). This mechanism controls stemborers and fall armyworms (Chidawanyika et al., 2014; Midega et al., 2018; Erdei et al., 2022). Desmodium also suppresses the parasitic striga weed through a variety of mechanisms, most importantly allelopathy. Root exudates of desmodium contain novel isoflavanones, that induce abortive germination or inhibit radicle growth of striga seeds (Hooper et al., 2015) resulting in suicidal germination of striga and depletion of the seedbank in the soil (Khan et al., 2008). Desmodium also improves soil health through biological nitrogen fixation, increasing organic matter input from residues, improving phosphorus availability, and conserving moisture (Drinkwater et al., 2021; Ndayisaba et al., 2021). Other benefits of push-pull include improved abundance and activity of arthropods, some of which help biological pest control while others break down plant materials into humus. These benefits boost grain yields, while grasses and desmodium provide fodder, enabling crop-livestock integration. These demonstrated benefits of PPT systems drive the impetus to expand PPT to other crops and cropping systems, and to other geographical regions, each with their own set of challenges and requirement (Lang et al., 2022).

Push-pull technology has been shown to significantly increase smallholder farmers' income and food security (Khan et al., 2008; Kassie et al., 2018). Its uptake by farmers, however, lacks parity with these demonstrated benefits. In East Africa, farmers have been applying push-pull technology majorly in maize and occasionally in sorghum (Khan et al., 2014). This is partly likely to be due to the lack of options for integrating the technology with other crops like vegetables, and to compatibility with other sustainable farming practices such as crop rotation (Chidawanyika et al., 2023). In addition, the pressures on land available for other food and cash crops constrain the adoption and expansion of push-pull practices (Niassy et al., 2022). Further intensification of push-pull system may enable synergistic benefits that would improve farmers' livelihoods, food security, and the environmental sustainability and resilience of the farming system. However, to date, no published information exists on what practices and crops farmers would like to integrate into push-pull systems. A participatory needs assessment is required to identify potential practices and crops that could expand the scope of push-pull beyond cereal production and fodder components on small plots. This study aims to fill this gap by participatively exploring farmers' perspectives on the push-pull system and its compatibility with other smallholder sustainable intensification practices, in order to identify farmers' needs and preferences for further intensification of the push-pull system.

2. Materials and methods

2.1. Study site

The study was carried out in Kisumu, Siaya, and Vihiga counties in western Kenya. The three counties represent areas of contrasting socio-ecological conditions. Socio-ecological conditions do influence the cultivation of specific food crops and specific tree crops, e.g., cultivation of *Erythrina abysyinica* tree in Vihiga county which is believed to cure mumps.

The Kisumu site is located at latitude 0°20′–0°50'S, longitude 33°20′–35°20′E, with an elevation range of 1,134–1,400 m; Siaya site is located at latitude 0°00–0°06'S, longitude 34°16′–34°23′E, with an elevation range of 1,200–1,500 m; Vihiga is located at latitude 0°00′–0°30'N, longitude 34°40′E–34°43′E, with an elevation range of 1,300–1900 m. Rainfall in western Kenya ranges between 1,200 and 2,763 mm *per annum* in Vihiga, 1,000 and 1800 mm in Kisumu, and 800 and 1,600 mm in lower areas of Siaya. The long-term and short-term average annual rainfall and temperature across the three counties is shown in Table 1. There are two main cropping seasons in western Kenya, corresponding to the long rains (received between April and July) and the short rains (received from September to December). The onset of rainfall in the counties is variable and unpredictable. For example, the short rains of 2021 began in early August in Kisumu, late August in Vihiga, and mid-September in Siaya. In 2022, the onset of long rains, occurred end of March 2022 in Vihiga and mid-April in Siaya and Kisumu.

The counties are also areas of widespread cereal production by smallholders, but where cereal production is constrained by striga, stemborers, and fall armyworms. Vihiga has a high population density and is characterised by very small farms (on average 0.41 ha per household) that are intensively farmed (County Government of Vihiga, 2018). Kisumu is characterised by medium-sized farms, on average 1.0 ha per household (County Government of Kisumu, 2018) while Siaya is characterised by relatively large farms, on average 1.5 ha per household (County Government of Siaya, 2013). Despite the prevalence of the triple challenges of pests, weeds and poor soil fertility for cereal production, agriculture remains the mainstay in the region through farming, herding, fishing, and related enterprises such as bee keeping.

2.2. Selection of participants

Participatory needs assessment through focus group discussions (FGD) and key informant interviews (KII) were used to identify crops and cropping systems and available sustainable intensification practices in the region. A sampling frame consisting of a list of all farmers known to practice push-pull in each of the three counties was obtained from the International Centre of Insect Physiology and Ecology (ICIPE), Thomas Odhiambo campus. ICIPE has been disseminating PPT and has maintained a database consisting of the details of the farmers, names, and locations of the initial adopters of the push-pull technology. These records provided a sampling frame from which we selected push-pull farmers located in the study area. These farmers were practicing or had practiced push-pull farming for several years to manage stem borers, striga weed and, more recently, fall armyworm in their cereal farms. These farmers also have a better understanding of the technology from the experience of using push-pull, which provides a basis for comparison. From the sampling frame, 15 farmers currently practicing, or who had previously practiced the push-pull system were randomly selected in each county. An additional 15 farmers who were not practicing (and had never practiced) push-pull technology were randomly selected from the lists provided by lead farmers (for this context, a lead farmer is one who is familiar with the community, understands various sustainable farming practices, and has participated in different agricultural projects, including push-pull related projects), community leaders, and field assistants in each county. Care was taken to maintain a minimum distance of at least 500 m (or at least five households) between farmers, to avoid selecting participants from the same family.

We conducted ten FGD comprising nine groups of farmers (summing up to 85 participants) and one group of field technicians (summing up to seven participants). Each FGD comprised 7 to 12 participants, ensuring approximately 50% gender representation; except for the field technician group which was comprised only of men. Field technicians were selected based on their role in implementation of push-pull or other sustainable intensification practices (e.g., agroforestry and organic farming) and their involvement in agriculture in the region. Meetings with farmers took place at the homesteads of lead farmers in nine villages: Ebusatsi, Emakunda, and Mwikusi villages in Vihiga County; Kosio, Marera, and Yenga villages in Kisumu County; and Ng'ayo, Komonge, and Ndira B villages in Siaya County (Figure 1). Participants selected for KII comprised women and men, commodity traders (input suppliers),

TABLE 1 Periodic (1982–2016) and annual (2017–2022) average rainfall and temperature in Western Kenya.

Year	1982–2016	2017	2018	2019	2020	2021	2022
Rainfall (mm)	1765.8	1961.8	2216.2	2530.8	2763.4	1754.5	735.2
Temperature (°C)	23.1	23.4	22.6	23.0	22.5	23.0	23.2

Rainfall for 2022 was estimated over four months (January – April).

FIGURE 1
Location of villages (venues) where focus group discussions were conducted in Kisumu, Siaya, and Vihiga counties in Western Kenya. Nine village-level meetings were held between May and August 2021; a 10th meeting with field technicians was conducted in Kisumu.

lead farmers, local leaders (e.g., Assistant Chiefs or Chiefs), agricultural extension officers (government officials within the agricultural sector who are tasked with training, informing and also offering services to farmers within a sub county region), advisory providers (i.e., NGOs involved in technology transfer) and researchers. We selected key informants purposively for the specific information they possessed based on their involvement in agriculture or agribusiness in the region. Twenty-five key informants participated in the interviews held physically (15 participants) and virtually (10 participants) based on the convenience and adherence to the COVID 19 protocol of the Ministry of Health, Kenya. In a second stage, the validation and ranking of the FGD data were performed within the same region. Ninety-nine participants were selected to participate in ranking crops and highlighting their suitability for sustainable intensification in push-pull systems. These 99 participants comprised the 85 participants in the focus group discussion and 14 extra farmers from the same study site who had not participated in the focus group discussions for various reasons, including non-availability and also, to a parsimonious number of FGDs for ease of analysis. The 14 extra farmers were selected for validation because they met the same criteria for selection of FGD participants, i.e., they are cereal farmers, and their farms have a history of the triple problems of poor soil fertility, stem borer pests, and the striga weed. They were also willing and able to participate in the validation of the results of FGD.

2.3. Data collection and analysis

A questionnaire was developed and used to guide the FGD and KII. Detailed information was captured on crops and cropping systems, available and preferred sustainable intensification practices, motivation for particular crops or cropping systems, farmers' knowledge and aspirations, and support systems. The interview sessions were facilitated by a team of trained research assistants (comprising a moderator and a note/record keeper) and supervised by the researchers. During the FGD, researchers presented the objectives of the exercise, explained the role of various stakeholders, and highlighted the procedures for communication. Participants were encouraged to use a language with which they were most familiar and comfortable. Where a participant used the local/ native language, a member of the team most versed with the dialect served as an interpreter. Prior to the study, ethical approval was provided by the Independent Ethics Regulation Committee (IERC) of Jomo Kenyatta University of Agriculture and Technology (JKUAT). JKUAT's IERC is authorized by the National Commission for Science, Technology and Innovation (NACOSTI) to issue an approval for research in Kenya on its behalf. To ensure a free, prior and informed consent, a written consent statement to participate and to allow recording of sessions was distributed and explained, and verbal consent was obtained from participants prior to all discussions. A similar approach was used for the key informant interviews. Each FGD session and KII lasted approximately 1 h or until no new information was forthcoming. Validation of the FGD data was carried out with 99 farmers (41 in Vihiga, 30 in Kisumu and 28 in Siaya). The validation tool was a questionnaire developed based on data collected from the FGD and KII. Farmers were asked to rank food crops, tree crops, intensification practices and benefits from the crops. All responses per question across the counties were anonymized and combined for each group. The data were organized into structured data sheets and then cleaned. The responses were categorized into four major themes and patterns were established based on the responses to the questions per group or key informant. The number of times various themes were mentioned in a group or by key informants was used

TABLE 2 Crops grown and livestock kept by farming households in Kisumu, Siaya, and Vihiga counties in western Kenya.

Crop/animal classification	Crops/animals
Cereals	Maize (10), sorghum (5), millet (4)
Grain legumes	Common bean (10), cowpea (*Vigna unguiculata*) (8), soybean (7), green gram (*Vigna radiata*) (2), pigeon pea (*Cajanas cajan*)
Tubers	Sweet potato (10), cassava (10), arrowroot (*Colocasia esculenta*) (2)
Fruits	Avocado (*Persea americana*) (5), mango (*Mangifera indica*) (6), pawpaw (*Carica papaya*) (4), watermelon (*Citrullus lanatus*) (2), banana (8), citrus spp.
Indigenous vegetables	Amaranth (3), African nightshade (*Solanum* spp.) (7), cowpea (8), spider plant *(Cleome gynandra) (5)*, crotalaria (*Crotalaria* spp.) (1), jute mallow (*Corchorus olitorius*) (3), Ethiopian Kale (*Brassica carinata*) *(1)*
Exotic vegetables	Collards (*Brassica oleracea*) (7), spinach (*Spinacia oleracea*) (2), spring onion (*Allium fistulosum*) (1), bulb onion (*Allium cepa*), tomato *(4)*, carrot (*Daucas carota*), coriander *(Coriandrum sativum)*, spices
Fodder crops	Napier grass (*Pennisetum purpureum*) (5), Brachiaria (5), Desmodium (5), Lucerne
Oil crop	Sunflower (*Helianthus annus*), groundnut *(10),* Bambara nut (*Vigna subterranean*) (1), sesame (*Sesamum indicum*) (1)
Cash crops	Tea (1), coffee (1), cotton (*Gossypium herbaceum*), sugarcane (*Saccharum officinarum*) (1), rice (1), sisal (*Agave* spp.), cassava and hibiscus (1)
Trees and shrubs Livestock and poultry	*Grevillea robusta (5), Calliandra calothyrsus (5), Markhamia lutea (3), Leucaena leucocephala (2), Sesbania sesban (4), Eucalyptus* spp. (3), *Tithonia diversifolia (1), Moringa oleifera (1), Casuarina equisetifolia*, *cypress* spp. (1), *Croton* spp., and *Maesopsis eminii* Cattle, goats, sheep, donkeys, chicken, quails, turkey, guinea fowls and rabbits

The list represents all the crops grown and livestock mentioned during the ten focus group discussions. The type of crop or livestock differ between farmers and counties. The numbers in brackets represent the number of discussion groups that mentioned the crop or animal. Those crops or animals without numbers were mentioned only by key informant.

as a frequency measure. The data were analysed in Microsoft Office Excel. The results are discussed based on the themes emerging from the guiding questions.

3. Results

3.1. Crops and cropping systems

The study revealed that farmers in Kisumu, Siaya and Vihiga produce a variety of crops, including cereals, legumes, tubers, fodder crops, exotic and indigenous vegetables, fruits, trees and shrubs, cash crops, and oil crops (Table 2). According to the farmers and field technicians, maize and common bean (*Phaseolus vulgaris*) are the main crops cultivated in the region, though a respondent in Vihiga, reported a shift from maize cultivation to banana (*Musa* spp.) production because the latter is more profitable. Field technicians reported groundnut *(Arachis hypogaea)*, sweet potato (*Ipomoea batatas*) and banana as common across the three counties; tea (*Camellia sinensis*) and coffee (*Coffea arabica*) are common in Vihiga; soybean (*Glycine max*), rice (*Oryza sativa*) and tomato (*Solanum lycopersicum*) are common in Kisumu; while sorghum and cassava (*Manihot esculenta*) are common in Siaya. Similarly, key informants reported maize (25/25), common bean (20/25) and groundnut (15/25) as the most common crops in the region. A slight variation in crop production per county was reported by farmers for sweet potato in Kisumu, sorghum in Siaya and banana in Vihiga. These crops are grown in six identified "cropping systems," which we define here as a specific type of crop combinations or practices used on a farm. Different cropping systems are sometimes nested on the same farm within the same field, or on different parcels. The cropping systems highlighted in the FGD and KII include intercropping, crop rotation, monocropping, crop-livestock farming, agroforestry, and push-pull technology.

Crops and cropping systems are usually selected based on land availability and farmers' preferences. Farmers with relatively large farms, for example, 3 to 10 acres in Siaya (reported by technicians) tend to practice monocropping and crop rotation, while those with small farms (less than 1 acre) prefer intercropping. Maize and sorghum are intercropped or rotated with common bean, groundnut or cowpea and occasionally with tubers such as sweet potato or cassava. Here, monocropping involved pure stands of maize, vegetables, sorghum, common bean, soybean or groundnut. This practice was popular among farmers who want to mechanize production, those involved in agricultural projects with specific requirements, commercial farms, or among farmers who simply want to minimize crop competition. Crop rotation also occurs at the plot-level (e.g., in kitchen gardens), where maize is alternated with indigenous vegetables. There is now a shift from the production of vegetables in kitchen gardens to commercial scales, especially for indigenous African vegetables. All cropping systems mentioned by the farmers but one (i.e., monocropping) were also cited as sustainable intensification methods that they use to increase the productivity of their farms in an environmentally-friendly way.

Respondent farmers cultivate specific crops for income, fodder, firewood and fruits. Cash and oil crops (Table 2) are important sources of income and also provide raw materials utilized in neighbouring industries. Fodder crops are grown for own livestock use and for sale. Fodder crops may be grown in monocrops or as intercrops for particular purposes; for example, desmodium, Napier grass and brachiaria are grown as components of the push-pull system. Most farmers grow diverse trees species on-farm (Table 2). Trees and shrubs are mainly cultivated for income, firewood and fruits. Some trees are included in crop fields (e.g., *Grevillea robusta*) while others are planted in woodlots (e.g., *Eucalyptus* spp. in Vihiga) or along boundaries (e.g., *M. lutea*) depending on farmers' needs and knowledge. Cattle, goats, pigs, sheep and chicken were reported as the most common livestock and poultry in the region (Figure 2).

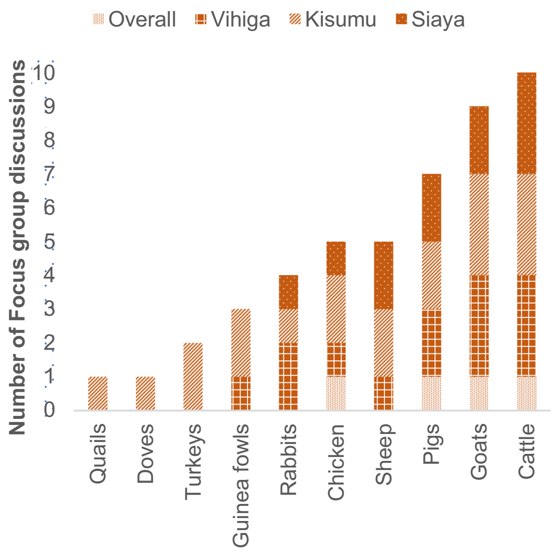

FIGURE 2
Livestock and poultry mentioned during focus group discussions in Western Kenya. All the groups mentioned ownership of cattle but dairy cattle and dairy goats were specifically mentioned in two groups in Siaya and by field technicians. "Overall" represents the field technician group who mentioned the livestock that are common in the region.

Farmers in the region occasionally practice fallowing (for a few months or several seasons) and use the fallow portions of their land as grazing fields to improve soil fertility. Respondent farmers are aware of climate variabilities and embrace a variety of adaptation strategies. They plant maize during the long rain season and common beans or cowpea during the short rain season to mitigate the effect of heavy rains on legumes, increase income and diversify diets. Farmers use both local and improved varieties. The majority perceived local varieties to be tolerant to pests and resilient to drought; those who used improved varieties cited uniform maturity and high yield as the main motivation. Key informants highlighted that the use of improved varieties is higher in Vihiga than in Kisumu and Siaya.

3.2. Sustainable intensification practices in the region

Respondents mentioned poor soil fertility, pests (such as stemborer, fall armyworm, and termites), and high cost of inputs as major constraints to crop production. They were also aware of, and mentioned several practices they are using to address these challenges and increase crop yield without increasing the area of cultivation (i.e., intensification practices, many of which are seen by the farmers as sustainable while others are not; Table 3). Intercropping, crop rotation, use of organic manure and use of inorganic fertilizer were mentioned as common intensification practices by 9 out of 10 groups; 7 out of 10 reported using improved varieties and monocropping, whereas 6 out of 10 groups reported crop-livestock farming (Figure 3). Conservation agriculture, agroforestry and fallowing were more rarely reported in FGD as commonly practiced intensification practices. In contrast, key informants mentioned push-pull (15/25), use of improved varieties (9/25) and agroforestry (8/25) as commonly available intensification practices. According to key informants, practices are considered sustainable if they conserve the soil, address fertilizer and seed resource needs, and improve soil nutrients. According to this perception, 9 out of 12 practices and cropping systems were explicitly considered as sustainable by key informants, whereas practices not seen as sustainable by key informants could be considered so by farmer respondents (Table 3). We thus note that the concept of sustainable intensification was not always well understood or agreed upon among the respondents.

3.2.1. Farmers' motivation for sustainable intensification

Subsistence (food) and income generation are the main reasons for intensification of farming systems in Kisumu, Siaya and Vihiga counties. Other motivations include improved soil health, management of pests, higher crop yield and food security, and fodder provision (Tables 3, 4). The respondents mentioned intercropping and crop rotation as the main strategies for improving crop yield, increasing the number of harvestable products, and ensuring food security. They intercrop common bean and/or vegetables with maize as a means of ensuring food security. The former matures before maize, providing food when cereal stocks are depleted; the latter (e.g., kales) is harvested across seasons for food or income. Intercropping is also used to reduce chances of total crop failure. Crops such as cassava and sweet potato act as a safety net during hunger as they can be stored *in situ*; others such as sorghum and millets are preferred for their nutrition and perceived medicinal value. Farmers were aware of the role of legume-based intercropping (e.g., cowpea, common bean, groundnut, and soybean) for nitrogen fixation. Intercropping with tuber crops, such as sweet potato, was mainly aimed at soil conservation. Inorganic fertilizers are used alone by farmers who do not have livestock and are not able to purchase manure. The incorporation of green manure from shrubs (*T. diversifolia* and *Tephrosia vogelii*) and residues from intercrops or rotated crops is also practiced. Motivations that were specifically reported by key informants include income from sale of seeds, food security and mitigation of climate change effects.

Livestock, poultry and bee keeping enterprises are employed to diversify farm productivity and nutrient cycling. These enterprises provide manure, meat, milk, and honey for subsistence and sales. Sale of livestock and poultry (both local and improved) is perceived as an easy source of income; to cater for emergencies such as school fees or buy other items that are not produced on farms. Agroforestry is common in the region, owing to the need for firewood, fodder, fruits, and other tree products (Table 2). *Calliandra calothyrsus, Leucaena leucocephala, Sesbania sesban,* and *Tithonia diversifolia* were identified as the most common trees for meeting the dual needs for fodder and firewood. Fruit trees are beneficial for food and income through the sale of fruits, firewood and timber. Other benefits of trees include medicinal purposes (Moringa and Tithonia), windbreaks, shade, erosion control, soil moisture conservation, source of green manure and also as a youth and women empowerment tool. One key informant (in Siaya) reported having trees to provide nectar for bees. Several ecological benefits of trees were reported by key informants *viz.* soil fertility improvement, nutrient cycling, protection of river banks, and cultural ecosystem services such as aesthetic (ornamental) and boundary demarcation. Agroforestry, crop-livestock integration and use of manure are some of the preferred intensification practices for environmental friendliness.

TABLE 3 Cropping systems and practices for yield improvement identified through elicitation during participative focus group discussion in Western Kenya.

Cropping system (*)/ sustainable intensification ($)/ intensification practice (#)	Description	Motivation for the practice	Limitations
Intercropping*$	Cultivation of two or more crops on the same piece of land at the same time. For example, maize and common bean (most common), maize and other legumes (cowpea, soybean, or green grams) or maize and vegetables (emerging)	Minimize risk of total crop failure, increase harvestable products, diversify income, reduces cost of inputs	Difficulty in management such as weeding
Crop rotation*$	Growing single or mixed crops in succession on the same piece of land. For example, maize in the first season followed by a legume (e.g., common bean) or another crop (e.g., sweet potato) in the second season.	Reduce soil compaction	It is not possible with perennials such as desmodium or trees
Monocropping*#	Growing of a single crop exclusively, and also in successive seasons, on a piece of land.	Higher yields in the short-term, easier management of pests	Lower yields in the long-term, soils become vulnerable to erosion, risk of total crop failure.
Crop-livestock integration*$	The combination of crop cultivation with livestock and or poultry farming.	Increase farm productivity, reduce external inputs (fertilizer, manure and animal feed).	Labor intensive because of multiple activities
Agroforestry*$	An integration of woody perennials around or within crop fields or pastureland.	Provides multiple products and services, currently used for youth and women empowerment	Lack of seeds and seedlings, takes longer to realize benefits.
Push-pull technology*$	A companion cropping system that involves intercropping maize with a forage legume (desmodium), and planting a forage grass (brachiaria) around the intercrop. Vegetable integration is still in the experimental phase.	Improve crop yield, control of insect pests (stemborer, fall armyworm), regulate striga weed, and improve of soil fertility, provide fodder	Currently restricted to maize in small plots, labor intensive, seeds are expensive and not readily available, desmodium can become weedy
Use of improved varieties$#	Cultivation of improved varieties for different crops	High crop yield	Heavily depends on external inputs, prone to pests (e.g., maize weevils), affected by the existence of poor seed quality in the market and farmers' preference for local varieties
Conservation agriculture$	A set of soil management practices that minimizes soil disturbance and maintains permanent ground cover (e.g., with crop residues or live mulches, use of grass leaves or other material).	Soil conservation, improve yields	Lack of knowledge on the practice, competing needs for residues, residues makes ploughing or planting difficult, some cover crops do not have immediate benefits to the farmer
Manures$	Application of compost (rotted organic matter made from waste residues from plants), farmyard manure (decomposed mixture of dung and urine of farm animals along with litter and leftover material from roughages or fodder fed to the cattle) or green manure (leafy biomass, e.g., from *T. diversifolia* incorporated in the field prior to planting).	Improves overall soil health, makes the farm resilient to drought and floods, adds organic matter	Requires knowledge on composting process and material for composting, is time consuming, labor intensive and bulky to transport. Inadequate material for composting

(Continued)

TABLE 3 (Continued)

Cropping system (*)/ sustainable intensification ($)/ intensification practice (#)	Description	Motivation for the practice	Limitations
Inorganic fertilizer$#	Use of inorganic fertilizers during planting and top-dressing, mainly Di-ammonium Phosphate (DAP) or Calcium Ammonium Nitrate (CAN), respectively	Improves crop yield in the short term (first two seasons)	Reduces crop yield in the long-term, poor soil health when used extensively over time, expensive to purchase
Good agronomic practices$	A set of agricultural practices that are aimed to achieve maximum productivity, including right choice of seed, proper spacing, proper timing	Increases crop yield, mitigate effects of climate change	Limited knowledge and skills, time consuming for proper spacing
Fallowing*#	A set of farming practices whereby arable land is left uncultivated for seasons or years.	Improve soil fertility, soil moisture retention, pest management	Limited size of land to allow fallowing

We classified the data in a manner such that, the asterisks (*) indicate practices mentioned by respondents as a cropping system, the dollar sign ($) indicates practices considered by respondents to be sustainable intensification practices, and (#) indicates intensification practices not considered to be sustainable. Monocropping, use of inorganic fertilizers and use of improved varieties are intensification practices, which some, but not all farmers perceived as sustainable.

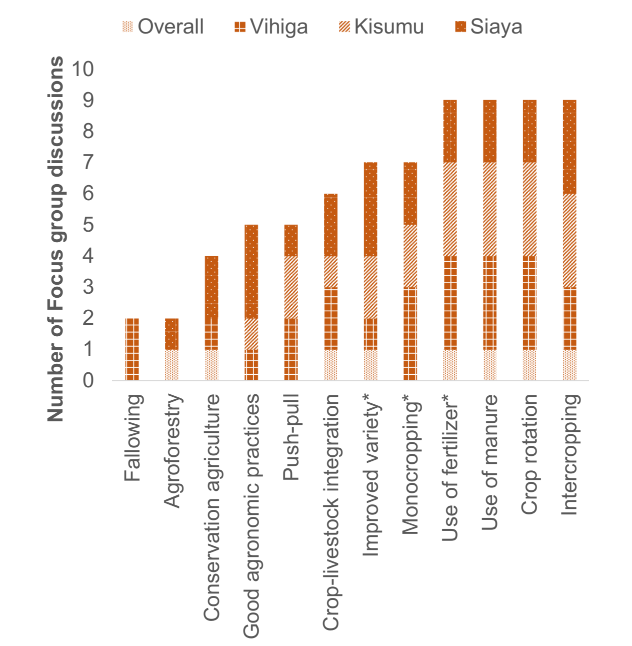

FIGURE 3
Approaches used by farmers in Western Kenya to increase the yield of maize without expanding the area under cultivation and while conserving the environment. Descriptions of the practices are provided in Table 3. "Overall" represents the field technician group who mentioned the practices that are common in the region. Practices with asterisks (*) are intensification practices mentioned by farmers that are considered sustainable by some, but not all farmers.

3.2.2. Factors limiting the adoption of sustainable intensification practices

Despite the benefits of sustainable intensification, farmers still face several challenges (Table 3). Limited knowledge and skills about emerging technologies, land tenure and ownership, high initial costs, and poor targeting of technologies were the main challenges associated with the adoption of such practices. Farmers cited that they lack the requisite skills and training in sustainable intensification and specifically for adoption of agroforestry and conservation agriculture, and for the management of push-pull. Competing needs for food, fodder and firewood were mentioned alongside shortage of land; this would favor intensification such as intercropping as opposed to crop rotation. Furthermore, land is traditionally owned by men and inherited by children, often sons. Land issues were enumerated along with socio-cultural norms about gender, ownership and especially on decision making about the use of land. Often women are the ones who work on the farms but men make the decision on what is grown. Land ownership problems were also cited, for example on leased parcels, where the owner restricts how the land is being used and may not allow growing of perennial crops. In other cases, the land owner may call off a leasing agreement when a project has been implemented but they are not interested in the posterity of the project. Regarding the targeting of technologies, respondents are reluctant to adopt a technology that does not meet their immediate needs such as food, income and firewood. As a result, farmers often elect to implement technologies with a clear benefit in the short term (such as additional food from intercropping with beans, for example) rather than a long-term benefit with potential costs at implementation (e.g., agroforestry, push-pull technology).

High cost and low availability of farm inputs restrict farmers from integrated soil fertility and pest management through the inclusion of fertilizers, manure, and pesticides. Application of fertilizers was perceived as the quickest way to improve the soil fertility in the medium term, but the yields tend to decline over time. Although preferred, the use of manures as a sustainable intensification practice is limited because of lack of knowledge on and material for composting, and due to high labor intensity of this practice.

3.3. Push-pull technology: awareness, benefits, and limitations

On average, 95% of respondents were aware that push-pull technology was introduced to control maize stalk borers, eliminate

TABLE 4 Ranking of priority crops and sustainable intensification practices (ordered in decreasing preference) in Vihiga, Kisumu and Siaya county, based on the validation questionnaire of 99 farmers developed from initial FGD and KII data.

	Vihiga (41 farmers)		Kisumu (30 farmers)		Siaya (28 farmers)	
Sustainable intensification practices	Crop-livestock integration, intercropping, crop rotation		Intercropping, Crop-livestock integration or crop rotation		Crop-livestock integration or intercropping, crop rotation	
Priority crops produced	Maize, common bean, banana		Maize, common bean, sweet potato		Maize, common bean, sorghum	
Crop benefits	Maize: food, income, fodder		Maize: food, income, fodder		Maize: food, income, fodder	
	Common bean: food, income, fodder		Common bean: food, income, improved fertility		Beans: food, income, manure or composting	
	Bananas: food, fodder, income		Sweet potato: food, income, improved soil fertility		Sorghum: food, income fodder	
Overall priority benefits (%)	Food	75	Food	95	Food	98
	Income	66	Income	73	Income	88
	Fodder	40	Fodder	22	Fodder	18
Priority trees	Eucalyptus, Grevillea, Makharmia		Grevillea, Eucalyptus, Markhamia		Grevillea, Markhamia, Mango	
Tree benefits	Eucalyptus: income, firewood, construction material		Grevillea: construction material, income, firewood		Grevillea: timber, income, construction material	
	Grevillea: firewood, income, construction material		Eucalyptus: income, timber		Markhamia: income construction material/ timber, firewood	
	Makharmia: firewood, construction material, income		Markhamia: construction material, firewood, income		Mango: food, income, firewood	

striga weed and improve soil fertility, although only a few currently practice it on their farms. Some respondents started practicing and stopped after some seasons when support (e.g., free inputs) ceased or a project ended; a few (5%) others had never heard about or practiced push-pull technology. Respondents who practiced push-pull emphasized the positive impacts on crop production and provision of fodder (Table 3). In addition to the products and services from push-pull systems, participants who are farmer teachers (i.e., experienced farmers trained for various projects by different research and educational institutions, e.g., ICIPE on push-pull technology, and developmental NGOs. In most cases, they are the pioneer adopters of a technology) and opinion leaders noted that sharing their experiences with push-pull through radio, farmer field schools, and exchange programmes contributed to building their social capital.

The respondents identified several weaknesses limiting the application of push-pull technology (Table 3). They consider push-pull technology to be a labour-intensive technology. It takes longer to maintain a push-pull plot (carefully removing other weeds without damaging the desmodium) compared to non-push-pull plots, although the effort could be leveraged elsewhere if the weeding is used to get fodder for livestock. Because of the perennial nature of the companion plants, deep ploughing on the whole plot is not practical, and this leads to soil compaction and couch grass establishment in the push-pull plots. The lack of adequate knowledge about the management of push-pull plots has greatly contributed to the perception in our study area that push-pull plots are 'specially dedicated plots for research' and that local livestock breeds cannot feed on desmodium, even though desmodium actually represents a prime fodder rich in protein (Khan et al., 2008; Kassie et al., 2018). Even though the total productivity of an average push-pull field is high, farmers pointed to the existence of trade-offs between food crops and fodder. By their submission, the fodder component occupies a large fraction of the push-pull plot, which may not be appealing for farmers who do not have livestock. Besides, some farmers lack market for the fodder; a component which they think can be incorporated in the system for better results. Push-pull fields are (re-)established every season, for example, in areas where livestock freely graze in crop fields after harvest (e.g., Alego Usonga in Siaya and Seme in Kisumu), thereby compromising the original perennial design. This limits the ecological functions of push-pull, and increases the costs of establishment and maintenance.

3.4. Options for adaptation and further intensification of push-pull technology

Farmers identified 18 priority crops to meet their needs through ranking (Table 4). Among these, maize (90%), common bean (49%) and banana (37%) were mentioned as the top priority crops in Vihiga; maize (97%), common bean (70%) and sweet potato (33%) in Kisumu; and maize (96%), common bean (79%) and sorghum (36%) in Siaya. Seven priority trees were mentioned, *viz.*, Grevillea, Eucalyptus, Makharmia, Calliandra, Moringa, Sesbania and Tithonia (Table 4). Further, we explored farmers' aspirations regarding further intensification of push-pull. Similarities were observed for some of the preferred/ proposed sustainable intensification practices between FGD and key informants. Figure 4 shows sustainable intensification practices that farmers considered to be of interest for further intensification of the push-pull system. Agroforestry, intercropping with legumes, crop rotation and crop-livestock integration ranked high among potential intensification options across the three counties. Integration with agroforestry aims to address firewood and fodder supply, create resilient systems, and diversify income. In this regard, trees that improve soil fertility and provide fodder and firewood

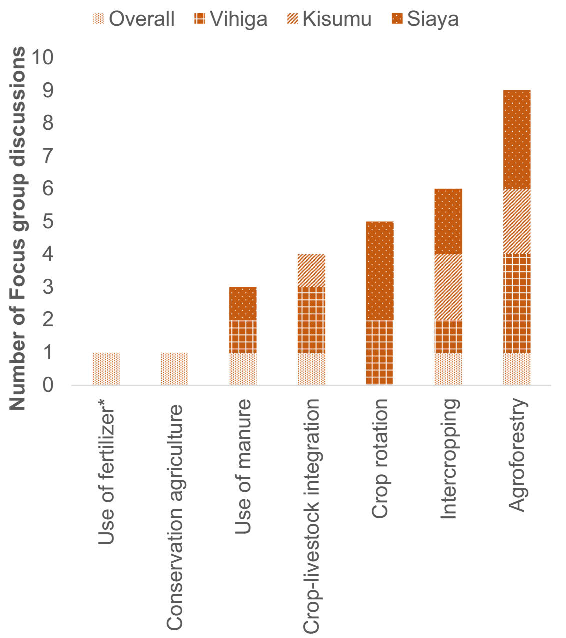

FIGURE 4
Sustainable intensification practices suggested by focus group discussion for further intensification of push-pull in Western Kenya. The use of fertilizer alone was reported as a key intensification practice in the region by field technicians though it is not sustainable.

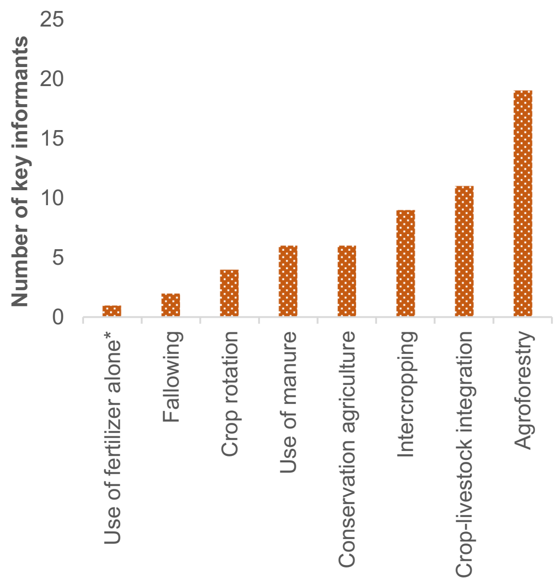

FIGURE 5
Sustainable intensification practices preferred for further intensification of push-pull technology, based on key informants ($n = 25$).

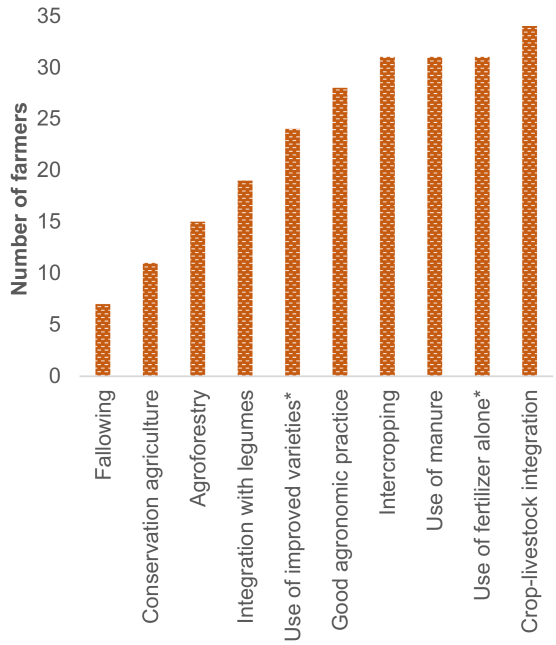

FIGURE 6
Sustainable intensification practices preferred for further intensification of push-pull technology, based on a validation questionnaire of individual farmer respondents ($n = 99$). Elements included in the questionnaire were selected based on the outcomes of key informant discussions. Integration with legumes refers to applying legumes as intercrops or rotated crops, while intercropping applies to all crops, e.g., vegetables, tubers.

simultaneously were proposed. While some farmers mentioned that trees cannot fit into conventional push-pull plots (usually between 10 m × 10 m and 30 m × 30 m), the majority argued that trees can be integrated as long as a suitable design and guidelines are provided and adhered to. Intercropping and crop rotation, mostly with legumes, aim to enhance food and nutritional security by providing additional edible products that are not offered by the current push-pull companion crops. Crop-livestock integration was proposed as a way to enable markets for fodder and ensure nutrient cycling. Key informants also identified agroforestry, crop-livestock integration, and intercropping as key practices for push-pull intensification (Figure 5).

Validation of the practices identified by FGD and KII as promising sustainable intensification practices for integration with the push-pull technology was performed through a targeted questionnaire administered to 99 individual farmer respondents (Table 4). Using the validation questionnaire, farmers identified crop-livestock integration, use of fertilizers, use of manure, and intercropping as the foremost practices for expanding the utility of push-pull in the region (Table 4, Figure 6). For integration with agroforestry, individual respondents of the validation identified *G. robusta* and *M. lutea* as trees that can be included in crop fields without compromising crop yields. Eucalyptus was preferred in woodlots for sale and timber, and offers potential for cultivating desmodium. Crop rotation is applicable in areas with large sizes of land (e.g., Siaya); maize has to be included in the rotation plan and can be rotated with common beans, vegetables (collards, cowpea, and nightshades), groundnut, green grams, or sorghum.

All respondents mentioned having received some training or technical information on the intensification of agriculture and general agricultural production. However, they highlighted that the information was mostly insufficient, often lagging in time given the timing of activities in a farming season; for example, information about fertilizer being delivered long after the planting season and being partly unreliable. Some respondents did not have practical knowledge on sustainable intensification. Actors such as non-governmental organizations (NGOs), research institutions such as the International Centre of Insect Physiology and Ecology (ICIPE) and the Kenya Agricultural and Livestock Research Organization (KALRO), and farmer groups were identified as critical for adoption of technologies. They were identified as the main sources of information, in addition to mass media and institutions of higher learning. The extension officers were limited by support in terms of transport and generally the officer-to-farmer ratio is always low. Information received was varied, and covered the use of fertilizers, composting, push-pull technology, the use of improved varieties, and agroforestry.

4. Discussion

Understanding the context-specificity of farmers' needs and choice of farming practices within and across geographies is crucial for targeted technological dissemination to succeed. Hence, intensification technologies should be adapted to meet farmers' needs across the target areas. The current study is one of the few studies that provide direct feedback from smallholder farmers, which is decisive in defining research priorities and actionable interventions. Since push-pull is one intensification technology with multiple benefits, integrating it with compatible crops and farming systems can benefit many enterprises and improve farmers' livelihoods. There is need for researchers to be cognizant of the motivations, perceptions and challenges of farmers when seeking co-adoption of several sustainable intensification practices (Kanyenji et al., 2020). This can harness, but also promote indigenous knowledge, customized based on the diversity of cultural and socio-economic norms. Compared to conventional research, farmer-led research has self-reinforcing and long-lasting impacts on food and nutrition security among farmers (Waters-Bayer et al., 2015). Farmers in Kisumu, Siaya and Vihiga counties integrate a variety of annual and perennial crops, vegetables, and trees for livelihood, though maize and common bean dominate the landscape. These findings agree with a recent report that identified diverse crops and cropping systems on smallholder farms in western Kenya (Kansiime et al., 2021). The type of crop grown depends on farm size (Okeyo et al., 2020), farmers' educational level (Jambo et al., 2019), household needs (Valbuena et al., 2015), and access to information (Awiti et al., 2022). For example, sorghum is largely grown in Siaya, sweet potato in Kisumu, and banana in Vihiga. These crops are primarily grown for food security and partly for income (Ng'endo et al., 2018; Okeyo et al., 2020; Awiti et al., 2022). The industrial use of sorghum and recent commercialization initiatives have increased its demand in the region (Njinju et al., 2022). Sorghum (and sweet potato) are drought tolerant (Motsa et al., 2015), and are widely promoted as alternative crops that buffer smallholder farmers against climate-induced shocks (Okeyo et al., 2020). The diversity of crops encountered underscores that diversification is key to achieving food security among smallholder farmers, with intercropping being the most preferred practice for farmers with small parcels.

Farmers use different cropping strategies to address low crop productivity associated with poor soil fertility and pests in the region. The most common cropping systems mentioned are crop-livestock integration, intercropping, and crop rotation (where land is adequate). These practices, together with agroforestry were also mentioned as critical forms of sustainable intensification of push-pull. Minimum tillage, improved maize varieties, crop diversification (i.e., legume–maize intercropping and crop rotations), soil and water conservation practices, inorganic fertilizers, and the use of animal manure are commonly promoted intensification practices in the study region (Kassie et al., 2015). The use of hybrid seeds is accompanied by use of pesticides because they are susceptible to pests, use of fertilizers on the other hand is preferred because the soil fertility is improved faster/within a short period of time. Crop-livestock integration improves a system by providing manure but it takes a series of seasons to be able to bring the soil to a stable nutrient content to support plant growth without external fertilizers (Njoroge et al., 2017) and these are the conventionally promoted SI in western Kenya. Agroforestry is a source of livelihood for many farmers in western Kenya (Reppin et al., 2020). High value crops (e.g., legumes and vegetables) are candidate crops for integration with push-pull because of their contribution to food and nutritional security, high income relative to cereals (Gido et al., 2016) and the potential to fight against zoonotic diseases (Chidawanyika et al., 2023). Farming practices including diversification with grain legumes, agroforestry, green manures, conservation agriculture, and integrated nutrient management with mineral and organic fertilizers are reported to improve the performance of maize-based systems in Africa (Droppelmann et al., 2017). For example, intensification of maize with long-duration pigeon pea increases food and biomass production (Droppelmann et al., 2017); and fast growing, high leafy biomass trees with light crown are suitable for integration in croplands. However, farmers need training on the right approach to tree-crop integration. A recent review showed that the integration of grain legumes and dryland cereals can enhance soil organic carbon (Kuyah et al., 2022); soils with high organic carbon are resilient to drought and floods and can also increase farm production (Iizumi and Wagai, 2019). However, fertilizers are often expensive and scarce, making them less economical (De Groote et al., 2010). Contrary to our study, Jindo et al. (2020) observed that farmers considered fertilizer application as a sustainable intensification strategy because yield was increased and the economic status of the farmers did not affect their adoption.

Smallholder farms in western Kenya intensify farming mainly for food security and income. Intercropping and crop rotation increase the variety of harvestable products, reduce chances of crop failure, and can increase crop yield when complementary (Mupangwa et al., 2021). Several studies have shown that intercropping maize with legumes increases crop yield, biomass (Kermah et al., 2017; Ndayisaba et al., 2021), fodder supply (Mupangwa et al., 2021), income diversification, and soil fertility (Drinkwater et al., 2021). Incidence of low yields in crop-rotated fields has been reported, suggesting that complementary intensification, such as the application of manure or microdosing of fertilizers, is required to increase and sustain productivity (Droppelmann et al., 2017). The use of improved varieties and inorganic fertilizers are considered sustainable intensification practices (Kassie et al., 2015), yet the outcome of our study associates the use of improved varieties with excessive use of farm inputs such as pesticides and fertilizers which are expensive and have negative impact on the soil over a long period of time. Desmodium and Tephrosia intercrops with maize inhibit stemborers, African armyworm, and striga weed (Zhang et al., 2020). Furthermore, intercropping is gaining attention as a strategy for climate mitigation and adaptation (Jambo et al., 2019; Mupangwa et al., 2021). Although maize-legume intercropping has multiple benefits, a careful targeting of crop combinations is necessary to maximize returns (Ojiem et al., 2014). This is because some farmers are not aware of the right combinations and agronomic management that can reduce tradeoffs and maximize benefits. Intercropping, though regularly promoted, may be unsustainable when poor shading and complementary fertilizer requirements constrain potential crop productivity (Kiwia et al., 2019). Crop rotation has been reported to improve soil fertility, increase microbial diversity, and enhance resilience of the farming system (Rodríguez et al., 2020); these benefits can increase yield and lower production costs (Tariq et al., 2019). Agroforestry was highly recommended by farmers in the FGD and by key informants, but individually, farmers did not prefer combining it with push-pull technology. This is mainly because farmers are not sure of the mode of tree intensification in push-pull fields. Furthermore, agroforestry through cropland tree integration has been reported to compete with food crops for soil moisture (Kuyah et al., 2021). All the practices identified for push-pull intensification have the potential to create resilience in farming systems, improve soil fertility, control pests and diseases, and increase productivity (Snapp et al., 2021).

Most respondents were aware of the pest control, soil improvement and socio-economic benefits of push-pull technology. However, multiple challenges that limit the adoption of push-pull were also mentioned. According to farmers, inadequate technical knowledge, high initial capital, and high initial labor requirements have constrained the adoption of the push-pull farming system. As with other knowledge-intensive technologies, acquiring this requisite knowledge has remained a challenge, limiting push-pull adoption (Midega et al., 2016; Niassy et al., 2022). Specifically, high costs of desmodium and brachiaria seeds put the initial capital outlay beyond the reach of many smallholder farmers (De Groote et al., 2010). Regarding labor, hired farmhands mostly dislike weeding push-pull plots, citing that it is time consuming (Niassy et al., 2022). One respondent noted that push-pull faces competition from other pest management strategies, such as the application of pesticides and biopesticides, and the use of improved varieties. There is currently limited evidence comparing push-pull and improved varieties, but the use of striga-resistant varieties is not considered to be economically viable for most farmers (De Groote et al., 2010).

The main hindrance to the adoption of sustainable intensification is the lack of knowledge and/or limited information on sustainable intensification. Awareness and training on sustainable intensification are still largely inadequate, sporadic, and unreliable. This limits most smallholder farmers who demonstrate willingness to adopt these practices, but lack technical expertise. Problems of inadequate capacity and dearth of information are associated with limited agricultural extension (Midega et al., 2016). Much of the advisory services to smallholder farmers are provided by research institutions, such as ICIPE, non-governmental organizations, and input suppliers who in most cases have a target to meet and therefore their information is biased and specific to target groups. Integration of field days, farmer field schools, and farmer teachers into research projects and developmental interventions can bridge the knowledge gap and enhance adoption (Murage et al., 2011). This approach is, however, subject to the vagaries of competitive project funding, is inherently limited in time, and cannot address training needs at the scale necessary to have a country-wide and long-term impact on practices. Some of the intensification practices, e.g., the use of mineral fertilizers, are perceived by farmers as sustainable though they may not be considered as such by scientists. There is therefore a need to develop further training on sustainable intensification practices, so as to bridge this knowledge gap among the respondents.

A second major limitation relates to inadequate financial resources. A recent study in Tanzania and Malawi identified the lack of financial resources as the leading setback for the adoption of intensification practices (Jambo et al., 2019). In western Kenya, access to fertilizer has remained beyond the reach of smallholder farmers because of inadequate finances (Misiko et al., 2011), and outlays associated with the adoption of technologies tend to be high. Other limitations are related to cultural beliefs, whereby some respondents consider their local varieties to be less costly and climate-resilient. There is need to understand the needs of farmers when designing sustainable intensification pathways, which often differ and could affect a targeted dissemination of the technology (Jindo et al., 2020).

5. Conclusion and implications

This study identified intercropping, agroforestry, crop rotation (where land is sufficient) and crop-livestock farming as desirable options for farmers, for further intensification to improve the ecological and economic performance of the push-pull technology. Intercropping and crop rotation with vegetables and legumes provide an opportunity to diversify diets, incomes and farming systems, but present a new challenge in plot design and manipulation of trophic interactions. Agroforestry offers a potential solution that is desirable for farmers to address the problems of fodder and firewood supply, and the provision of fruits for dietary diversity (e.g., mango and avocado). Limited diversification options, lack of knowledge, lack of support systems, and market access were identified as overarching challenges with sustainable intensification in the region. This study contributes to ongoing efforts and forms a foundation for future research aimed at upscaling the benefits in smallholder farming systems in western Kenya and the entire East Africa. As our findings suggest, research efforts to intensify and diversify push-pull technology and increase its usefulness need to consider and optimize the system with edible legume-intercropping, agroforestry, as well as crop rotation. Future research focusing on promotion of agroecological practices should also prioritize those practices outlined by the farmers. For policymakers, a gap between the application of agricultural technologies such as push-pull technology with policy development by government institutions has been revealed. Additionally, there is a need to integrate push-pull technology and further promote its intensification in government policies. It is supposed that involving government agricultural staff, field extension officers, and local administrative leaders will facilitate better adoption. This study highlights the need to involve all relevant stakeholders and other existing value chains along the production and consumption lines to achieve enhanced acceptability and increase adoption. Development initiatives for smallholder farming systems can benefit from a participatory research approach to identify, promote and fund innovative technologies and farming practices that are directly beneficial to farmers, given their preferences and prevailing circumstances.

This study identified an immediate need to integrate push-pull with legumes and assess its role in the diversity of food diets, and its potential to offer delivery of alternative services such as improvement of soil fertility in the region. Arising therefore is the need to evaluate the suitability and effectiveness of the highlighted push-pull-based integrated systems across different agro-ecological and socio-cultural contexts.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

The studies involving human participants were reviewed and approved by Jomo Kenyatta University of Agriculture and Technology (JKUAT) Institutional Ethics Review Committee (IERC). National Scientific and Ethics Committee (NSEC) – NACOSTI to offer guidelines and create accreditation standards for ISERCs. NSEC is committed to enabling and supporting ethical research in Kenya. The participants provided their written informed consent to participate in this study.

Author contributions

SK and SB conceived the research idea. SB, SK, SW, and MG collected the data. SB conducted data analysis and interpretation with inputs from SK, AO, FC, and EM. SB wrote the first draft of the manuscript. All authors contributed to the article and approved the submitted version.

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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.

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