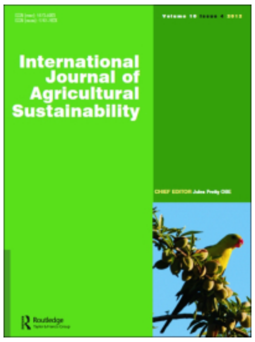

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Bridging the gap in agricultural innovation research: a systematic review of push–pull biocontrol technology in sub-Saharan Africa

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ABSTRACT
Biological control for sustainable plant protection in sub-Saharan Africa (SSA) is gaining attention due to low crop productivity caused by pests, increasing costs of agrochemicals, and their harmful impact on health and the environment. A valuable case is the Push–pull technology (PPT) developed by the International Centre of Insect Physiology and Ecology (ICIPE). However, evidence for the success of PPT in reducing pest prevalence has not translated from experimentation and demonstration to wider-scale on-farm uptake. A systematic review was conducted to explore the research gaps, benefits of PPT, adoption determinants, barriers to uptake, and how farmers choose to adopt and adapt the technology. The study found a large body of evidence on the biophysical benefits of PPT, which comes from a relatively narrow set of ICIPE-led or managed experiments in Western Kenya. Besides, evidence of its social and economic benefits is less robust. Documented barriers to adoption include initial establishment costs, labour intensiveness, risk averseness of farmers, socio-cultural rigidity, and inadequate access to information and inputs. The review highlights the need for qualitative research, an in-depth examination of the social dynamics of innovation and decision-making processes on farms, and institutions' role in shaping innovation for sustainable agricultural development.

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Push–pull technology; biocontrol; integrated pest management; agricultural innovation; Africa

1. Introduction

Insect pests, weeds and diseases cause up to 40% losses in crop production, costing the global economy at least $220 billion yearly (FAO, 2021). Invasive pests alone are estimated to cost around $70 billion annually, posing a serious threat to food security (Hulot & Hiller, 2021). Across sub-Saharan Africa (SSA), native and invasive pests threaten food production (De Groote et al., 2020). Smallholder farmers who produce up to 70% of SSA's consumable food rely on agrochemicals to manage their farms' pests (Bagheramiri & Keshvarz Shaal, 2020; D'Annolfo et al., 2021). Aside from the increasing cost of agrochemicals, inappropriate use has been linked to food safety issues, the development of pesticide resistance, and environmental contamination (Ratto et al., 2022a).

Despite scientific evidence of the potential benefits of biological control alternatives to chemical pesticides, their adoption and use among smallholder farmers in the region remains low (Ratto et al., 2022a). Studies have suggested that several interacting factors influence technology adoption decisions (Arslan et al., 2022; Olum et al., 2020), including farmers' socio-demographics, attributes of the

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technology and agroecological, institutional, political, cultural and psychological factors (Kabunga et al., 2012; Pannell et al., 2014). The inability to find unequivocal determinants of adoption has been linked to diversity in context and the complexity of factors that influence decisions and technology performance on farms (Meijer et al., 2015; Olum et al., 2020; Whitfield et al., 2015).

Biocontrol innovation refers to nature-based pest control methods, which include the use of living micro-organisms and natural enemies, agricultural practices such as carefully selected intercrops and mixed farming, as well as biopesticides and bio-fumigation to control pest infestation in the field (Fravel, 2005; Hulot & Hiller, 2021). The International Organization for Biological Control (IOBC) reported that biocontrol frequently faces slow or delayed adoption (Hulot & Hiller, 2021). Nevertheless, numerous recorded classical biological control interventions in Africa have existed since the 1980s (Neuenschwander et al., 2003). For instance, the introduction of Encyrtid wasps has proven to be effective in managing the cassava mealybug pest infestation which resulted in about 90-95% reduction in crop losses (Neuenschwander, 2004). A recent meta-analysis of 99 biological control intervention studies on 31 crops in SSA shows that, in comparison to non-biocontrol methods, biological control pest management interventions decrease pest abundance and crop damage and lead to increases in crop yields (Ratto et al., 2022b).

Push–pull technology (PPT) was developed by the International Centre of Insect Physiology and Ecology (ICIPE) for smallholder farming systems in 1997 (Khan et al., 2008a). This particular biotechnology is a valuable case study for understanding innovation processes and adoption dynamics in SSA, as it represents a set of scientifically-derived principles and practices that have evolved and been differently applied over time. PPT is based on a dual mechanism of planting a pest-repellent forage legume (*Desmodium* Spp) in between cereal crops, which exerts the '**push'** effect. Concurrently, an attractant fodder (Napier grass, *Pennisetum purpureum* or *Brachiaria* Spp) which exerts the '**pull'** effect, is planted along the perimeter of the field to draw the insect pest (e.g. stemborer) away from the main cereal crop and field (Mala et al., 2020; Mutyambai et al., 2019). Meanwhile, root exudates produced by *Desmodium* Spp suppress the parasitic Striga weed in the rhizosphere (See Figure 1).

PPT has been pitched as a multi-beneficial, pro-poor innovation to control crop pests (e.g. Striga parasitic weed, stemborer and fall armyworm insect pests) in the cereal field, improve soil fertility, and provide a source of animal feed (Cheruiyot et al., 2021). Three versions of the technology have been disseminated by the ICIPE and partners (Cheruiyot et al., 2021). The first generation of PPT developed in 1997 is referred to as conventional PPT (i.e. *D. uncinatum* 'push' + Maize 'main crop' + Napier grass 'pull'). In 2011, the second generation PPT, also known as Climate-smart PPT (CS-PPT), was developed to respond to drought stress and Napier stunting disease (i.e. *D. intortum* 'push' + Maize 'main crop' + *B. Mulato* II 'pull'). In 2020, a more drought-tolerant third generation PPT was developed in response to changing climatic conditions, spider mites attack on *B. Mulato* II, and high cost and scarcity of *D. intortum* (i.e. *D. incanum* 'push'+ Maize 'main crop' + *B. xaraes* 'pull')(Cheruiyot et al., 2021).

Approximately 280,000 PPT farmers are currently on record with ICIPE (http://www.icipe.org), a significant number but far below ICIPE's goal of reaching millions of African farmers with the technology (Gatsby Charitable Foundation, 2014; ICIPE, 2015). Previous authors have argued that the multifunctional PPT needs to be scaled-up amongst African farmers to increase food security and reduce poverty (Chepchirchir et al., 2018; Khan et al., 2008a; Khan et al., 2014). However, the majority of the studies on PPT present results that are particular to a specific location, site, region and farmers' group (Amudavi et al., 2009b; Misango et al., 2022; Murage et al., 2011b; Muriithi et al., 2018). This creates a need to gather evidence from different socio-cultural and geographical settings to draw a firm conclusion about the benefits of PPT, drivers and barriers to adoption, including research gaps and outlook. No systematic review has attempted to synthesize and collate evidence regarding the benefits of PPT and its translation into farmers' fields and practices across different contexts and countries within SSA. This study seeks to understand; (1) What are the benefits of PPT, and what are the remaining uncertainties and evidence gaps?; (2) How has the adoption and uptake of PPT been studied, and what does this reveal about the drivers of, and barriers to, the adoption of PPT?; and (3) What do we know and not know about how farmers make choices about, experiment with, adapt and adopt PPT? Our systematic review aims to guide future research on PPT by highlighting gaps while also presenting policymakers, research, and

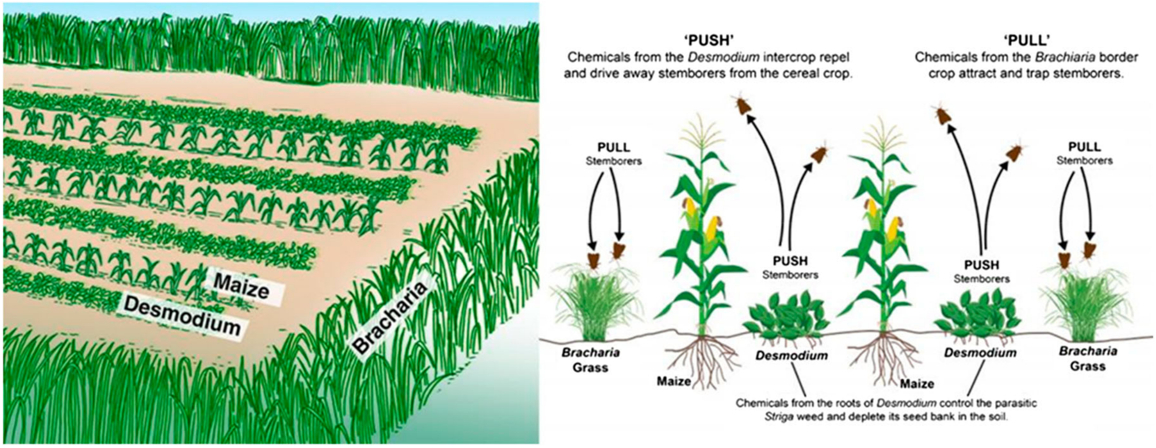

Figure 1. Climate-smart push-pull technology mechanisms for suppressing Striga weed and stemborer pest (ICIPE, 2022).

development organizations with thought-provoking information regarding agricultural innovation and adoption dynamics more broadly in SSA.

2. Methodology

2.1. ROSES protocol for systematic review

The present study adopted the RepOrting Standards for Systematic Evidence Syntheses (ROSES) protocol for literature review. The ROSES guides are specifically designed for systematic maps and reviews in the field of environmental management (Haddaway et al., 2018; Shaffril et al., 2020). Based on the ROSES protocol, the systematic search strategy involves identifying articles, screening, and assessing eligibility. These steps are followed by a quality appraisal of selected articles, data abstraction, acquisition, and analysis (Ratto et al., 2022a; Rijal et al., 2022; Shaffril et al., 2020).

2.2. Generation of research questions

The research questions generated for this study were based on the Population, Interest, and Context (PICo) framework commonly used by researchers to develop relevant questions for systematic reviews (Ratto et al., 2022a; Rijal et al., 2022). In this study, **the population** is referred to as smallholder farmers. **Interest** refers to push–pull technology, while **context** is restricted to sub-Saharan Africa (Table 1).

Table 1. Inclusion and exclusion criteria based on PICo(s).

PICo(s)	Inclusion	Exclusion
Population	Smallholder farmers	Large scale farmers
Interest	Push-pull technology	Other management practices
Context	sub-Saharan Africa countries	Non-sub-Saharan Africa countries
Study type	Peer-reviewed articles published in English language only	Non-peer-reviewed and review articles

2.3. Systematic literature searching strategies

Three major processes commonly used in the systematic search of literature were adopted in this study. These processes include identification, screening, and eligibility assessment (article appraisal and synthesis), presented in Figure 2, and detailed in the following section.

2.3.1. Identification

The process of identifying relevant articles involved searching for related terms and synonyms of major keywords of interest ('smallholder farmer,' 'Push–pull technology,' and 'sub-Saharan Africa') and terms used in previous studies (Table 2). The literature search was conducted on two reputable databases: Web of Science (WOS) and Scopus. WOS and Scopus are widely known for assembling a collection of quality articles with advanced searching functions and robustness in terms of discipline, thus being suitable for a systematic review of literature in multiple fields of study (Falagas et al., 2008; Zhu & Liu, 2020). The search string was tailored to accommodate keywords and their synonyms which was developed using Boolean operators (OR, AND), truncation, phrase search, and field code function (Table 2). The search in Scopus was conducted

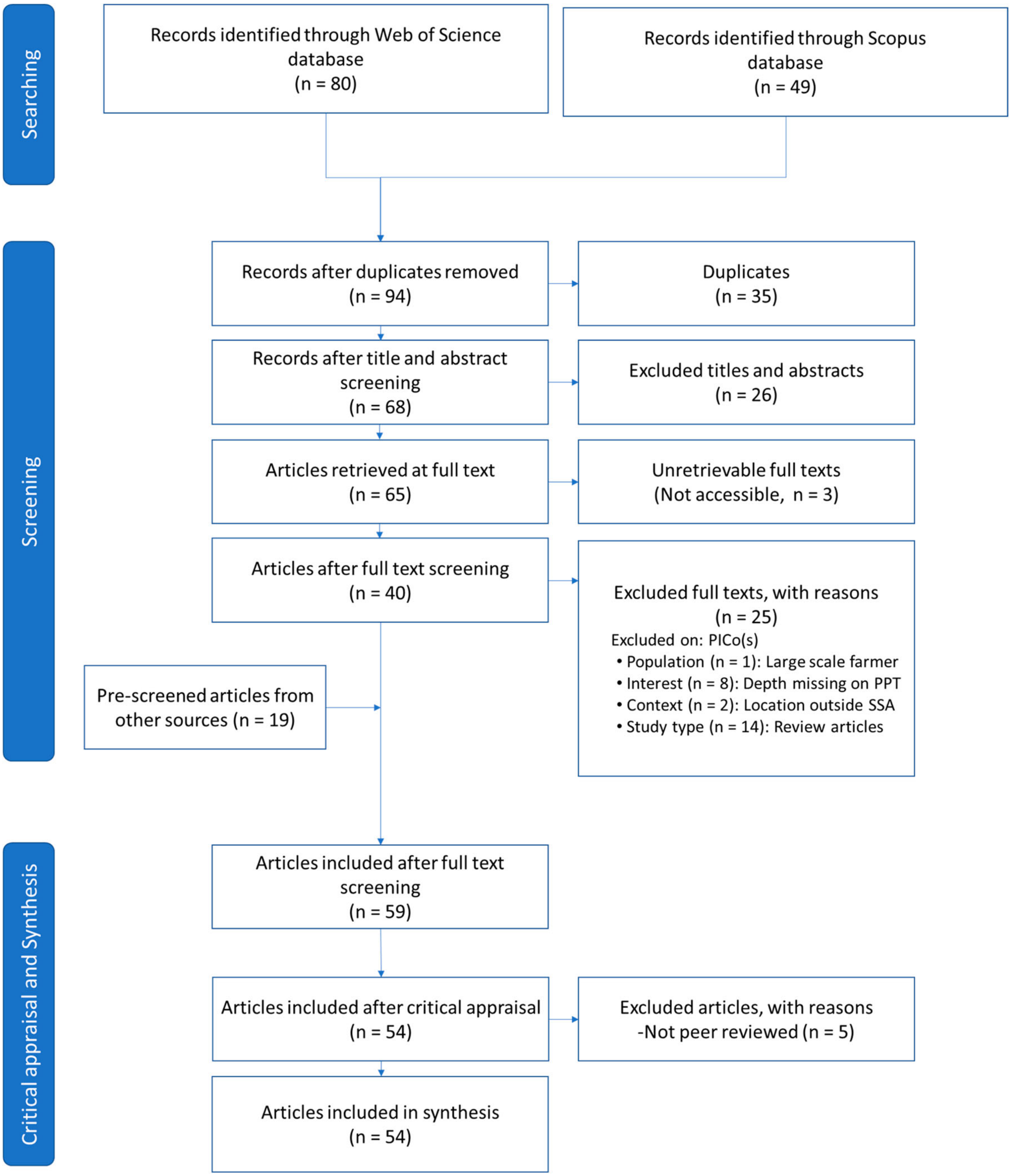

Figure 2. The ROSES flow diagram represents the systematic search approach and results.

under the Title, Abstract, and Keyword category: TITLE-ABS-KEY. Meanwhile, the search in WOS was carried out under the TOPIC category. No specific time period or restriction was applied to the search.

2.3.2. Screening and quality assessment

A total of 129 articles were imported into EndNote referencing software, where 35 records were automatically and manually removed as duplicates, leaving a total of 94 articles left for further screening.

Table 2. The search string and sources of articles.

Database	Search String	Results	Time frame
Web of Science	TOPIC = ('Push-pull*' OR 'Push-pull technolog*' OR 'Push-pull farming' OR 'Push-pull system' OR 'Push-pull intercrop*' OR 'Climate-adapted push-pull*' OR 'Climate-smart push-pull*' OR 'Conventional push-pull*' OR 'Original push-pull*') AND ('Farmer*' OR 'Smallholder farmers' OR 'Smallholder*' OR Smallholding* OR Smallholder farms OR 'Smallholder farming systems' OR 'Farming household*' OR 'Agric*' OR 'Farm*') AND ('Africa*' OR 'sub-Saharan Africa*' OR SSA)	80	All years
Scopus	TITLE-ABS-KEY = ('Push-pull*' OR 'Push-pull technolog*' OR 'Push-pull farming' OR 'Push-pull system' OR 'Push-pull intercrop*' OR 'Climate-adapted push-pull*' OR 'Climate-smart push-pull*' OR 'Conventional push-pull*' OR 'Original push-pull*') AND ('Farmer*' OR 'Smallholder farmers' OR 'Smallholder*' OR Smallholding* OR Smallholder farms OR 'Smallholder farming systems' OR 'Farming household*' OR 'Agric*' OR 'Farm*') AND ('Africa*' OR 'sub-Saharan Africa*' OR SSA)	49	All years

The following stage of the screening process involved a careful assessment of titles and abstracts with emphasis on PICo(s), inclusion and exclusion criteria (Table 1) that resulted in the exclusion of 26 papers, leaving 68 articles. Articles excluded in this stage include those that focused on other pest management strategies, articles that did not include any PPT components (e.g. *Desmodium*, Napier or *Brachiaria* Spp), and articles that focused on the laboratory analysis of the chemical compounds released in a PPT cropping system. Irretrievable full texts account for three (3) articles, while the full texts of 65 articles were accessible and retrieved.

Additionally, on the screening of full texts, 25 articles were excluded based on the PICo(s) framework to leave 40 articles. The reasons for excluding papers at this stage include studies not focused on smallholder farmers, depth missing on PPT, study locations outside of sub-Saharan Africa, and review articles. In addition, the reference lists of the retained 40 articles were then checked, from which 19 additional papers were discovered that were found to be eligible for inclusion according to the inclusion criteria. Five (5) articles were further excluded because they were not peer-reviewed (book chapters and conference proceedings). Ultimately, 54 articles were included in the present study for synthesis (Figure 2).

2.3.3. Data abstraction and analysis

This study comprehensively synthesizes and summarizes existing empirical research that includes a range of research designs and methods (Rijal et al., 2022; Whittemore & Knafl, 2005). Essential information was extracted and captured in Excel for each of the 54 articles selected for synthesis. The data extracted included bibliographic information such as author names, article titles, and year of publication. Other vital information extracted included study location, crop-livestock system of focus, version of PPT studied, research type, sample sizes, beneficial impact of PPT, statistical and analytical methods used for investigating adoption, barriers to uptake, and farmers' innovation decisions. Information abstracted from the analyzed articles was categorized into appropriate themes by observing patterns, counting, and noting similarities and relationships in the literature (Shaffril et al., 2020). The analyzed articles in this study differed in their approach, variables examined, and statistical techniques. Given this diversity in metrics and methodology, a narrative synthesis was considered more suitable than a meta-analysis to avoid misleading findings and provide a complete overview of all available evidence (Olum et al., 2020). The analysis in this review was considered to have presented 'strong evidence' if at least five studies took a similar stand on the same point of view and 2/3 reported a significant effect (Kopper & Ruelle, 2022).

3. Results

3.1. What evidence of the benefits of PPT has been generated, and what are the remaining uncertainties and evidence gaps?

The geographical location of research sites in SSA was clustered around the shores of Lake Victoria in Eastern Africa (Figure 3). Most of the studies in the selected articles focused solely on maize cropping systems (45), with three (3) studies considering both maize and sorghum, two (2) studies focused on dairy farming, and only one (1) study each focused exclusively on finger millet and sorghum. Conventional PPT was the focus of most of the studies (21), followed by climate-smart PPT (10), conventional and climate-smart PPT (3), climate-smart and third generation PPT (1), a component of any of the PPT versions (12), or not specific about the PPT variant (7). Field

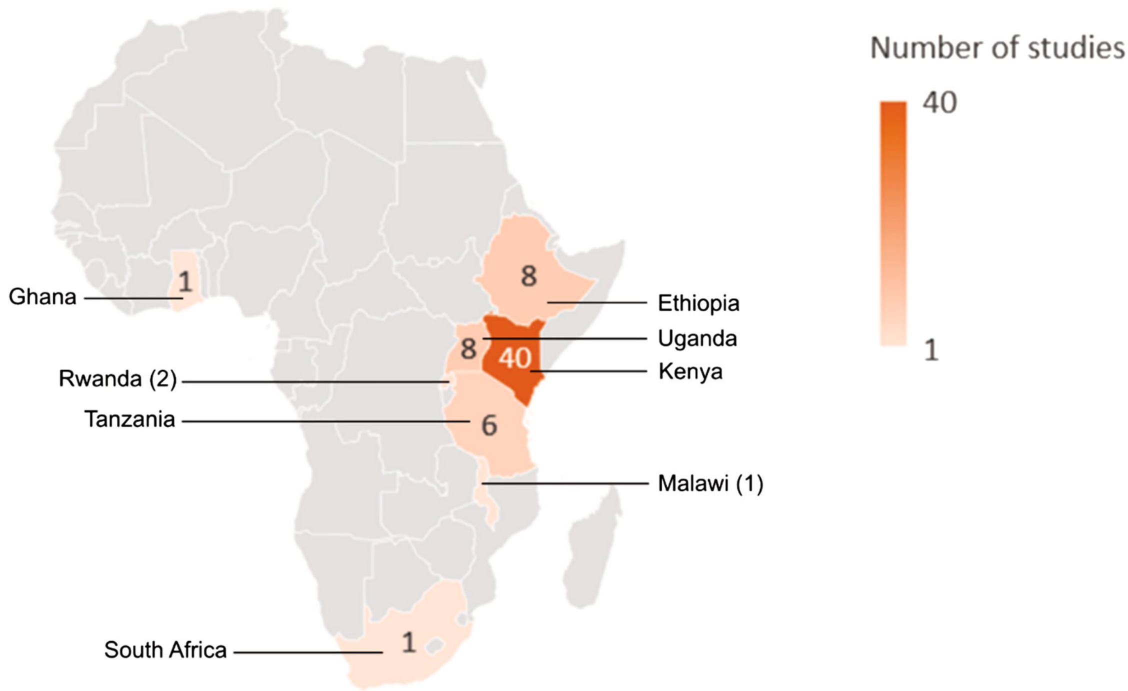

Figure 3. Geographical location and the number of studies conducted in sub-Saharan Africa.

experiments were the most common research type (21), followed by surveys (19) and mixed research types (14), with ICIPE leading most of the research in Western Kenya. Most of the studies were conducted on-farm (20), followed by on-station (7), on-farm and on-station (7) and the majority generated and analyzed quantitative data. However, only two (2) studies generated quantitative and qualitative data and one (1) study generated and analyzed only qualitative data. Research gaps are evident in the limited focus on other crops and farming systems beyond maize, a limited number of studies generating social-economic benefits and qualitative data, and the limited regional coverage beyond East Africa.

The beneficial impacts of PPT largely focus on the ability of the technology to reduce stemborer and fall armyworm infestations, suppress Striga weed, improve soil health and cereal yields (Khan et al., 2008a; Kumela et al., 2019; Murage et al., 2015b; Ndayisaba et al., 2021) (Table 3). The availability of quality fodder for improved livestock health and dairy production is another major benefit associated with PPT in SSA (Maina et al., 2020; Maina et al., 2021) (Table 3). These benefits were measured using yield, pest control, soil fertility, economic and ecological indicators. When comparing PPT plots to control treatments and other practices (e.g. maize and food legume intercrop), yield performance is often determined by the percentage increase in harvested grain and plant height. Pest control effectiveness was measured by calculating the percentage reduction through pest counts and damage assessments. Soil fertility was usually measured by assessing the changes in soil organic matter, soil nitrogen, or other soil nutrients. Economic benefits were evaluated through net income gains in terms of cost–benefit ratios, factor productivity, and net present values, while increases in the abundance or diversity of beneficial insects and natural enemies or other organisms determined ecological benefits.

While many studies have demonstrated the potential agronomic benefits of PPT, evidence about the social and economic benefits of the practice is less robust at the household and community levels (Table 3). For instance, it has been reported that PPT requires high initial investments, with benefits accruing over time (De Groote et al., 2010). Still, less research has explored the affordability and cost-effectiveness of the technology over an extended period, particularly in relation to perceived opportunity costs, and the effects of unexpected shocks or social changes on farmers' decisions to adopt PPT. Additionally, there is a need for further

Table 3. Key benefits of PPT generated from the literature.

Research focus	Number of articles	Beneficial impacts of PPT in SSA
Technical performances (Pest control, improve yield, soil fertility and livestock production)	29	• Stemborer and Striga weed infestation levels were lower in PPT plots in Western Kenya, resulting in higher yields (Khan et al., 2006; Khan & Pickett, 2008; Midega et al., 2014; Ndayisaba et al., 2020). • Climate-smart and conventional PPT reduced stemborer, fall armyworm, and Striga infestations effectively in Kenya, Uganda, Tanzania, and Ghana (Hailu et al., 2018; Midega et al., 2015; Midega et al., 2018; Yeboah et al., 2021). • PPT system produced higher maize yields than other farmer practices (Midega et al., 2014; Ndayisaba et al., 2020; Vanlauwe et al., 2008). • Long-term intercropping of maize and *Desmodium* (push plant) improves soil microbiome composition, organic matter, and plant-accessible nutrients (Cheruiyot et al., 2021; Drinkwater et al., 2021; Mwakilili et al., 2021; Ndayisaba et al., 2021; Ndayisaba et al., 2022). • *Brachiaria* grass (pull plant) improves livestock feed sufficiency and milk production in Eastern Kenya (Maina et al., 2020; Maina et al., 2021).
Socio-economic performances	10	• PPT in a maize cropping system offers significantly higher net present values, yields and gross margins (Chepchirchir et al., 2018; Khan et al., 2008b). • PPT is more profitable than other farmers' practices but comes with a high initial investment cost in Western Kenya (De Groote et al., 2010). • PPT increases the net income of maize farmers, reduces household labour for weeding and ploughing and increases women's expenditure on children's well-being and consumption goods (Diiro et al., 2021; D'Annolfo et al., 2021; Kassie et al., 2018). • Expansion of PPT plots reduced the mean probability of household poverty and increased household incomes and food consumption per capita in Eastern Uganda (Chepchirchir et al., 2017).

research on labour burden/productivity and gender analysis to help address inequality and unintended consequences. Furthermore, there is a need to investigate how PPT can be effectively integrated with other pest management strategies, including other biological control measures and cultural practices, ecological effects of PPT across scales and in different cropping systems, and the scale determinants of PPT adoption. Such research can inform decisions regarding the scalability of the technology. Further research is also required on policy barriers to push–pull adoption and strategies to address them.

3.2. How has the adoption and uptake of PPT been studied, and what does this reveal about the drivers of, and barriers to, the adoption of PPT?

Out of the reviewed studies, twenty (n = 20) examine the factors that affect the adoption of PPT, which have been studied primarily through surveys, while a small number of authors integrated focus groups, interviews, and field observation (Table 4). In most cases, authors adapted quantitative and linear econometric models to analyze the determinants and extent of PPT adoption. Much of the PPT adoption studies showed that sociodemographic variables remain a key driver of PPT adoption among smallholders in SSA (Table 5). Farmer age is often used as a proxy for experience in the articles analyzed, and the positive effect of age on adoption is attributed to older farmers in four articles (n = 4). Older farmers with experience and understanding of a decline or total loss of farm produce to pests are more likely to take up PPT (Amudavi et al., 2009b; Maina et al., 2020). The impact of gender on PPT adoption remains a subject for debate, as four articles have indicated a positive effect of PPT adoption for men (male = 4), while an equal number of articles have found a positive effect for women (female = 4). However, disparity exists in gender preference and access to resources that slow down the rate and intensity of adoption (Muriithi et al., 2018). For instance, a multi-country study that includes Kenya, Uganda, Tanzania, and Ethiopia found that women who are the most vulnerable were more inclined to adopt PPT only if they had access to resources needed as the technology attributes favour women's preferences, by reducing labour, compared to men (Murage et al., 2015b). Likewise, female-headed households that belong to social or agricultural groups are observed to increasingly adopt PPT in gender-related studies (Chepchirchir

Table 4. Research types and locations, drivers and barriers to PPT adoption (n = 20).

Author (s) and Year	Region of site location (s)	Type of research	Sample size	Version of PPT	Significant factors driving PPT adoption	Key barriers to PPT uptake
Khan et al. (2008a)	Western Kenya	Farmers' survey & field experiment	923	Conventional	Age, gender, household headship, PPT attributes, access to extension, knowledge of pest damage and PPT.	
Amudavi et al. (2009a)	Western Kenya	Farmers' survey	1492	Conventional	Educational level, farm location and distance, severity of pest damage, knowledge of PPT attributes, and participation in field days.	
Amudavi et al. (2009b)	Western Kenya	Farmers' survey	672	Conventional	Age, group membership, marital status, educational level, access to input, finance, and farmer-teacher extension.	•Older farmers resist change.
Murage et al. (2011a)	Western Kenya	Farmers' survey	491	Conventional	Participation in field days, farmer field schools, and access to farmer-teacher extension.	
Murage et al. (2011b)	Western Kenya	Farmers' survey	491	Conventional	Gender, educational level, household size and income, group membership, livestock ownership, access to extension (including farmer-teacher) and participation in field day.	•Labour demand in establishing and maintaining plot.
Murage et al. (2012)	Western Kenya	Household survey	491	Conventional	Farm location and size, access to extension (including farmer-teacher), participation in field days, and farmer field schools.	
Mwangi et al. (2014)	Western Kenya	Household survey	326	Conventional	Household income, size and headship, group membership, livestock ownership, and farm location and distance to major centres.	
Murage et al. (2015a)	Western Kenya, Northern Tanzania & Ethiopia	Farmers' survey & field experiment	898	Climate smart	Age, gender, access to inputs, intensity of pest infestation, and knowledge and perception of PPT.	•Initial cost of establishment and availability of inputs.
Murage et al. (2015b)	Western Kenya, Northern Tanzania, Eastern Uganda & Ethiopia	Farmers' survey	461	Climate smart	Gender, expected benefits from PPT attributes, farm size, access to extension, severity of pest damage and knowledge of PPT.	•Labour demand in establishing and maintaining plot.
Chepchirchir et al. (2017)	Eastern Uganda	Household survey	560	Not specific	Gender, educational level, household and farm sizes, access to extension services, and participation in field days.	•Labour demand in establishing and maintaining plot.
Muriithi et al. (2018)	Western Kenya	Household survey & field experiment	4472	Not specific	Age, educational level, marital status, group membership, access to extension, farm distance to market and participation in field days.	• Women inadequate access to information, land, credit, and other vital resources. • Socio-cultural rigidity and practices (e.g. mono-cropping, crop rotations). • Labour demand in establishing and maintaining plot.
Kassie et al. (2018)	Western Kenya	Household survey, focus group & field experiment	642	Not specific	Age, educational level, group membership, livestock ownership, farm location, soil fertility, participation in field days and access to finance.	
	Southern Ethiopia	Household survey	71	Climate smart		•Farmers' risk averseness.

Kumela et al. (2019)					House size, land ownership, farm size, expected benefits from PPT attributes, knowledge of pest and PPT.
Murage et al. (2019)	Western Kenya, Eastern Uganda, Northern Tanzania	Farmers' survey	2615	Conventional	Age, gender, educational level, intensity of stemborer and pest infestation, participation in field days, knowledge of PPT, and access to mobile phones.
Gwada et al. (2019)	Western Kenya	Household survey	240	Not specific	Gender, marital status, farm size, access to extension (including farmer-teacher) and inputs, intensity of pest infestation and participation in field days.
Maina et al. (2020)	Western & Eastern Kenya	Household survey	237	Pull component of climate smart	Age, group membership, expected benefits from PPT attributes, livestock ownership, and access to extension services and training.
Niassy et al. (2020)	Eastern Rwanda	Household survey	587	Not specific	Educational level, marital status, group membership, farm size, land ownership, household income and headship, access to extension services and finance, expected benefits form PPT.
Gebreziher et al. (2021)	Northern Ethiopia	Scheduled interview & field experiment	9	Conventional	Intensity of pest infestation, knowledge of PPT and expected benefits, access to extension services and training.
Maina et al. (2021)	Western & Eastern Kenya	Household survey	237	Pull component of climate smart	Awareness of pest damage and knowledge of PPT benefits, access to information and extension services.
Misango et al. (2022)	Eastern Rwanda	Household survey	194	Not specific	Gender, group membership, livestock ownership, expected benefits from PPT attributes, access to information and extension services.

et al., 2017; Gwada et al., 2019; Murage et al., 2015a; Muriithi et al., 2018).

Furthermore, eight articles (n = 8) showed that formal education has a positive effect on the pace of understanding and utilization of technology (Amudavi et al., 2009a; Amudavi et al., 2009b; Chepchirchir et al., 2017; Kassie et al., 2018; Murage et al., 2011b; Niassy et al., 2020). In addition, authors of four articles (n = 4) showed that marital status positively influences PPT adoption, as jointly owned farms were seen to receive agricultural information and inputs quickly compared to farmers managed by a single farmer. However, single farmers without dependents may possess higher financial strength compared to their married peers in certain cases (Amudavi et al., 2009b; Gwada et al., 2019). Again, household size was found to be a significant driver of PPT adoption in four articles (n = 4). Household size is sometimes used as a proxy for labour availability. A large household size (i.e. 6 and above) translated to the availability of labour and more hands to assist with farming, which positively influenced adoption. However, PPT practices are labour-intensive at the early stage, and farmers constrained by labour availability might be discouraged from adopting or restrained from expanding plots allocated to PPT practice (Chepchirchir et al., 2017; Murage et al., 2011b).

Households or farmers with high on/off-farm income were more flexible with investment in farming, hence, three articles (n = 3) suggested that it positively influenced adoption compared to their low-income colleagues who might not be able to offset the initial cost of the establishment (Murage et al., 2011b; Mwangi et al., 2014; Niassy et al., 2020) (Table 5). Furthermore, farm size significantly drove PPT uptake in six articles (n = 6), where farmers with 3–4 acreage for cultivation were seen to quickly trial and adopt PPT compared to their counterparts with smaller farm sizes (e.g. ≤ 1-2 acre) (Chepchirchir et al., 2017; Gwada et al., 2019). Meanwhile, eight articles (n = 8) showed that farmers who belong to social or agricultural groups had improved access to learning and sharing of knowledge regarding the potential benefits of PPT, which had a positive effect on adoption (Amudavi et al., 2009b; Kassie et al., 2018; Maina et al., 2020; Misango et al., 2022; Murage et al., 2011b; Mwangi et al., 2014). Moreover, the authors of six articles (n = 6) showed that livestock ownership significantly increased PPT adoption among smallholder farmers in SSA (Mwangi et al., 2014).

Table 5. Categories and effects of significant factors driving PPT adoption and barriers in SSA (n = 20).

Themes	List of major factors	Number of articles showing significant factors impacting adoption	Effects on adoption	Remarks
Farmer and household socio-demographics	Age	4 (old) 2 (young-middle)	Positive Positive	Age is often used as a proxy for experience
	Gender	4 (female) 4 (male)	Inconclusive	Gender of participants or household head
	Educational level	8 (formal)	Positive	
	Marital status	4 (married)	Positive	
	Household size	4	Positive	Household size is sometimes used as a proxy for labour availability
	Household income	3 (higher)	Positive	On and off-farm income
	Group membership	8	Positive	Social or agricultural groups
	Land ownership	2	Positive	Less evidence is provided in the literature concerning ownership status and effects on adoption
	Livestock (unit) ownership	6	Positive	
Innovation characteristics	Accrued attributes	6	Positive	Stemborer, fall armyworm and Striga control, soil, and crop yield improvement.
Farm characteristics and biophysical factors	Farm location and distance	5 (distance)	Negative	Distance to homestead, administrative centres, road, or market
	Farm size	6	Positive	Smallholder farm sizes do not usually exceed 4 acres in SSA
	Soil fertility levels	2 (low)	Positive	Less evidence is provided in literature with regards to soil fertility and effects on adoption
Institutional factors	Access to extension and training	13	Positive	Inclusive of private and public extension services
	Technology dissemination pathway	12	Positive	Pathways include field days, farmer field schools and farmer teachers etc
	Access to credit	3	Positive	
	Access to input market	5	Positive	Inputs such as *Desmodium* seeds
Psychological factors	Knowledge, awareness, and perception of PPT benefits	8	Positive	
	Perception of constraints and severity	11	Positive	
	Risk averseness	1	Negative	Associated with age in the literature

Additionally, authors of six articles (n = 6) showed that the aggregate and accrued attributes of PPT, such as control of stemborer, Striga, fall armyworm, soil fertility and maize yields improvement, significantly and positively drove PPT adoption among smallholder farmers in SSA (Table 5). For instance, Mwangi et al. (2014) compared two contrasting Striga weed management technologies and found similar adoption rates for conventional PPT and Imazapyr-resistant maize (IR) technologies at 37% and 36.3% respectively. Nevertheless, the potential adoption rates of PPT were greater than IR by 20% (Mwangi et al., 2014). Also, Murage et al. (2015a) sampled 898 respondents and found that the majority were willing to adopt PPT in Tanzania (92.1%), Ethiopia (88.6%), and Kenya (84.3%) due to the accrued attributes and expected benefits.

Five articles (n = 5) showed that farm location and distance to tarred roads, administrative centres and markets was a significant factor that negatively impacted PPT uptake (Niassy et al., 2020). It is assumed that farmers or farms close to field trials or research stations are expected to adopt PPT faster than their counterparts in places farther away from the source of information (Amudavi et al., 2009a; Mwangi et al., 2014). A sizable number of articles (n = 13) showed that adequate access to extension and training significantly and positively increased the possibility of PPT uptake (Table 5). For instance, farmers' interaction with ICIPE's technical staff and extension workers increased the chance of PPT adoption among smallholder farmers (Khan et al., 2008a). However, twelve articles (n = 12) showed that the type of dissemination channel used was an important determinant of PPT adoption and positively affected the message when used effectively.

In addition, farmers' access to credit positively increased the probability of PPT adoption in three articles (n = 3), as it offered farmers the power to buy inputs and hire labour to maintain the plot when required (Amudavi et al., 2009b). On the other hand, Niassy et al. (2020) found that farmers with resource constraints, such as those who needed credit for crop production, were less likely to pay for PPT in Eastern Rwanda. Moreover, five articles (n = 5) showed that access to the input market positively influenced smallholders' adoption of PPT (Murage et al., 2015a). In other words, the ability to access inputs such as *Desmodium* seeds and market opportunity to sell off their fodder for livestock drives uptake. Despite the complexities of the farmer-herder conflict in Africa (Arslan et al., 2022), there has been limited examination of the impact of free-range grazing tenure systems on the uptake and expansion of PPT. The role of land ownership status (owned/rent) in SSA as a barrier to PPT uptake requires further examination.

Farmers' knowledge, awareness, and perception of PPT benefits significantly affected their attitude towards PPT uptake (Table 5; n = 8), while farmers' perception of constraints severity, such as damage caused by stemborer, Striga, and fall armyworms, positively increased PPT adoption in eleven articles (n = 11) (Gwada et al., 2019; Khan et al., 2008a; Maina et al., 2021; Murage et al., 2015a; Murage et al., 2019). Moreover, one article reported that fear of uncertainty and risk aversion negatively affected adoption as farmers were indecisive after receiving information and training about PPT (Kumela et al., 2019).

3.3. What do we know and not know about how farmers make choices about, experiment with, adapt and adopt PPT?

There is limited research on how farmers choose to experiment with, adapt and adopt PPT. Existing studies have primarily focused on dissemination pathways and impacts on farmers' adoption decisions. For instance, Amudavi et al. (2009a) found that 80% of research participants in Western Kenya were aware of the biology of stemborer and Striga, as well as the implementation strategies of PPT through Field Days. Similarly, Amudavi et al. (2009b) reported that Farmer-Teachers and Follower-Farmers dissemination channels significantly increased farmers' decision to adopt PPT, with their technical efficiency averaging 78% and 71% respectively. Furthermore, Murage et al. (2011a), who ranked participants preferred dissemination pathways, suggested that farmers with little education favoured Field Days, farmers with a small acreage of land favoured Farmer-Teachers, farmers belonging to groups favoured Farmer Field Schools, and young educated farmers desired printed materials. Other studies in Western Kenya revealed that field days had the biggest influence on the speed of conventional PPT adoption, followed by the Farmer-Teachers pathway (Murage et al., 2011b; Murage et al., 2012).

Regarding gender effect, a multi-country study conducted in Western Kenya, Eastern Uganda, and Northern Tanzania by Murage et al. (2019) reported that women farmers understood PPT and showed more interest than men after training during Field Days. Meanwhile, in Northern Ethiopia, Gebreziher et al. (2021) evaluated pre- and post-training perceptions of farmers on fall armyworm and conventional PPT. Findings suggested that farmers responded positively to having gained adequate knowledge and skills related to PPT after the training and were willing to try the technology. However, while these studies provide valuable insights into the effectiveness of diffusion strategies on PPT uptake, they do not fully explore the specific circumstances that may influence individual farmers' decisions within farming households and communities on whether to adopt or not. Additionally, there is limited knowledge on dis-adoption and adaptation, future research needs to acknowledge the dynamic nature of innovation decisions and contextual changes over time when exploring this topic. Beyond education and training, there is limited understanding of the role of socio-cultural differences, norms, social networks (e.g. farmer groups), how farmers experiment with and adapt PPT to their specific biophysical contexts (e.g. needs and agroecological or emerging agro-climatic conditions) and how this affects its efficacy.

4. Reflection on research gaps and future outlook

Our systematic literature review and analysis highlights limited PPT research coverage in SSA's Central, Western and Southern African regions. Additionally, much of the PPT research focused on its technical performances, relying heavily on quantifiable metrics and often taking place in controlled environments such as on-station trials by ICIPE and partners or researcher-managed on-farm experiments. Given the pressing concerns regarding climate change, which exacerbates problems with crop pests, and ambitions to scale up PPT across Africa, it is crucial to broaden our perspectives and explore new avenues to evaluate the efficacy of the technology beyond just maize cropping systems and Kenya's agroecological conditions.

Studies on PPT adoption often apply over simplistic categorisations of adopters and non-adopters without capturing the nuanced nature of the practice, i.e. that PPT might be practised to different extents within and across farms, that different aspects of PPT practice might be differently applied, and that these dynamics might change over time. Only two studies explore the extent of land cultivated using PPT to measure its intensity of use. Based on observations in the analyzed articles, studies that rely on structured questions to gather information on a narrowly conceived intervention at a particular moment often struggle to acknowledge the intricate and constantly evolving processes that underlie farmers' decision-making and innovative practices (Pannell et al., 2014; Whitfield, 2015). For instance, none of the studies on PPT adoption utilized ethnographic research methods to understand the local context and farmers' decision-making processes, thereby limiting the understanding of the innovation processes around PPT.

While precise execution of agricultural innovation at research stations or researcher-managed on-farm trials provides a highly accurate evaluation of the innovation, it may not accurately reflect the feasibility and suitability of these practices for smallholder farmers (Hermans et al., 2020; Stevenson et al., 2014). Furthermore, the socio-economic literature on PPT has yet to comprehensively examine the impact of under-explored social dimensions such as acceptability, history, trust, interactions, power relations, culture, morality, norms, and group dynamics on the uptake. This lack of information on the social dynamics and experiences of farming in different contexts makes it challenging to understand what works, under what conditions, where and why.

Thus far, the trend observed in the analyzed articles exemplifies the way research and development organizations have approached scaling agricultural technology by categorizing potential users based on geography or demographics and relying heavily on the model of technology transfer (Glover et al., 2016; Hermans et al., 2020; 2021). Moreover, the review highlights that the linear econometric models used to examine PPT adoption have been limited in capturing the complexities of the innovation and decision-making processes. Similar to other innovations introduced to Africa, there has been a narrow focus as to what does or does not shape PPT uptake (i.e. demographic, socio-economic conditions and technology performances), with several authors recommending awareness creation, increased access to information and investments in intensive dissemination of the technology as the way to boost adoption (Chepchirchir et al., 2017; Gebreziher et al., 2021; Kassie et al., 2018; Misango et al., 2022; Murage et al., 2015a; Muriithi et al., 2018).

It has been suggested that PPT is a knowledge and management-intensive technology, potentially complicating its acceptance by farming communities (Murage et al., 2015a; Murage et al., 2015b). To better understand these claims, it is essential to study how agronomic knowledge is shared and spread within these communities and whether increased exposure over time will enhance knowledge. One area that has been overlooked is how various forms of knowledge are shared and understood within farming communities, which are often centred around lead farmer and demonstration plot models by external organizations such as ICIPE for promoting PPT. Despite the advancement in the communication space, only one study specifically analyzed the role of mobile phones in PPT uptake (Murage et al., 2019). However, while much research has focused on the farm social context, there has been less emphasis on research and developments' social and institutional contexts, how research approaches, agendas, institutional strategic objectives, and norms shape the nature of technology development, delivery, and experiences of innovation. Our review reaffirms the linearity and oversimplification of innovation processes in prior technology transfer and adoption studies (Glover et al., 2019). In support, Glover et al. (2016) argue that the adoption-diffusion model of Rogers (1995), which is often used to understand adoption processes, is not holistic enough to help researchers and developmental organizations ascertain the extent of technological change or the environment within which it takes place. In addition, much research has been tailored towards understanding the efficacy and technicalities around innovation, not minding other complex aspects of innovation and decision-making processes (Glover et al., 2016; Glover et al., 2019).

In this regard, a different research approach is needed to gain deeper insights into the innovation processes, farming contexts and decision-making dynamics in SSA. Recent studies have recommended using an innovation systems perspective to shed light on the complexities and innovation processes (de Boon et al., 2022), which sees factors that shape innovation as multifaceted. Meanwhile, Smith et al. (2021) shared a similar view and have recently adapted Smits (2002) conceptualization of innovation in their attempt to understand the complexities around agricultural innovation. In addition, agricultural innovation system approaches have recently been used in the literature to analyze key stakeholder roles, organizational capacity, and collaborations to better understand pertinent issues around agricultural technology (Chinseu et al., 2022). This approach can be deployed in the case of PPT and other agricultural innovations in SSA, by considering diverse actors and institutions that are involved in the innovation processes while examining the interactions and interdependencies between them.

Meanwhile, Hermans et al. (2023) use of innovation landscape analysis, which encompasses the research and development context as well as the farm systems context, captured interaction space and complexities in the scaling of conservation agriculture in Malawi. These recent developments mark a departure from the conventional linear approaches in prior adoption studies, suggesting a shift from reductionist studies of technology adoption to a focus on the farming system that a practice is incorporated into and the innovation processes involved. This approach can also be applied to PPT and other agricultural technologies in SSA, to ensure that the needs and perspectives of different farmers and groups are considered and that the innovation process is more inclusive, socially robust, and better suited to local contexts.

5. Conclusion

Given the low rate of technology adoption among smallholder farmers, this systematic review explored the state of research on PPT as a case of agricultural biocontrol innovation in SSA. Our paper captured the benefits of PPT, evaluation approaches, drivers, and barriers to adoption while presenting research gaps and future outlooks. Existing studies have focused on evaluating PPT technical performances, socio-economic benefits, technology dissemination pathways and adoption decisions. Factors that influence PPT adoption have been linked to farmers' perception of PPT efficacy, socio-demographics, and institutional factors. While many studies have evaluated adoption and non-adoption within the farming system, they have yet to examine in depth how groups or individual dynamics and situation peculiarities lead to farmers making innovation decisions concerning PPT. Identified barriers to PPT uptake include labour demand and the initial cost of establishment, access to inputs, implementation difficulty, and cultural practices such as mono-cropping and crop rotations. However, ICIPE remains the primary source of published information on the technology, which could introduce a particular institutional framing and bias to these findings. Besides, most of the articles analyzed in the review come from Eastern Africa. Although the findings from this study could benefit diverse stakeholders in the African food sector, future research with a novel empirical approach, such as ethnography, participatory action research and on-site observation, is needed to unravel not only the biophysical factors but also the transitional, social-political, cultural and institutional contexts within which PPT is being promoted in Africa.

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