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Research Paper

Strengthening banana seed systems among smallholder farmers in Bugiri District, Uganda☆

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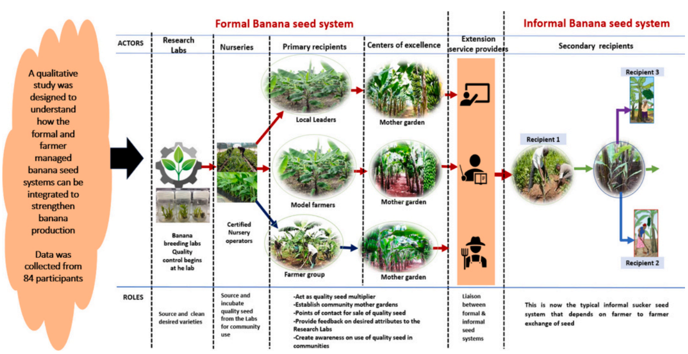
HIGHLIGHTS

- The banana seed system is dominated by informal farmer seed exchange.
- The formal sector supports new breeder varieties, the informal maintains landraces.
- Harmonizing differing quality perceptions fosters integration of the two systems.
- Integrating both systems strengthens seed access, varietal enrichment and quality.

GRAPHICAL ABSTRACT



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ABSTRACT

Context: Farmer-managed banana seed systems support biodiversity but risk spreading pests and diseases. As demand for high-quality disease-free seed grows, formal seed systems with strict standards offer a solution. However, guidance on how to effectively integrate these systems and key actors remains limited, hindering sustainable banana production.

Objectives: The study investigates interactions between formal and farmer-managed banana seed systems, addressing: (i) What structures and pathways define the formal and farmer-managed banana seed systems? (ii) What are the roles and responsibilities of stakeholders facilitating interactions within the integrated seed systems?

Methods: A qualitative approach was used to analyze interactions between formal and farmer-managed seed systems through 12 key informant interviews and 12 focus group discussions. Content and thematic analysis were used to identify crucial structures, pathways, and stakeholder roles in facilitating these seed system interactions.

Results and conclusions: The farmer-managed seed system dominated, relying on trusted informal exchange of suckers, while formal seed sources like research institutions and certified nurseries were rarely used. Stakeholder engagement focused on seed sourcing, mother garden establishment, and awareness creation. Harmonizing

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differing quality perceptions would foster system integration. A proposed strategy outlines stakeholder roles to integrate formal and farmer-managed systems, ensuring local adaptability and genetic diversity preservation.
Significance: Integrating formal and farmer-managed banana seed systems offers a scalable pathway for delivering clean, disease-free planting material of the desired varieties to smallholders. By clarifying stakeholder roles and linking certification with farmer-led multiplication, this approach informs seed policy and development investments that improve seed quality, strengthen biosecurity, and sustain access to locally adapted planting material.

1. Introduction

Worldwide, seed systems are fundamental segments to agricultural development efforts to attain increased food and income security (Nabuuma et al., 2022; McGuire and Sperling, 2016). For most developing countries, the seed systems of vegetatively propagated crops predominantly rely on farmers own seed or informal exchanges between friends and family (Mariel et al., 2024; Abizaid et al., 2016). This informal exchange of planting materials usually referred to as farmer-managed seed system, traditional seed system or local seed system, is majorly dependent on farmer traditional knowledge of seed selection, sourcing, retaining and management as well as local diffusion mechanisms (Kilwinger et al., 2019; Almekinders and Louwaars, 2002). As such, the farmer managed seed system plays a vital role in conservation of local landrace varieties and in the seed security of Vegetatively Propagated Crops (VPCs) at community levels (Almekinders et al., 1994; Coomes et al., 2015).

Banana is perennial with no true “seed” and sucker propagation is the primary method of seed multiplication. Offshoots, or suckers, growing around mother plants' stems are uprooted and replanted to establish new plants (Tumuhimbise and Talengera, 2018). In the banana (*Musa* spp.*)* seed system of East and Central Africa, most smallholder farmers depend on suckers as seed and planting material sourced from friends, neighbors, relatives or own fields, usually within a short distance to establish new gardens (Lwandasa et al., 2014; Kilwinger et al., 2019; Nduwimana et al., 2022). In Uganda, this seed system is unique, featuring a diverse range of banana varieties (Karamura et al., 2012). This farmer-managed seed system is generally preferred over the formal seed system due to its accessibility, cost-effectiveness, and perceived reliability. Even when planting material is available on the market, many farmers opt to use their own seed to minimize expenses and mitigate risks associated with farming, such as unpredictable weather, patterns, pest infestations, and fluctuating market prices. Additionally, farmer reliance on “own seed” is also due to the complications of investment in the economic production of vegetative planting materials that relate to low multiplication rates, bulkiness, high perishability, cost of storage and transportation (Waigumba et al., 2016). Vegetatively propagated planting materials pose a high-risk of transmitting pests and diseases on-farm and across farms because the seed is a contiguous part of the older mother plant which is seldom certifiably disease free (Jogo et al., 2013). Thus, seed degeneration (loss of seed quality and production potential due to the accumulation of pathogens in subsequent generations) is a major problem for all VPCs (Andrade-Piedra et al., 2020; Ogero, 2022).

The formal seed system, though shown to offer only a limited range of banana varieties (Mulugo et al., 2022; Simbare et al., 2020), remains a potential solution because it operates within specified quality standards and has advantages in accessing and introducing novel genetic materials through national and government breeding programs (Leyte et al., 2022). Within such a system, planting materials are typically released as **cultivars,** which are selectively propagated by humans to enhance desirable traits and consistently retain the characteristics of their parent plants. In contrast, a **variety** arises naturally through evolutionary processes and exhibits differences from the standard species (Lawrence, 1953). New varieties presenting superior qualities are often first introduced through the formal seed system. They are subsequently spread and shared between producers through the farmer-managed seed system, denoting wider acceptance of some of these cultivars (Almekinders and de Boef, 2000; Sperling and Almekinders, 2023). Strengthening the formal-informal linkages is an important step in improving the system, and the flow of new varieties into the hands of the farmers. Banana seed is often supplied as suckers (predominantly exchanged informally) or plantlets issued from tissue culture or macropropagation (the main forms of seed from the formal seed system). The former is robust, and its selection involves a direct observation of the mother plant, the parent garden or trusted producer; while plantlets are considerably smaller and require greater initial management to establish (Mulugo et al., 2022). However, the formal supply system does not have an obvious link with the mother plant, garden or social connection with producers. As such, the assessment qualities in seed selection as used in farmer exchanges and descriptors available from the formal seed system could be misaligned. Since the descriptors form a significant portion of seed value proposition within the informal system, this presents a notable gap in the proposed versus desired value, where novel breeder material were to be adopted by farmers without direct trusted evaluation as in the informal system.

Some of the underlying reasons for this gap relate to economic factors such as high cost of agri-technologies/seed, and higher labour and input requirements (Kabunga et al., 2012), farmer beliefs and attitudes towards seed from the formal sector (Mulugo et al., 2019), socio- cultural impediments to use of introduced agri-technologies (Mulugo et al., 2022) and a lack of community participation in research and development processes (Sanya et al., 2018). Bridging this gap therefore calls for an understanding of the interactions between formal and farmer-managed banana seed systems, specifically addressing: (i) What structures and pathways define the formal and farmer-managed banana seed systems? (ii) What are the roles and responsibilities of stakeholders facilitating interactions within the integrated seed systems? This is fundamental to improving investment and genetic turnover in the VPCs, to eventually escalate banana production and sustainability by taking advantage of superior seed.

2. Methods

The study was conducted in six banana growing communities in Bugiri district, Eastern Uganda. Bugiri district lies in the Lake Victoria Crescent (LVC) agroecological zone in Eastern Uganda. The region has a bi-modal rainfall pattern, receiving about 272 mm (11 in.) of precipitation annually and mean temperatures of 24 °C to 27 °C. In these conditions, the main crops grown include banana, coffee, sweet potato, maize, cassava, sorghum, millet and lowland rice (Mwebaze, 2011). Banana is an important perennial staple food, cultural and commercial crop in the district. Communities in the main banana growing areas: Buwunga and Nabukalu sub-counties were selected. Specifically, Kavule, Kayaigo and Namalena villages in Buwunga sub county and Kabasala, Isegero and Bukubansiri villages in Nabukalu sub county respectively were the study sites (Fig. 1).

A qualitative case study design was employed to enable an in-depth understanding of how.

formal and farmer managed banana seed systems can be integrated to strengthen banana.

production in Bugiri District. The study used Focus Group

Discussions (FGDs) and Key.

Informants (KI) as tool to gather data from 84 respondents (see Table 1).

We used Focus Group Discussions (FGDs) to collect in-depth qualitative data to characterize banana production systems in the study area, describe the structures and pathways of both formal and farmer-managed banana seed systems, and explore the roles and responsibilities of different stakeholder groups. In addition, Key Informant Interviews (KIIs) were conducted to capture expert perspectives. A total of 12 FGDs and 12 KIIs were conducted, with data collection continuing until thematic saturation was reached, as confirmed by Hennink and Kaiser (2022) that qualitative studies reach saturation at relatively small sample sizes, ranging from 9 to 17 interviews or 4–8 focus group discussions. We employed local leaders in the different villages to recruit the FGD participants based on age, sex, experience in banana production and the number of banana mats owned at the time of the study. In this context, a planted sucker develops into the primary mother plant, from which additional suckers emerge from the corm, collectively forming a clonal aggregation known as a "banana mat" or a genetically identical group of banana plants.

It was envisaged that men and women farmers with at least three consecutive years in banana production and ownership of at least 100 banana mats had adequate information to meet the objectives of the study. The FGDs used semi-structured discussion guides to gather information on banana varieties grown and their role in farming systems, identify seed sources used by smallholder farmers, and explore historical trends and the broader context of banana seed systems. A social network map was also developed within the focus groups to describe the seed pathways (seed flows or channels through which seed moves from a source to the user) that smallholder farmers in farmer managed seed systems used to access seed. Farmer responses were recorded based on consensus, where participants reached agreement on views, explanations, attributes, ideas, or reasons. Divergent opinions were noted separately and considered during data analysis.

Based on the results from the FGDs, key informant interviews were conducted with 12 respondents to triangulate the data especially on the seed sources and the seed pathways of the banana seed. With the help of the District Agricultural Officer, key informants were purposively selected based on their roles experience and knowledge of banana production and seed systems in Bugiri. It was believed that men and women farmers that were over 50 years of age and with a banana production experience of over ten years had the capacity to generate the historical events, describe trends, triggers and contexts in which the banana seed system evolved over the years. Four banana breeders from the National Agricultural Research Organization (NARO) were also interviewed to obtain the quality attributes of banana seed and describe the structures of a formal banana seed system.

We use content and thematic analysis to synthesize findings from 12 focus group discussions.

and 12 key informant interviews. Detailed notes taken during the FGDs and KIIs were.

transcribed verbatim into a word processing application, and

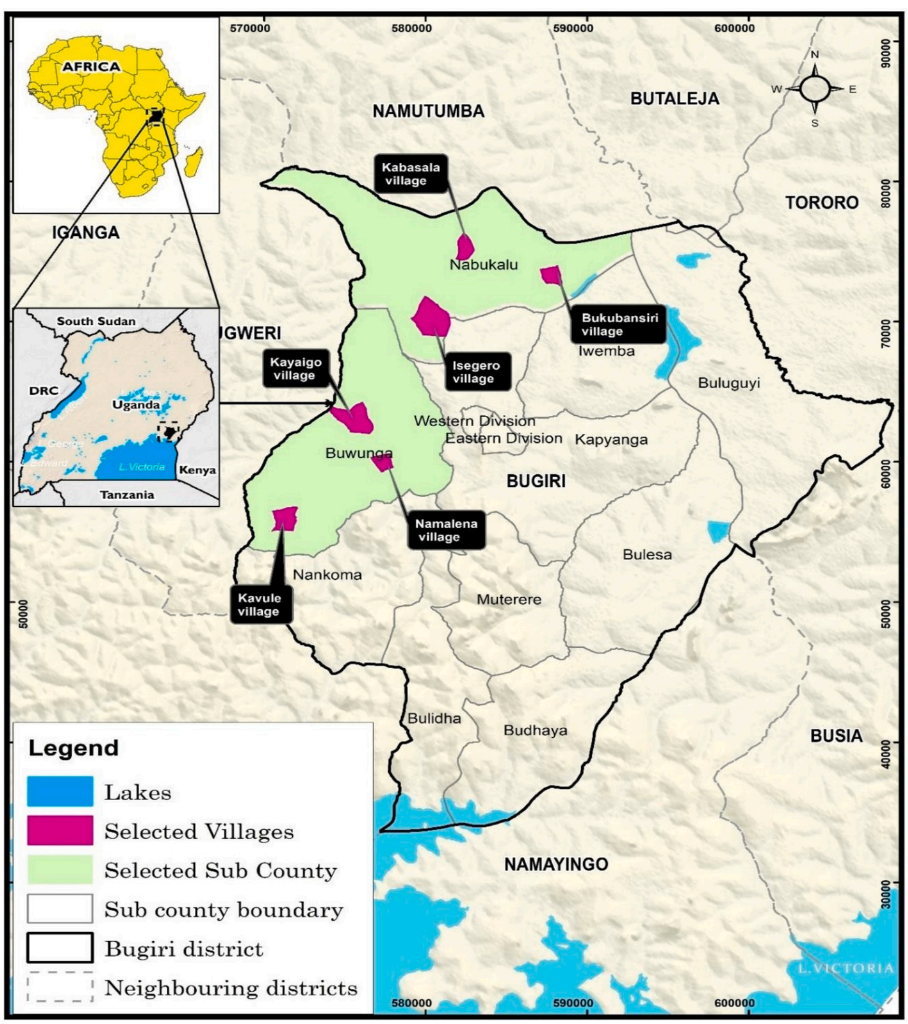

Fig. 1. Location of study villages in Bugiri District.

Table 1
Focus group discussions and Key informant participants by sex.

Location (Villages)	Number of FGDs by Sex			Key informants (KI) by sex		
	Male	Female	Participants	Male	Female	Number
Kavule	1	1	Male (6), female (6)	1	1	2
Kayaigo	1	1	Male (6), female (6)	1	1	2
Namalena	1	1	Male (6), female (6)	1	1	2
Kabasala	1	1	Male (6), female (6)	1	1	2
Isegero	1	1	Male (6), female (6)	1	1	2
Bukubansiri	1	1	Male (6), female (6)	1	1	2
Total	**6**	**6**	**72**	**6**	**6**	**12**

summarized in Microsoft excel. Open coding was conducted for data from each FGD and KII using Microsoft Excel to identify recurring codes and generate common themes that defined the structures, stakeholder roles, and seed provisioning pathways within the formal and farmer-managed banana seed systems. Content analysis was then applied to interpret the emergent themes and synthesize the findings into a coherent narrative, providing a comprehensive understanding of the major strategies to integrate the formal and farmer-managed banana seed systems.

3. Results and discussion

3.1. Socio-demographic characteristics of respondents

The socio-demographic characteristics of the respondents who participated in the FGDs are summarized in Table 2. Majority of the respondents (50%) were aged between 31 and 50 years, and a significant proportion (93%) were married. Forty six percent of the study participants attained primary and secondary school education, with most (89%) owning land, between 0.2 and 0.61 ha on which they grow bananas.

Majority of respondents owned between 10 and 200 banana mats, with 67% having less than 10 years of experience in banana farming. It was established that the Basoga ethnic group was predominant in the study communities, comprising 86% of the respondents with most of the respondents (82%) living in households of 1 to 10 family members.

Table 2
Socio-demographic characteristics of respondents ($n = 72$).

Variable		Frequency	(%)
Sex	Male	36	50
	Female	36	50
Age	Youth 18–30 years	17	23.8
	Middle age 31–50	36	50
	Older adults >51	19	26.2
Marital status	Married	67	92.8
	Single	2	2.4
	Widowed	3	4.8
Education	Primary education	33	45.5
	Secondary education	34	47.3
	Tertiary education	5	7.2
Household size (Count)	1–5	24	33.3
	6–10	35	48.8
	> 10	13	17.9
Land size under banana Cultivation (Ha)	0.20	47	65.5
	0.24–0.61	17	23.8
	> 0.61	8	10.7
Total land size owned (Ha)	0.40–2.02	47	65.5
	2.43–4.05	18	25.0
	> 4.05	7	9.5
No. of banana mats owned	10–100	32	44.1
	101–200	23	32.1
	> 200	17	23.8
Experience in banana farming (Years)	1–10	48	66.7
	11–20	10	14.3
	> 20	14	19.0
Ethnicity	Soga	62	85.7
	Others (Ganda, Teso, Samia)	10	14.3

3.2. Banana diversity within Bugiri communities

Twenty-seven banana varieties were found to be grown in the six study communities (Fig. 2 and Table 3). These varieties were predominantly from the Nakitembe clone set while other banana varieties belonged to the Musakala, Mbidde and Nakabululu clone sets (Karamura et al., 2012). It was established that several banana cultivars did not belong to any of the dominant banana clone sets. For example, in one of the FGDs in Kavule village a farmer specified:

> …*We realized that some of the banana suckers we received from the extension personnel and grow are too different from our well -known banana* types (Male FGD –Kavule village).

These included introduced cultivars such as FHIA 17, FHIA 01, FHIA 25, and KM5 (Kabana5), developed by the Fundación Hondureña de Investigación Agrícola (FHIA) in La Lima, Honduras (Table 3). These varieties were primarily grown for cooking (FHIA 01), dessert (FHIA 17), juice/brewing (FHIA 25), and both cooking and dessert purposes (KM5).

The diversity of varieties grown in the study communities were mentioned to be associated with a wide range of uses and preferences, ranging from food, income, cultural and medicinal properties. Table 3 shows the principal roles of the commonly grown banana varieties in the study communities. These also notably include newly introduced banana varieties as TC plantlets (marked with an asterisk *).

3.3. Trends in banana production in Bugiri communities

Banana production has long been an integral part of the cropping systems in Bugiri District. The analysis of perceived changes in banana productivity among farming communities revealed a distinct cyclical pattern characterized by an initial increase in productivity, followed by a prolonged period of decline, and a recent phase of partial recovery. As illustrated in Fig. 3, banana productivity reached its peak in the late 1960s before experiencing a sharp decline leading into the 2000s. Insights from key informants reveal that during the early years of banana cultivation, farmers reported high productivity levels, attributed primarily to favourable agroecological conditions characterized by the inherent soil fertility, low pest and disease pressure, and the use of healthy sucker planting material, as noted one male farmer.

> *"In the late 1960s, banana production was at its peak in this community. The climate was favourable, the soils were fertile, and pests and diseases were not as rampant as they are today."* (Male farmer, KI Bukubansiri village).

During this period, farmers relied solely on sucker planting material. However, over time, they began using a combination of suckers and tissue culture plantlets. As one breeder explained:

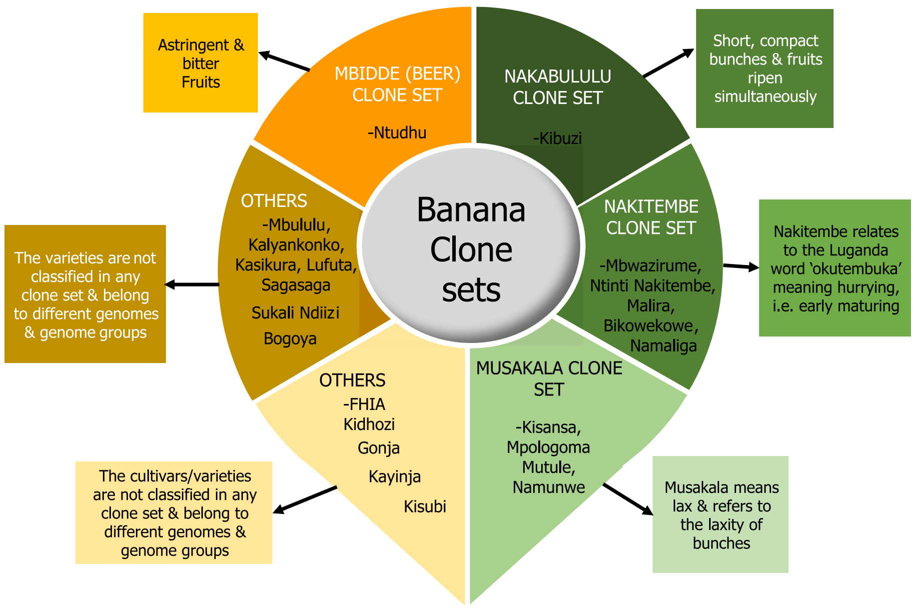

Fig. 2. Clone sets and their characteristics in Bugiri farming communities.

Table 3
Uses of commonly grown banana varieties.

Banana varieties	Clone set	Genome	Genome Group	Major Use
*Kisansa**	Musakala	East African Highland	AAA-EA	Cooking & Commercial
*Mpologoma**				
Mutule				
Namunwe				
*Mbwazirume**	Nakitembe	East African Highland	AAA-EA	Cooking
Nakitembe				
Ntinti				
Namaliga				
Bikowekowe				
Malira				
*Kibuzi**}	Nakabululu	East African Highland	AAA-EA	Cooking
Ntudhu}	Mbidde	East African Highland	AAA-EA	Brewing
Mbululu		East African Highland	AAA-EA	Cooking
Kalyankonko		East African Highland	AAA-EA	Cooking
Kasikura		East African Highland	AAA-EA	Cooking
Lufuta		East African Highland	AAA-EA	Cooking
Sagasaga		East African Highland	AAA-EA	Cooking
Bogoya		Gros Michel	AAA	Dessert
*FHIA 17**		Tetraploid hybrids	AAAA	Cooking & Dessert
*FHIA 01**		Tetraploid hybrids	AAAA	Cooking
*FHIA 17**		Tetraploid hybrids	AAAA	Juice/ Brewing
KM5 (Kabana 5) *				Dessert
Gonja		Plantain	AAB	Roasting
Kayinja		Pisang Awak	ABB	Brewing
Kidhozi				Multi-use
Kisubi		Ney Poovan	AB	Brewing
Sukali Ndiizi		Kamaramasenge	AAB	Dessert

*Newly introduced varieties.

"At first, farmers only used traditional suckers because that's what was readily available and familiar. But with increased awareness and support, many have now adopted tissue culture plantlets alongside suckers to improve yields and disease resistance."

It was also established that, during this period, population density was relatively low, and land was managed using longer fallow periods, which allowed for natural replenishment of soil nutrients.

"With a smaller population, land use intensity was lower, allowing for longer fallow periods, which helped maintain soil fertility."
(Female farmer KI, Bukubansiri village)

"At that time, there was very limited exposure to pests and diseases. Due to the relatively low intensity of banana cultivation, disease-causing pathogens had not yet spread widely across farms, which contributed to high productivity." (Male farmer KI, Isegero village).

"Banana production during this period was relatively low, and planting materials were sourced within communities. This, in turn, helped control the transfer of pests and diseases from outside the community." (Male farmer KI, Kayaigo village).

Although farmers initially planted carefully selected materials from healthy mats, banana productivity declined sharply between the 1970s and 2000s. This period was marked by severe plant stunting, bunch failure, and widespread field abandonment. Soil profiles showed signs of erosion and nutrient depletion, while pest and disease damage were reportedly visually extensive. This decline was accompanied by a shift in farmer livelihoods, with many reducing reliance on banana farming. This is corroborated with the insights from FGDs, as one participant put it:

"We planted suckers which were carefully selected from specific mats. They were either from our gardens, from friends or relatives. This was a sustainable source of planting materials because it ensured the continuity of our banana production. However, this practice remained common until the late 2000s when our plantations were severely hit with banana bacterial wilt, drastically reducing the availability of healthy suckers. Now, the extension agent is encouraging us to use tissue culture plantlets as a more reliable disease-free planting material for banana cultivation."
(Male FGD participant, Kayaigo village)

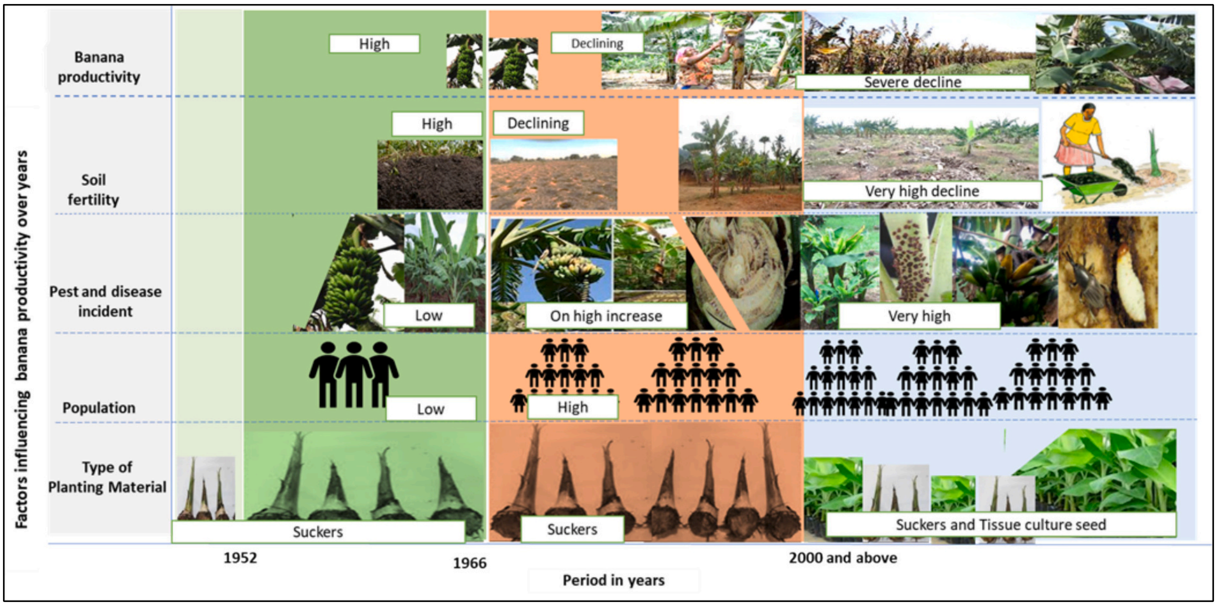

Fig. 3. Perceived trends in banana productivity in Bugiri farming communities.

This decline in banana productivity was attributed to several interrelated factors. Rising human population density increased pressure on land, resulting in continuous banana cultivation. This led to soil nutrient depletion and heightened vulnerability to pests and diseases, most notably banana weevils, nematodes, fusarium wilt, banana bacterial wilt and black sigatoka, which collectively caused a sharp drop in productivity.

This phase was further exacerbated by continued use of low-quality suckers and inadequate disease management. These challenges significantly reduced yields over the years, as reflected in the remarks of a female farmer below.

> *"Back then, every household had a thriving banana plantation. We never worried about shortages because the conditions were just right for production. Today, the story is different—our banana plantations are shrinking, and the yields have drastically dropped,"* lamented a female KI from Kayaigo village.

Initially, banana production relied exclusively on suckers, which were commonly sourced from existing plantations. However, the spread of diseases through infected suckers contributed to declining yields.

> *"In the past, we only used suckers from our own plantations or from neighbors. It was an easy and familiar method. But over time, we started noticing that some newly established plants were weak and dying early. We later realized that the leaves were wilting, turning yellow, and drying out, and that these symptoms were spreading through the sharing of suckers,"* explained an elderly male farmer male farmer KI from Kabasala village.

In response to persistent productivity challenges, research and agricultural institutions began introducing tissue culture banana seedlings in the early 2000s to farmers. These disease-free seedlings offered a promising alternative to conventional suckers, aiming to enhance seedling vigor, reduce pathogen transmission, and improve overall yields. The shift towards tissue culture banana seedlings reflects a cyclic nature of production decline and regeneration within smallholder banana farming system, which is an adaptive strategy to rejuvenate banana production under deteriorating traditional farming conditions.

There are however, mixed perspectives on how bananas were first introduced to Bugiri District. While some farmers in the study communities believe that bananas are native to the area, others claim that the first banana suckers were introduced from Central Uganda, where bananas had long been established as a staple food crop. One farmer recalled how her grandmother visited a friend in Central Uganda and returned with a few banana suckers, which she planted and later multiplied into a thriving plantation.

> *"I remember my grandmother telling us that she visited a friend in Buganda and brought back a few banana suckers. She planted them in our garden, and over time, they multiplied into a big plantation. From our garden, neighbors and friends also came for suckers,"* shared an elderly male participant from a FGD in Isegero village.

This account suggests that bananas may have been introduced to the region through farmer-to-farmer exchange of planting material, predominantly suckers, long before the introduction of tissue culture seedlings. It highlights the crucial role of farmer-managed seed systems, which are deeply rooted in local knowledge, preferences, and social networks. These informal seed systems have historically facilitated crop introduction, adaptation, and resilience, demonstrating their continued importance in sustaining agricultural biodiversity and food security.

3.4. Farmer-managed banana seed system in Bugiri District

From the focus group discussions, it was established that farmers select banana suckers based on specific visual attributes that indicate the plant's health, vigor, and potential for successful growth and high yield (as illustrated in Fig. 4). Farmers emphasized the importance of these traits in ensuring productive banana cultivation:

> "When choosing suckers, we look for those that are strong, with thick stems and healthy *leaves. These show that the plant will grow well and produce good bananas."*
>
> (Male FGD participant, Namalena village)

> *"We choose suckers from mother plants that have big, healthy bunches and show resistance to diseases."*
>
> (Female FGD participant, Isegero village)

> "When selecting banana suckers, we look for banana mats with big bunches, many *clusters, and large fingers. The bigger the efflorescence, especially when it blooms, the better. And we only choose sword suckers because they grow strong and produce better yields. These are the signs of a healthy plant that will perform well in the field."*

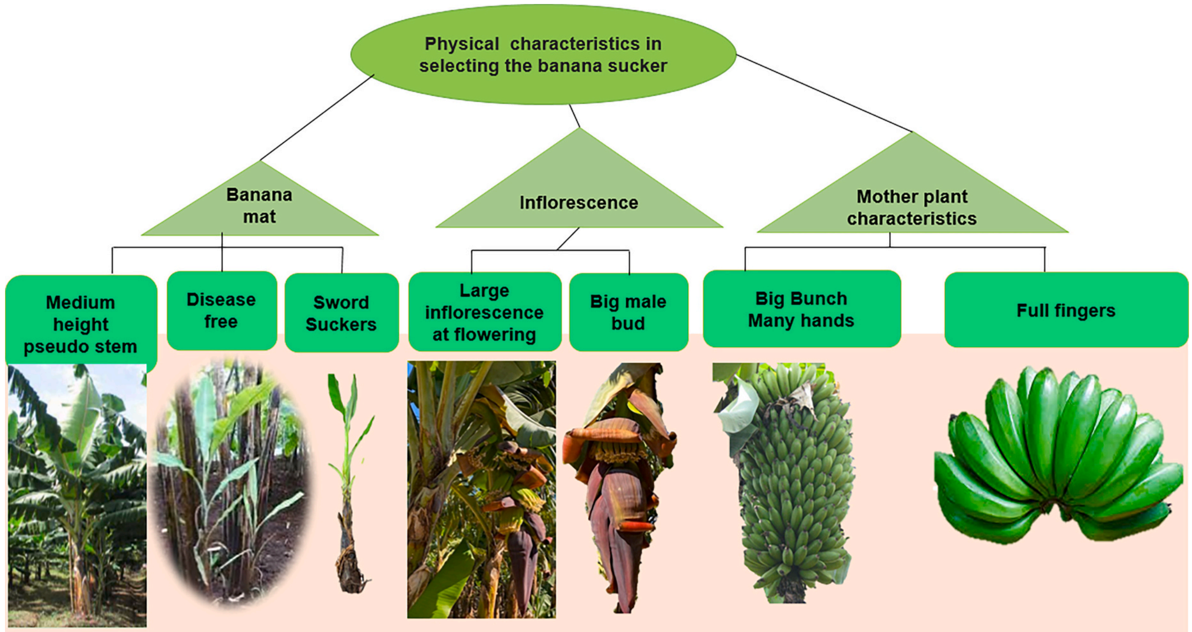

Fig. 4. Farmer selection criteria of good quality suckers in Bugiri.

(Male FGD participant, Kabasala village)

"We also consider the growth pattern—suckers from productive plants with deep green leaves and thick stems are the best because they establish quickly and yield well."

(Female FGD participant, Kavule village)

From the findings, the farmer managed banana seed system primarily relies on suckers as the main planting material, with existing banana mats serving as the primary source. The selection process is based entirely on the physical observation of phenotypic attributes, underscoring the importance of farmers' traditional knowledge in maintaining plant health and productivity. This practice plays a crucial role in preserving desirable traits, enhancing crop resilience, and sustaining banana production in local farming communities.

By assessing these characteristics, farmers evaluate the quality and suitability of planting material for propagation, a practice that closely aligns with the physiology of the banana plant. Various studies (Kusena et al., 2017; Herpers et al., 2017) affirm that farmer-led seed systems have the capacity to select high-quality planting material and recommend that such systems be recognized, aligned, and promoted to meet the evolving needs of smallholder farmers in sub-Saharan Africa. Furthermore, this method of selection is not merely an individual practice but is often shared within farming communities through social networks, reinforcing the collective knowledge and sustainability of traditional seed systems.

3.5. The role of social networks in the farmer managed banana seed system

Social networks play a crucial role in shaping the farmer managed banana seed system, which largely relies on personal connections within the distribution chain. These networks enable farmers to connect with family, friends, and other community members, fostering trust-based institutions that facilitate the exchange of planting materials (Fig. 5).

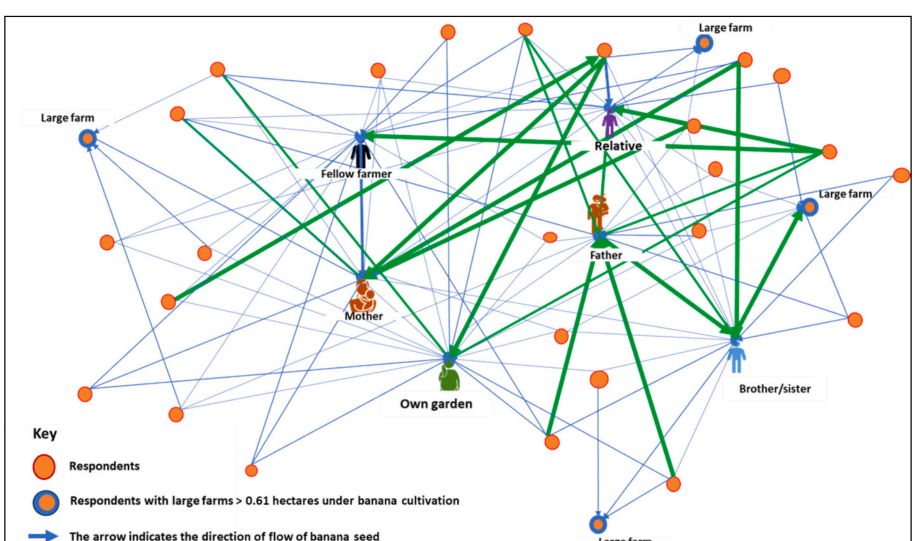

Fig. 5. Sucker Flow Pathways among small-holders in Bugiri banana farming communities.

Additionally, social ties provide multiple layers of evaluation through trusted referrals, serving as pathways for the dissemination of information and agricultural innovations while leveraging existing relationships.

Fig. 5 illustrates the network map and dynamics of planting material exchange, with a focus on banana suckers that serve as essential planting materials for banana production in the district. The nodes in the network represent individual actors, differentiated by type. Red circular nodes denote smallholder farmers without banana plantations, while blue circular nodes with inner dots represent farmers who own and cultivate large banana farms (> 0.61 ha). Key actors, such as immediate family members (mother, father, siblings), extended relatives, and fellow farmers are depicted using distinctive human icons to indicate their central role in the sucker-sharing network. The edges (lines) between nodes show the direction of banana sucker exchange, with arrows indicating the flow from donor to recipient. Blue arrows represent occasional or one-time exchanges, while green arrows highlight strong or frequent interactions, suggesting trusted and recurrent pathways of sucker dissemination. Line thickness represents the relative strength and frequency of reported linkages: thick lines correspond to connections repeatedly mentioned and strongly emphasized across multiple FGDs, whereas thin lines indicate less frequent or less emphasized linkages.

The network reveals a highly interconnected system comprising informal exchange mechanisms. Centrality is especially pronounced among kinship ties, with actors such as the mother, father, and other close relatives emerging as key hubs serving as primary sources or intermediaries for planting material. In addition, farmer-to-farmer exchanges contribute significantly to the flow of suckers, indicating the importance of horizontal linkages within the community's seed system.

These findings indicate that banana seed distribution is perceived to be deeply rooted in local seed sourcing, with farmers primarily obtaining planting materials through kinship networks and their own gardens. Within these kinship-based networks, planting materials are exchanged predominantly among family members and close acquaintances, reinforcing trust, reciprocity, and social cohesion. The strength of these social bonds significantly influences the flow of banana seed from one farmer to another. Farmers in Kayaigo village emphasized the importance of these connections in accessing planting material:

> *"In our community, we rely on each other when it comes to getting banana suckers,"* one farmer shared during a focus group discussion. *"If I need planting materials, I first ask my relatives or close friends because I trust them. We exchange suckers among ourselves, knowing they come from healthy gardens."* (Female FGD participant, Kayaigo village)

> Another participant added,

> *"This farmer managed system has been in place for generations. We don't just take suckers from anyone—we get them from people we know and trust, which helps ensure we plant good-quality bananas."* (Male FGD participant, Kayaigo village)

> *"In our community, we mostly get banana suckers from relatives and close friends. It's easier to trust family because you know where the plant is coming from and that they will always help if you need more."* (Female FGD participant, Namalena village)

These interactions are deeply woven into cultural traditions that sustain both agricultural practices and social bonds within communities. This aligns with Singh (2004), who argues that social networks play a crucial role in technology transfer and enhance the success rate of innovations.

Within the farmer managed seed system, a distinct group of banana farmers exists, those who are self-sufficient and source suckers exclusively from their own farms. These farmers typically have well-established, expansive banana plantations that provide an ample supply of suckers to meet their planting needs. Their deep knowledge of banana cultivation, combined with access to diverse and resilient banana varieties, allows them to sustain and expand their plantations independently.

As one male farmer KI explained,

> "I have been selecting and replanting suckers from my own farm for years. I know which ones grow well in my soil and can withstand drought."

> Another farmer echoed this sentiment, adding the following:

> *"When I need to expand my plantation, I don't have to buy seed from elsewhere. I have all the suckers I need right here."* (FGD participants Kayaigo village)

While these farmers do not seek planting materials from others, they often share surplus suckers with fellow farmers, thereby indirectly supporting the broader agricultural network without actively participating in reciprocal exchanges. Despite its benefits, this farmer-to-farmer seed exchange system lacks formalized structures, making access to quality planting material highly dependent on social connections. The network is largely invisible, meaning that farmers without the right connections may struggle to obtain good planting material. Unlike formal seed systems with designated distribution points, the sucker is not considered a "public good" within the farmer managed banana seed system. There are no structured mechanisms where any farmer can reliably access quality planting material whenever needed.

Participants in FGDs highlighted these challenges:

> *"Getting good banana suckers depends on who you know,"* explained one farmer. *"If you don't have the right connections, it's difficult to find healthy planting material."* (Female FGD participant, Namalena village)

> Another participant added,

> *"There's no organized place where any farmer can just go and pick quality suckers. You have to rely on friends or family, but if you're new in the area or don't have those ties, you might struggle to get good planting material."* (Female FGD participant, Namalena village)

A major limitation of this system is its lack of inclusivity, as farmers with limited social networks may struggle to access the desired quality of planting material. This reliance on personal connections creates barriers for newcomers, marginalized farmers, or those without strong kinship ties. While farmer-led seed systems have proven effective in selecting high- quality planting material, there is a need for more approaches to ensure equitable access. Strengthening seed distribution networks whether through organized farmer groups, community seed banks, or agricultural cooperatives could help bridge this gap and enhance the sustainability of banana production in Bugiri District and beyond. Additionally, digital solutions can be leveraged to strengthen these connections, especially given the increasing access to mobile phones and the internet in the area (Atamanov et al., 2023).

3.6. Stakeholders and structures of the formal banana seed system in Bugiri District

The formal banana seed system, though not widely prevalent at the farm level, was mentioned in individual interviews to play a crucial role in the broader agricultural landscape by ensuring the availability of disease-free, high-quality planting materials. In fact, it is a backup for all farmers. Fig. 6 highlights a well- coordinated system for the propagation and distribution of banana planting materials with several key players from breeding centers to individual farmers- as was mentioned by all interviewees.

The system is often managed by agricultural institutions or specialized nurseries who use advanced techniques to produce uniform and resilient banana seed. Because of this, the formal banana seed system is easier to characterize in terms of structures, products and actors (Bishaw and Turner, 2008; Louwaars, 1994). The process begins at genetic

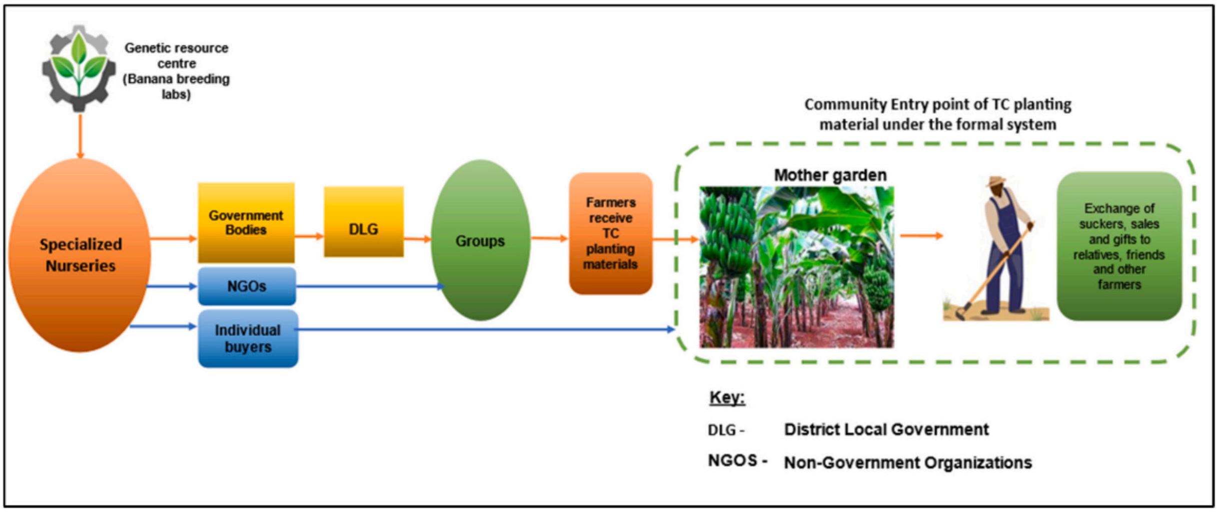

Fig. 6. Stakeholders in the formal banana seed system.

resource centres where tissue culture seed is developed and passed on for quality control and multiplication by specialized nurseries. After multiplication in specialized nurseries, the seed has three primary distribution pathways. The seed is purchased by governmental and non-governmental organizations through their agricultural programs who then deliver them free of charge to farmer groups. For example, a key informant emphasized;

> *"The journey of this banana seed starts in research centres where they are carefully developed. From there, they go to specialized nurseries for multiplication. Once ready, organizations both government and NGOs step in, buying the seed and distributing them to farmer groups at no cost. This way, even small-scale farmers can access high-quality planting material without struggling to afford it"*. (KI, Breeder)

These groups further propagate the seed to establish their own mother gardens. Individual buyers may also purchase seed directly from the nurseries to establish their own banana gardens. Ultimately, the resulting suckers from these gardens find their way into farmer managed seed systems through informal seed exchange networks. This was described by one of the interviewees:

> *"Some farmers buy tissue culture seedlings directly from nurseries to start their own banana gardens. Later, the suckers from these gardens are shared among neighbours, friends, and relatives through the traditional exchange system. Even though most small-scale farmers rely on informal seed sharing, the nurseries remain important because they provide disease-free planting materials when our local sources are affected by pests and diseases"*. (KI, Breeder)

It is therefore evident that while the formal system is not commonly used by most smallholder farmers, it serves as a critical backup for the farmer managed seed system as it provides a reliable source of clean planting materials where traditional methods fail due to disease outbreaks to sustain the production of large quantities of planting material.

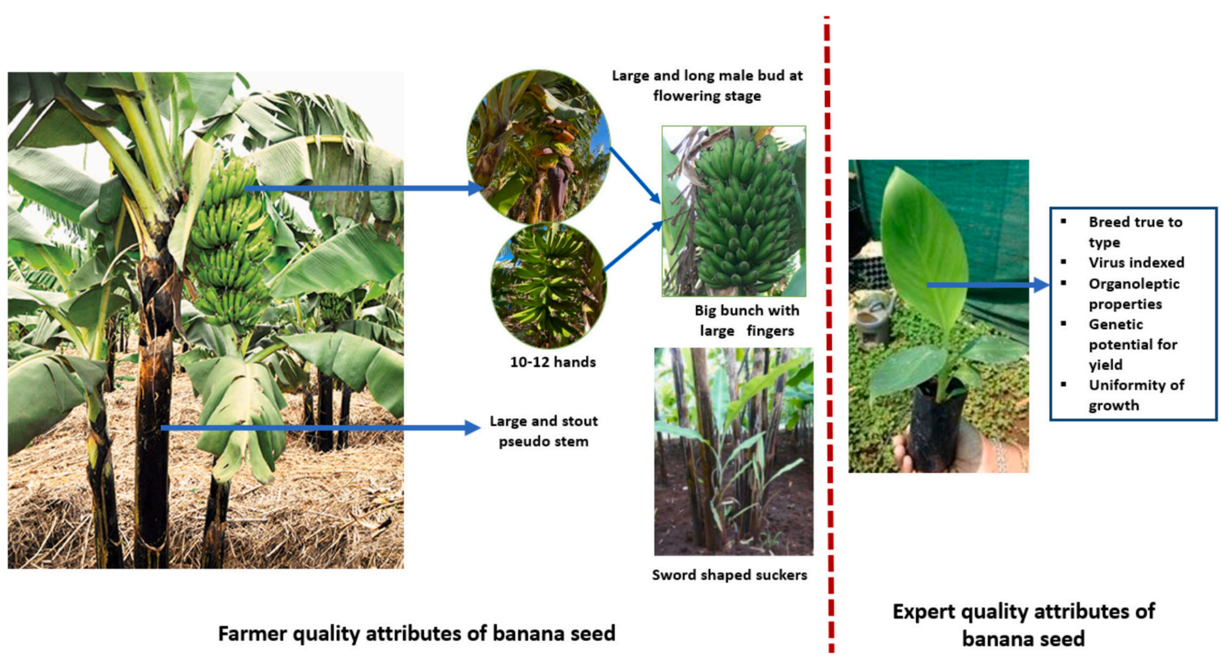

Fig. 7. Farmer and Expert Quality Attributes of the Banana Seed.

3.7. The integrated sucker-tissue culture banana seed system

The integration of farmer-managed and formal banana seed systems is driven by the mismatch between the observable banana seed characteristics valued by farmers and the traits provided through tissue culture banana (Fig. 7). Farmers express concerns about this disconnect, highlighting the practical challenges they face when adopting tissue culture plantlets.

> *"When we plant suckers from our own farms, we know exactly what we are getting—whether it's Mpologoma, Kibuzi, or Nakitembe. But with tissue culture, we can't be sure,"* shared a female farmer from Kavule village.

Another female FGD participant from the same village added,

> "At first, all tissue culture plantlets look the same. You can't tell if it's a cooking banana, a sweet banana, or one meant for brewing until much later."

The ability to select healthy suckers based on observable traits is key to farmers' decision-making.

> *"We look at the size of the corm, the color of the leaves, and even how the mother plant is performing before choosing a sucker,"* explained a male farmer from Kabasala village.

Another farmer noted,

> "With our traditional methods, we select suckers that we know will survive in our soils and withstand drought."

Beyond adaptability, market and food security concerns also shape farmers' preferences.

> *"If I plant the wrong variety, I could lose an entire season, which is a huge risk for my family's food and income. At the early stage, they all (TC plantlets) look the same. You can't tell if you are planting a cooking banana, a sweet banana, or one meant for brewing until much later. By the time you realize it's not what you expected, you have already invested time, labor, and resources"* said an FGD participant from Kyampisi.

Similarly, another FGD participant from the same village emphasized,

> "The bananas we grow must meet what the buyers want—taste, texture, and size matter. A variety that doesn't sell well is not useful to us."

These perspectives underscore the key challenge of adopting tissue culture plantlets: the uncertainty surrounding early-stage identification and adaptability. To enhance uptake, the formal seed system must incorporate farmers' knowledge, improve labelling and extension services, and develop participatory selection approaches that align with farmers' practical needs.

Additionally, these interactive narratives also highlight farmers' deep understanding of their farming environment and their reliance on key phenotypic traits to identify good banana suckers. Quality is assessed based on observable traits, ensuring that the selected suckers align with their production needs. In contrast, breeders define quality in terms of genetic fidelity, emphasizing the importance of true-to-type breeding, uniform bunch formation, desirable organoleptic properties for consumers and virus indexing of mother plants to produce disease-free plantlets for large-scale propagation. While these perspectives differ, they are ultimately complementary. Farmers' phenotypic selection criteria are, in essence, expressions of the plant's genetic makeup, reinforcing the validity of both approaches in defining quality banana seed. Integrating these viewpoints can bridge the gap between traditional and formal seed systems, improving adoption and ensuring the production of planting materials that meet both scientific standards and farmer preferences. Therefore, the farmer managed and formal seed systems can coexist and overlap, and together ease the movement of quality and locally meaningful seed.

As discussed above. a functional and efficient banana seed system requires a complementarity between the formal and farmer managed seed systems. Fig. 8 shows how this complementarity can be built with the different stakeholder groups.

Figs. 8 shows the roles and interactions among the different stakeholder groups between formal and farmer managed banana seed systems. In the formal system, research laboratories initiate the process by sourcing and cleaning banana varieties to ensure disease-free, high-quality seed. This seed is then transferred to certified nurseries for multiplication. Local leaders, model farmers, and farmer groups then act as primary recipients and establish community mother gardens where the seed is further multiplied and distributed to smallholder farmers. Once the clean planting materials reach farm communities, community-based exchanges of planting materials, sharing suckers through local networks are triggered.

Extension service providers play a crucial role in bridging the formal and farmer managed seed system by disseminating information, providing training, and facilitating knowledge exchange. Extension services serve as seed sourcing for desirable cultivars, establishment of community mother gardens and awareness creation on use of quality seed within farming communities. It enhances sustainability by incorporating innovations from the formal system into local practices and creating a feedback loop that informs research and development. Moreover, integration ensures that the benefits of the formal system, such as disease resistance and improved yields, reach a broader range of farmers, thus creating a more resilient and productive banana seed system.

4. Conclusion and recommendation

This study highlights the structural and functional contrasts between farmer-managed and formal banana seed systems in Bugiri District, Uganda. While the farmer-managed system rooted in social trust and operated through informal sucker exchange—preserves cultivar diversity of farmer varieties, and supports local adaptation, it lacks inclusivity and quality control. Conversely, the formal system offers genetically verified, disease-free tissue culture (TC) plantlets, yet remains largely disconnected from the social and cultural practices of smallholder farmers.

The limited adoption of TC plantlets reflects deeper mismatches in how quality is perceived farmers emphasize observable traits, while formal systems prioritize genetic and physiological standards. Bridging this divide requires more than technical solutions; it demands the alignment of stakeholder roles, improved communication, and co-designed quality standards that reflect both scientific rigor and farmer preferences. This study, therefore, proposes a framework for integrating the two systems, outlining clear stakeholder responsibilities from seed sourcing and mother garden management to awareness creation and local engagement. Such integration can improve access to clean planting material, strengthen farmer trust in formal products, and promote timely delivery of seed. More broadly, it enhances genetic diversity conservation and contributes to the sustainability and resilience of banana seed systems for vegetatively propagated crops.

CRediT authorship contribution statement

Lucy Mulugo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Florence Birungi Kyazze:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Emmanuel Ngolobe:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis. **Aman Bonaventure Omondi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Funding acquisition,

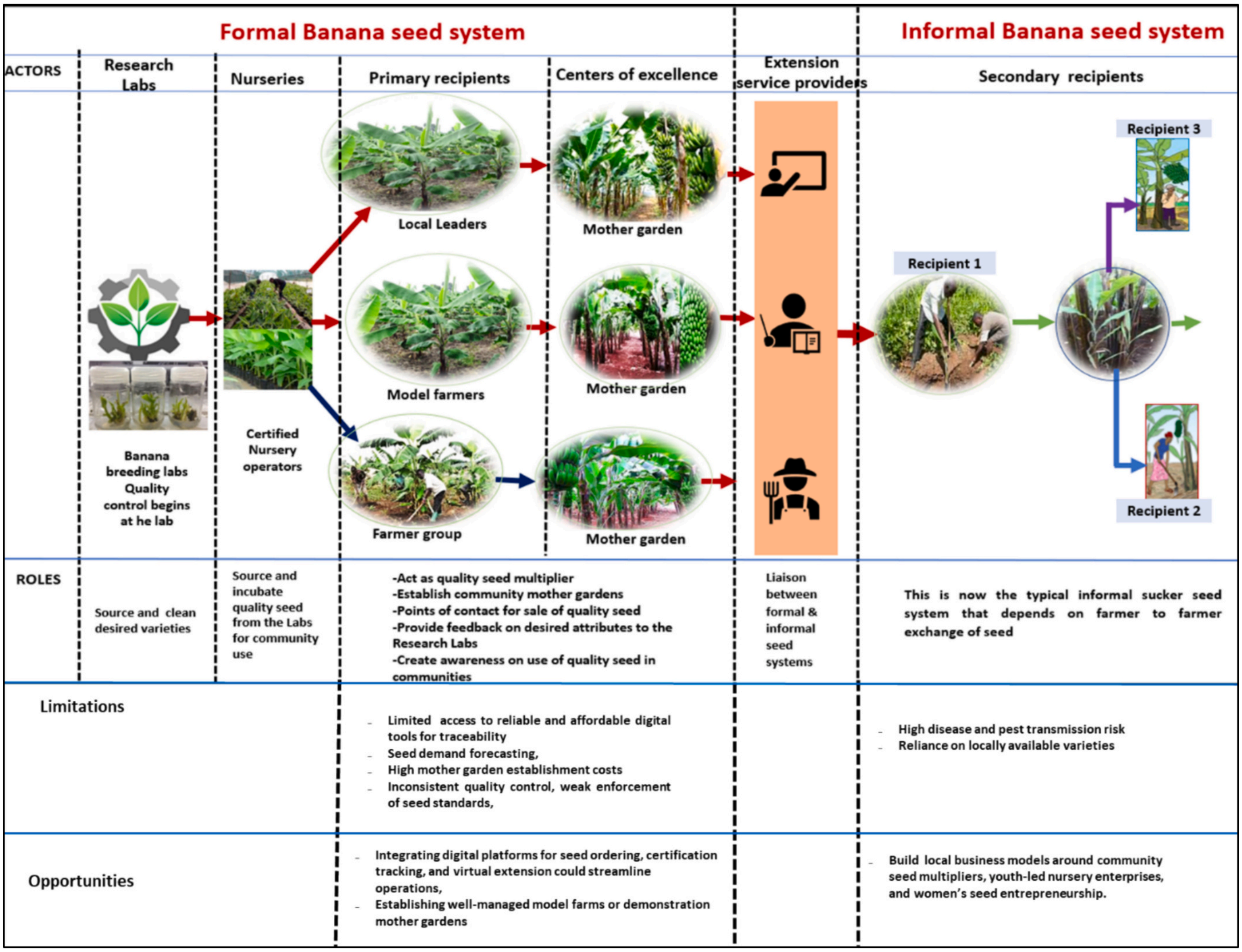

Fig. 8. The integrated sucker-tissue culture banana seed system.

Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Lucy Mulugo reports financial support was provided by One-CGIAR. Lucy Mulugo reports a relationship with One- CGIAR that includes:. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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