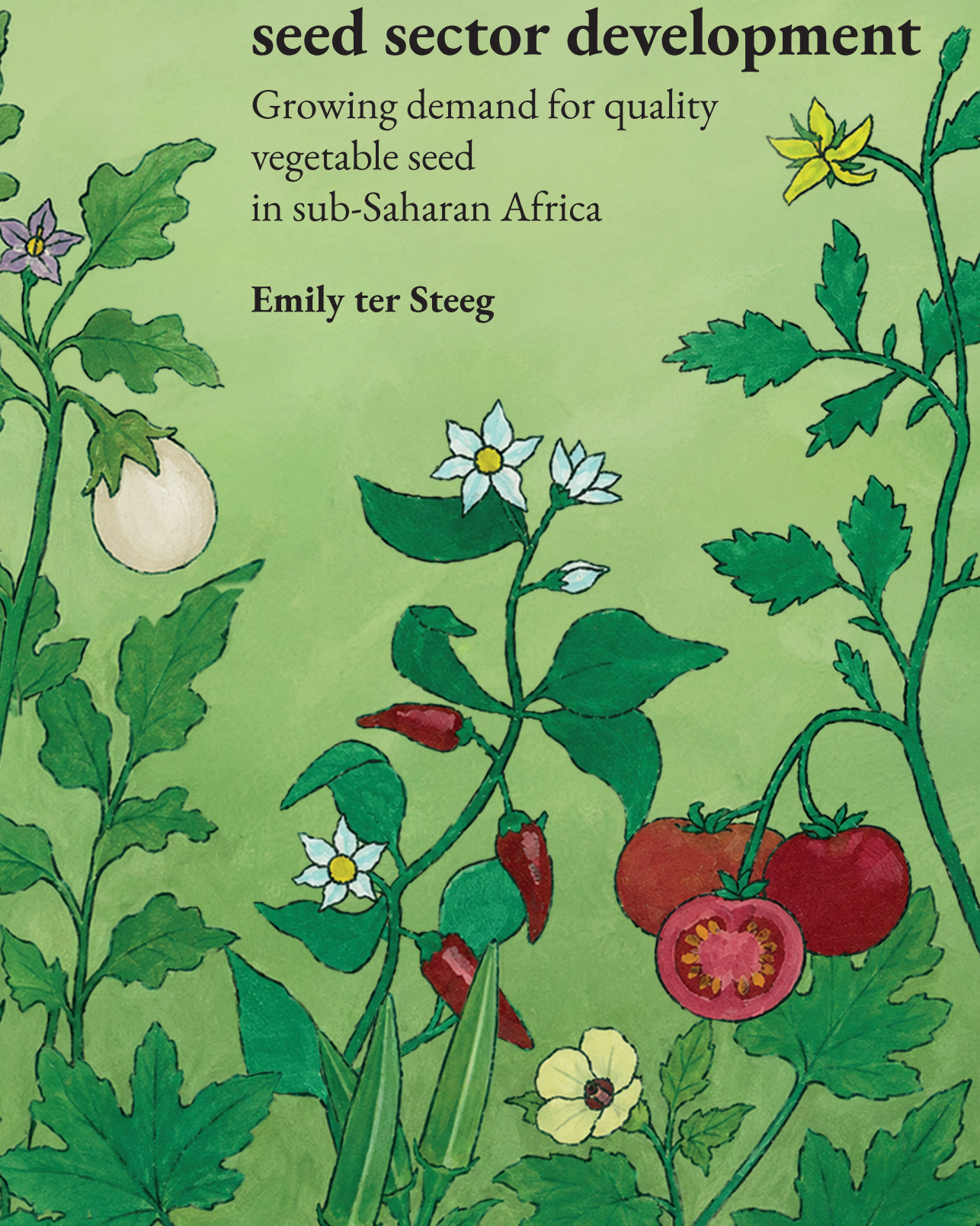
Market-driven seed sector development

Growing demand for quality vegetable seed in sub-Saharan Africa

Emily ter Steeg



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Thesis

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Sitting in a park in Paris France
Reading the news and it sure looks bad
They won't give peace a chance
That was just a dream some of us had

Joni Mitchell
California

The sky is always the sky.
Even though clouds and lightning come,
the sky is not disturbed.
And when the lightning does flash,
a wonderful sight may be seen.

Shunryu Suzuki
Zen Mind, Beginner's Mind

You're going to reap just what you sow

Lou Reed
Perfect Day

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1

Introduction

1.1 Problem definition

Quality seed of improved varieties is widely recognized as a key driver of food security, poverty reduction, and livelihood improvement. The potential impact of quality seed may be particularly large in sub-Saharan Africa (SSA) where poverty and food insecurity remain persistent. In the region, extreme poverty has not declined in contrast to global trends (World Bank, 2025), and food insecurity has even increased in the past decade (FAO, 2025). SSA also records the world's highest malnutrition rates and the lowest levels of vegetable production and consumption (Steenhuijsen Piters et al., 2021). A key factor underlying the underperformance of SSA on development indicators is the low productivity of its agricultural sector. While the agricultural sector in SSA has experienced growth, this has mainly resulted from the expansion of the amount of agricultural land rather than productivity gains (Jayne & Sanchez, 2021). Improving farm productivity critically depends on the use of agricultural technologies including fertilizer, irrigation and quality seed.

The use of such technologies remains low in SSA though with important variations between nations and farm types (Sheahan & Barrett, 2017). SSA did not participate in the Green Revolution, which rapidly spread agricultural technologies massively contributing to poverty reduction, to the same extent as other regions (Evenson & Gollin, 2003). Nowadays, the yield and technology gaps between SSA and the rest of the world are major, and SSA does not show signs of catching up (Suri & Udry, 2022). Giller et al. (2021) identify two trends in SSA: extensification and marginalization. Extensification refers to the expansion of the farm size without increases in technology. Marginalization refers to the fragmentation of farms into smaller units following population growth. Smallholders, who continue to dominate the agricultural landscape in SSA, face an economic lock-in: they do not have the capital to invest in increased farm productivity nor can they move into alternative jobs. Two pathways to improve smallholder incomes are highlighted by Giller et al. (2021): raising agricultural productivity and shifting toward high-value crops including vegetables. Both pathways will require external assistance because the farmers themselves do not have the means to make a change.

This thesis focuses on the introduction and sustained use of quality vegetable seed in SSA. Vegetables form an essential component of nutritious diets and constitute an important income source (Schreinemachers et al., 2021). From a consumption perspective, vegetables are a vital source of vitamins, minerals, phytochemicals, and dietary fibre (Steenhuijsen Piters et al., 2021). Insufficient vegetable consumption has significant health implications and has been identified as a major risk factor for mortality and morbidity in SSA (Afshin et al., 2019). The World Health Organization recommends a daily intake of at least 400 grams of fruits and vegetables, but only around 10% of the population in SSA currently achieves this level of consumption (Frank et al., 2019). The two main reasons for the low consumption levels of vegetables are limited availability and affordability (Steenhuijsen Piters et al., 2021). Additionally, Totin et al. (2024) have highlighted the impact of social institutions, which also inhibit vegetable consumption. From a production perspective, vegetables are high-value crops, which can be an important income source for smallholder farmers. Increasing productivity in cereal crops alone is unlikely to generate sufficient income growth for smallholders (Schreinemachers et al., 2021). There is clear evidence that the production of vegetable for exports contributes to household welfare, whilst the evidence is less clear when it comes to domestic markets (Muriithi & Matz, 2015).

Seed is a foundational component of agricultural production. Not all seeds are equal, and a distinction can be made between good and poor-quality seed. However, 'quality seed' is not a predefined concept and may have different meanings for farmers, governments and seed companies. In the academic literature, authors commonly use the terms improved, high-yielding or hybrid variety, and sometimes these are used interchangeably. These terms specifically refer to a seed's genetic qualities, which have been enhanced using plant breeding techniques tweaking them to human needs and preferences (Michelson et al., 2023). Seed quality further encompasses the physiological, sanitary, and analytical quality of the seed (Almekinders & Louwaars, 1999).[1] For farmers to unlock the potential of a seed, quality must be adequate across all four dimensions. The impact of the use of quality seed on agricultural productivity has been demonstrated for staple crops (Gaffney et al., 2016; Gollin et al., 2021) and vegetables (Schreinemachers et al., 2017). Beyond yield improvements, research shows how improved varieties contribute to economic development in terms of per capita income at the macrolevel (Gollin et al., 2021) and can contribute poverty reduction at the microlevel (Becerril & Abdulai, 2010; Mathenge et al., 2014). However, the benefits of adoption are not equally distributed as poor households face higher costs and lower returns, which makes them less likely to adopt such technologies (Moyo et al., 2007; Suri, 2011). Moreover, the use of quality seed can also improve food security, but these linkages are less clear and require more research (Mutea et al., 2025; Nabuuma et al., 2022).

Farmers access (quality) seed via seed systems, which are networks of stakeholders performing activities which impact access to and use of seed. A well-functioning seed system ensures farmers' physical and financial access to sufficient amounts of quality seed of their preferred crop varieties at the right time (FAO, 2016). A distinction is typically made between informal and formal seed systems (Tripp, 1997). Informal seed systems are also called 'farmer-managed' seed systems as farmers themselves produce seeds or obtain seed via informal sources like social networks or local markets. In formal seed systems, farmers are 'seed users,' and seed is produced and distributed through specialized, regulated value chains (Almekinders & Louwaars, 1999). In practice, seed systems tend to fall along a spectrum between informal and formal, with various intermediary forms (Westengen et al., 2023). In SSA, informal seed systems are dominant for most food crops (Coomes et al., 2015). Louwaars and de Boef (2012) have estimated that 80% of the seed of all crops used in SSA originates from informal sources. This share is lower for vegetables for reasons discussed in section 1.3 (Schreinemachers et al., 2021).

Westengen et al. (2023) have distinguished three basic seed system functions: variety development and management, seed production, and seed dissemination. Variety development and management refers to activities such as the breeding, maintenance, and conservation of varieties. Seed production ensures that enough seed is available for farmers. The application of seed multiplication techniques can contribute to physiological and sanitary quality and maintaining the genetic identity of the seed. Seed dissemination entails the distribution of seed from the place of production and/or storage to farmers. During this process, handling and storage conditions can

[1] Genetic quality refers to varietal adaptation, identity, and purity; physiological quality to seed germination and vigour; sanitary quality to the absence of seed-transmitted diseases; and analytical quality to the proportion of "good seed" relative to inert matter or other seeds.

impact seed quality. Christinck et al. (2018) have added a fourth seed system function, namely crop production and use underling the role of the seed users. This function is particularly relevant in the context of smallholder vegetable farming as 'seed use' often represents a critical hurdle: if farmers do not know how to grow an improved variety they cannot unlock its potential. Figure 1.1 illustrates the structure of seed systems based on these four functions.

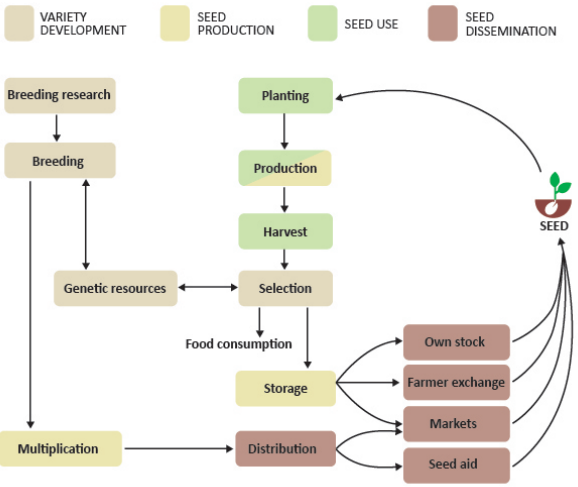


Figure 1.1: Schematic representation of a seed system with the different seed system functions represented in different colours. Adapted from Almekinders and Louwaars (1999), Scoones and Thompson (2011), and Kilwinger (2022).

Seed sector development aims to improve the performance of seed systems by increasing the availability of, improving access to, and expanding the use of quality seed among farmers (Kilwinger, 2022). The historical outlook on seed sector development follows a linear model in which 'inferior' informal seed systems are gradually replaced by 'superior' formal seed systems (Douglas, 1980). Louwaars (2007) has critiqued this vision on sector development as it reduces the role of farmers to mere recipients of seed who need to be convinced to switch to new high-quality seed. Moreover, the vision wrongly assumes that seed sector development will be similar for different seed users and crops. Nowadays, the paradigm referred to as 'integrated seed sector development' is on the rise. This acknowledges the complementary nature of informal and formal seed systems and underlines the need to build linkages between the two to strengthen both (de Boef et al., 2025; Louwaars & de Boef, 2012). Meanwhile, the role of the 'formal' private seed sector remains unchanged: it still aims to increase demand for quality seed amongst farmers and to contribute to the expansion of the formal system (Hambloch et al., 2021; Schreinemachers et al., 2021). Meanwhile, other 'informal' private seed actors complement such formal value chains (Borman et al., 2025; Sperling & Almekinders, 2023). The focus of this thesis will be on the former category of private sector actors: seed companies, distributors, and agrodealers.

This brings us to the concept of market-driven seed sector development. In this thesis, market-driven seed sector development is defined as the process by which private sector actors take a

leading role in strengthening seed systems to increase the availability of, access to, and use of quality seed among farmers. While demand-driven approaches aim to understand existing demand among farmers to tailor formal seed supply to that demand, market-driven seed sector development also aims to create demand for quality seed 'developing the seed sector' (Almekinders, Mausch, et al., 2021). Markets are not yet (fully) functional, and hence, the public sector plays a facilitating role, but markets drive this change providing existing trajectories. This approach is in line with market failure theory, in which the public sector fixes, regulates, facilitates and de-risks the private sector (Mazzucato, 2016). The assumption underlying the Washington Consensus was that the private sector is the most efficient driver of (agricultural) development (Beumer et al., 2022; Gore, 2000). Ever since, the neoliberal narrative and private-sector approaches have remained dominant in seed sector development (Kilwinger, Almekinders, et al., 2025; McEwan et al., 2021; Westengen et al., 2019). Consequently, while the Green Revolution in Asia relied mostly on public efforts, new Green Revolution efforts for SSA are mostly focused on the private sector (Evenson & Gollin, 2003; Scoones & Thompson, 2011). Alliances are formed between public and private actors to incentivize the private sector to contribute to public policy aims (Scoones & Thompson, 2011). Meanwhile, this agenda has been heavily criticized. It has been linked to the degradation of agrobiodiversity as well as the increased the influence of (global) seed companies and the reduced seed sovereignty of farmers (Béné et al., 2019; Clapp, 2016; Kilwinger, Almekinders et al., 2025). A key concern is that companies remain profit-driven actors, and so inevitably focus on market opportunities. Consequently, a large group of crops and farmers is likely to be left behind (McEwan et al., 2021; Westengen et al., 2019). Please note that this thesis does not concern the introduction of genetically modified crops (GMOs), which are often associated with 'the private seed sector', as GMOs remain highly rare in vegetable crops compared to staple crops.

1.2 Research objectives

The overarching objective of this thesis is to analyse how a market-driven approach impacts the development of vegetable seed systems in SSA, and how this shapes farmer seed sourcing, livelihoods, and sector performance. This objective sits at the intersection of two gaps in the academic literature regarding vegetables and private-sector development. Bringing these two topics together, the thesis examines how private and public-private engagement in vegetable seed systems influence farmer seed sourcing decisions, rural livelihoods, and seed sector development. Vegetables seem to represent a blind spot for many researchers and policymakers, with nutritionists being an important exception. Most agricultural research, policies and seed system interventions focus on cereal crops rather than legumes, roots, tubers, fruits, or vegetables (Kuhlmann et al., 2023; Nabuuma et al., 2022). Consequently, while vegetables have been recognized for their potential to strengthen the livelihoods of smallholder farmers and contribute to food security, empirical evidence on the conditions under which this potential is realized remains limited. Moreover, the private sector is expected to take on a leading role in seed sector development, yet the implications of relying on a market-driven approach remain poorly understood. First, the private sector's vision for (vegetable) seed sector development and possible diversity within the private sector regarding this vision remain poorly understood. In particular, it is unclear to what extent private incentives align with public objectives, and where these interests

diverge. Secondly, there is limited empirical evidence on the impacts of market-driven seed sector development on farmer livelihood outcomes. Vegetable seed companies state that they seek to contribute to poverty reduction and nutrition outcomes, but so far, no or little scientific data is available to underpin impact claims (Access to Seeds Foundation, 2019b; East-West Seed, 2025; International Seed Federation, 2025). Thirdly, little is known about the entry points through which private actors can contribute to vegetable seed sector development. The private seed sector deploys a range of tools such as agricultural extension services, marketing, and branding that may shape farmer choices.

To address the overarching objective, three underlying objectives are addressed:

- Objective 1: To contribute to an improved understanding of the business models of vegetable seed companies in a development context.
- Objective 2: To assess the impact of a large-scale intervention in the vegetable seed sector, by a corporate foundation, on technology adoption and livelihood outcomes amongst different groups of farmers.
- Objective 3: To evaluate the extent to which product and agrodealer characteristics influence farmers' trust in seed quality and purchasing decisions.

The first objective seeks to improve understanding of the practices and strategies of vegetable seed companies operating in SSA and is addressed by Chapters 2 and 3. Chapter 2 focuses on the seed system function of variety development and examines how private seed companies decide which crops to invest in through breeding. By identifying the biological and economic factors that shape these investment decisions, the chapter clarifies why certain crops attract private-sector breeding efforts while others remain commercially unattractive and are 'left behind'. The chapter seeks to unravel the underlying rationale, thereby helping to identify crops where public or donor intervention may be needed. Chapter 3 extends this analysis by examining heterogeneity in vegetable seed company strategies across seed system functions: variety development, seed production, seed dissemination, and seed use. Contrary to the common assumption that the private seed sector constitutes a homogeneous group of profit-driven actors, the chapter demonstrates substantial variation in business models and strategic orientations. By developing a typology of seed company strategies, the chapter clarifies how different private-sector approaches shape vegetable seed sector development and the extent to which market-driven dynamics may contribute to broader development objectives.

The second objective focuses on assessing the impact of a seed system intervention in northern Nigeria and is addressed by Chapters 4 and 5. Both chapters primarily focus on the seed system function of seed use, as the intervention aims to strengthen farmers' understanding of the benefits of quality seed and good agricultural practices through agricultural extension. Scientific evidence on the effects of seed system interventions on technology adoption, especially livelihood outcomes, remains limited, particularly for vegetable crops (Nabuuma et al., 2022; Schreinemachers et al., 2021). Chapters 4 and 5 address this gap by evaluating a seed system intervention implemented by the corporate foundation East-West Seed Knowledge Transfer (EWS-KT). This extension programme is 'market-driven' because it contributes to the development of a viable product market for East-West Seed as well as other seed companies.

Moreover, the programme focuses on commercial vegetable production and hence, farmer attendance is also driven by commercial motives. Together, the chapters assess the intervention's theory of change, which states that market-driven agricultural extension leads to increased vegetable cultivation as well as the adoption of quality seed and good agricultural practices, which in turn enhance farmer livelihoods and food security. Chapter 4 examines the direct effects of the intervention on targeted farmers, while Chapter 5 analyses indirect effects by studying information dissemination and spillovers among neighbouring, non-targeted farmers within the same communities.

The third and final objective examines the role of trust at both agrodealer and product level in shaping farmers' seed purchasing decisions, and is addressed by Chapters 6 and 7. These chapters focus on the seed system function of dissemination, with particular attention to trust. It remains difficult to quantify the prevalence of poor-quality agricultural inputs, but persistent concerns about poor quality seed reduce farmers' willingness to invest. While vegetable seed companies often emphasize the need for stronger public regulation and enforcement, they also seek to take matters into their own hands by trying to offer quality guarantees up to the point of sale. The focus of Chapters 6 and 7 is on agrodealers, who despite their central role in last-mile distribution, remain an understudied group of actors (Dillon et al., 2025; Rutsaert et al., 2024). Chapter 6 explores distribution dynamics qualitatively by mapping the vegetable seed distribution system, documenting seed quality challenges, and identifying the agrodealer- and product-related factors that shape farmer trust. Building on these insights, Chapter 7 quantifies the effects of trust-related factors on farmers' willingness to pay for vegetable seed. Unlike Chapters 4 and 5, these chapters do not evaluate a specific intervention, but instead assess whether seed dissemination through trusted agrodealers and credible product signals can itself serve as an entry point for seed sector development by increasing farmers' willingness to invest in quality seed.

1.3 Theoretical perspectives: excludability-rivalry matrix

As explained, market-driven vegetable seed sector development requires public interventions as market are not yet fully functional. Moreover, we can predict up to what extent the private sector will contribute to public policy objectives using the excludability-rivalry matrix (Adams & McCormick, 1987). This classic framework is widely used in economics and political economy to analyse incentives for provision, governance, and collective action across different types of goods. Excludability refers to whether access to a good can be restricted to certain users (at reasonable cost), while rivalry describes whether one person's use of the good reduces its availability to others. The interaction of these two dimensions gives rise to four broad categories of private, club, public, and common goods. These categories describe types of goods based on how they are produced, valued, bought, and used. Access to private goods (excludable and rivalrous) can be controlled, typically through prices or ownership, and consumption by one individual limits consumption by others. For club goods (excludable but non-rivalrous), users can be prevented from accessing the good, but additional users do not substantially diminish its availability until congestion sets in. In case of common-pool goods (non-excludable and rivalrous), consumption by one individual reduces what remains for others, yet it is challenging to control access. Regarding public goods (non-excludable and non-rivalrous), individuals cannot be prevented from benefiting from them,

but one person's use does not reduce the benefits available to others. In the following paragraphs, this matrix is applied to the goods provided by the different seed system functions (Figure 1.2).

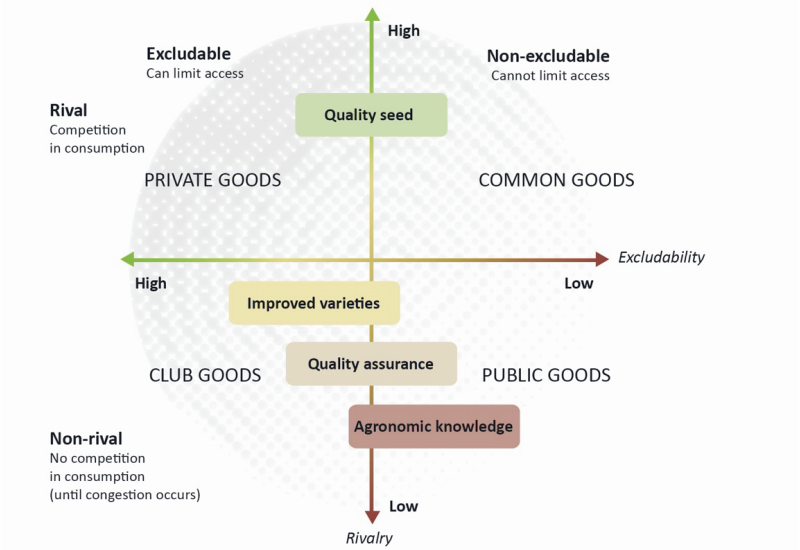


Figure 1.2: Excludability-rivalry matrix with four goods linked to the four seed system functions positioned on the matrix.

The first seed system function is variety development, which entails the breeding, maintenance, and conservation of varieties. The maintenance and conservation of genetic resources are often treated as public goods and are typically managed by public gene banks, but private seed companies also maintain germplasm collections to support their breeding programmes. 'Improved varieties' are the primary output of breeding programmes, which represent genetic knowledge and are intangible assets. In practice, one may need tangible assets like parent lines to use an improved variety, which can be scarce and thus, rivalrous. Still, improved varieties are essentially non-rivalrous: one seed company's ability to produce seed from an improved variety does not infringe upon another's ability to do so. Similarly, one farmer's use of an improved variety does not reduce another's potential to use it. However, access to this knowledge can be restricted, making varieties either excludable or non-excludable goods. Private seed companies may protect their varieties through intellectual property rights, or contractual arrangements, and can license them to partners, effectively creating club goods (Louwaars, 2007). In contrast, public research organizations may release varieties into the public domain, allowing seed companies or farmers to freely reproduce them and hence create public goods. Sometimes these organizations also require a small payment, again turning genetic resources into club goods.

The second seed system function is seed production, with quality seed (of improved varieties) as its primary output. Seed is a tangible good and therefore inevitably rivalrous: seed planted by one farmer cannot be used by another. Hence, the key dimension here is excludability: in this context, excludability refers to the degree to which farmers depend on third parties to obtain quality seed. Seed is non-excludable when farmers can easily produce farm-saved seed without major quality

loss (De Boef et al., 2015). Excludability can arise from biological, institutional, or market factors (Borman et al., 2025). Hybrid varieties, for example, lose performance when replanted, creating biological excludability and encouraging repeated purchase (Kloppenburg, 2005). High disease pressure may similarly create demand for clean seed produced under controlled conditions. Legal and institutional mechanisms such as intellectual property rights and value chain arrangements can also restrict reproduction (Louwaars, 2007). Private investment in seed production is most likely where both excludability and rivalry are high, leading to large market demand meaning there is a large market demand for quality seed. Where seed can be easily reproduced and seed markets are small, private incentives weaken and support for seed production may be needed.

The third seed system function is seed dissemination. This function centres on enabling transparent and reliable exchange in seed markets. In this thesis, the focus is on quality assurance as the key output of this function, as it provides the institutional conditions that make market exchange possible. Quality assurance systems, using certification and labelling, generate credible information about seed quality. In principle, these systems are largely non-rivalrous: one supplier's or farmer's access to quality assurance does not diminish another's. However, quality assurance systems face both capacity and enforcement constraints. In some contexts, limited regulatory capacity means only a fraction of seed in the market can be tested or certified (Mastenbroek, Otim, et al., 2021). Moreover, it might also be the case that farmers cannot easily verify or understand quality signals (Gharib et al., 2021). Consequently, systems become vulnerable to free-riding and the circulation of counterfeit seed can erode trust amongst market participants. As the credibility of quality assurance depends on system-wide compliance, it has strong public-good characteristics. Effective regulation, standard setting, and monitoring are therefore core public-sector responsibilities. Private actors can complement these efforts by investing in their own quality assurance systems such as the certification of agrodealers or product branding by seed companies. Where public enforcement is weak, trusted exchange may then become restricted to networks or value chains, giving it club-good characteristics.

The fourth seed system function is seed use, referring to farmers' capacity and knowledge to use seed effectively unlocking the benefits of quality seed of improved varieties. Knowledge is non-rivalrous: one farmer's learning does not reduce another's. Moreover, knowledge mostly functions as a public good because it is difficult to restrict its use once shared and generates spillovers. In this thesis, we focus on agricultural extension services as a means to diffuse knowledge and technologies. Agricultural extension has been qualified as "a (local) public good" underlining the importance of continued public investment (Takahashi et al., 2020). Moreover, Feder et al. (2011) have already shown that agricultural extension in a development context faces too many market failures to rely on pure private sector models. They identify 'embedded services' as the only viable option for a private sector model with companies providing extension linked to the sales of inputs or outputs (Table 1.1). In this way, knowledge may become partially excludable taking the form of a 'club good' as it is delivered through private training programmes, contract farming schemes, or advisory services tied to specific products.

Table 1.1: Financing and provision of agricultural extension services. Adapted from Feder et al. (2011).

Financing of service → Provision of service ↓	**Public sector**	**Private companies**	**NGOs**	**Farmers**
Public sector	Public extension	Public agents contracted by firms	Public extension contracted by NGOs	Fee-based public extension
Private sector	Publicly funded private providers	Embedded services with input sales and/or output marketing	Private extension contracted by NGOs	Fee-based private extension
NGOs	Publicly funded NGO extension	NGO agents contracted by firms	NGO extension	Fee-based NGO extension

Note: The models in light squares are common in vegetable crops, whilst models in the dark squares are uncommon in vegetable crops.

The application of the excludability and rivalry matrix to vegetable crops confirms that private actors are likely to take a leading role in seed sector development. Firstly, demand for improved varieties is high thanks to high product differentiation with strong consumer preferences related to colour, size, shape, taste, and texture as well as trader requirements for example regarding uniformity and storability. Also, vegetable production is characterized by strong seasonality and improved varieties can provide farmers with more flexibility in production planning (Steenhuijsen Piters et al., 2021). Secondly, demand for quality seed is also high because it is rather difficult for farmers to produce their own vegetable seed, especially in comparison to other crops like roots and tubers or cereals. Vegetable seed production is a separate and more time-consuming activity. For most major food crops, the harvested product can serve both as food and as seed. In contrast, for vegetables, seeds generally develop after the crop has been harvested, requiring selected plants to be kept in the field longer (Pandita et al., 2023). Also, many vegetables are cross pollinators, which reduces genetic purity rapidly, and some vegetables only produce seed under specific climatic conditions, which means farmers in tropical areas need to buy new seed every season (Schreinemachers et al., 2021). Moreover, hybrid breeding has been applied in most commercially important vegetables, which also requires farmers to buy new seed. As a result, vegetables generally represent a highly profitable business for seed companies. For this reason, authors have often concluded that formal seed systems or "commercialized seed delivery models" work for vegetables (Louwaars & de Boef, 2012; Mausch et al., 2021).

However, the matrix also points to two areas where vegetable seed markets may not (yet) function effectively, requiring public sector support. Firstly, ineffective quality assurance systems may hamper vegetable seed sector development. Vegetable seed is typically sold in small quantities at relatively high prices, which raises the stakes of quality assurance. In well-regulated markets, public quality assurance systems provide a baseline, and private companies tend to go beyond these standards. For the most technologically advanced tomato varieties, X-ray scanning is used to verify embryo viability for each individual seed (Incotec, 2025). In less developed markets, public quality assurance systems are often less reliable, which reduces the trust of farmers (Dillon et al., 2025; Michelson et al., 2023). Private actors may need to find ways to overcome this challenge taking measures into their own hands. Secondly, vegetable cultivation is knowledge-intensive and improved varieties require careful management to realize their potential (ter Steeg & Gildemacher, 2023). Moreover, Schreinemachers et al. (2021) have explained that public extension agents are

generalists and do not have the required technical knowledge to support vegetable farmers. Looking at Table 1.1, this means that besides the column with farmers financing the service, which is commercially unfeasible, the top row with the public sector providing extension services is also irrelevant for vegetables. This means the private sector actors or NGOs with specialized knowledge need to be involved in extension programmes, likely still requiring public funding due to the high cost. Interaction effects between functions may also arise, for example, shortcomings in seed dissemination and use can reduce private sector incentives to invest in variety development.

Finally, the excludability-rivalry matrix gives rise to two critical questions about market-driven approaches. Firstly, how far are public and private objectives aligned? Secondly, who will take responsibility for what? The private sector is likely to invest more in variety development and seed production when access to these goods can be restricted. Therefore, it is likely that seed companies will focus on hybrid breeding programmes, which offer natural intellectual property protection. It is also likely that the private sector will focus on crops for which quality seed is in high demand, meaning commercial vegetables with sizable markets. On the contrary, private investments will likely be lower in open-pollinated varieties as seed recycling cannot be prevented and in niche crops for which seed markets are small. Regarding seed dissemination and seed use, the private sector may invest in quality assurance and agricultural extension. However, again, the access to public quality assurance systems or knowledge programmes will likely be restricted and private models may only cover certain products or value chains. Similarly, the training programmes may take the form of embedded services for customers linked to the sales of certain inputs or outputs. As discussed above, market-driven seed sector development relies on incentivizing private actors to contribute to public policy objectives. This matrix reveals an inherent tension in this approach: public goals are broad farmer access to quality seed, poverty alleviation and improved food security, but this is not always a good fit with the excludability and rivalry required for viable seed business models.

The matrix plays a role throughout this thesis, enabling the evaluation of several of the assumptions listed in the previous paragraph. Chapter 2 addresses the question of private sector investment in different types of crops. It seeks to identify crop characteristics which determine the commercial feasibility of a hybrid breeding programme. Vegetables are generally deemed highly suitable for hybrid breeding programme because of their biological characteristics, but economic characteristics also play a role, and some vegetables may be more commercially appealing than others. Chapter 3 zooms in on the business models of vegetable seed companies in SSA. In this chapter, the questions of hybrids versus open-pollinated varieties and commercial versus uncommercial crops feature prominently. It also describes the private sector perspective on public involvement in the different seed system functions.

Subsequently, Chapters 4 and 5 examine an intervention by a corporate foundation that seeks to stimulate demand for (hybrid) vegetable varieties. The intervention is co-funded by a seed company and the public sector. These two chapters therefore speak to how a public-private partnership can catalyse market formation. Chapters 6 and 7 turn to the question of last-mile distribution and trust in seed markets. They examine whether weak quality assurance and limited trust constrain farmers' willingness to purchase quality seed. Particular attention is paid to the role of agrodealers and seed companies in building credibility through signalling and relationships.

These two chapters highlight that the functioning of vegetable seed markets depends not only on the availability of improved varieties but also on farmers' confidence in seed quality and supplier reliability.

1.4 Theoretical perspectives: technology adoption

The term 'adoption' has a long history in academic research and represents an extensive body of literature. In many studies, technology adoption serves as an indicator of the impact of development interventions (Leeuwis & Aarts, 2021). This is also the case for market-driven seed sector development, as the adoption of quality seed of improved varieties indicates success, whilst a lack of adoption indicates failure. However, how is adoption defined? Glover et al. (2016) have pointed out that many studies neglect to include a definition of adoption. Moreover, the studies including a definition mostly continue to define adoption in a binary manner (Vatsa et al., 2023). The reality is of course more complex, and for this reason, Feder et al. (1985) have already opposed the definition of adoption as a dichotomous choice. Some authors have looked at adoption intensity: the quantity applied, the share of farmland, or the number of technologies (Amankwah, 2023; Arslan et al., 2014; Oyetunde-Usman et al., 2021). However, the binary indicator still prevails in most quantitative studies for practical reasons, as it is difficult and costly to measure nuance at scale. Moreover, nuanced indicators do not necessarily improve measurement, as they may also increase complexity and the risk of data errors. In case of binary variables, farmers are typically categorized as adopters if they self-report growing an improved variety or have bought seed. A distinction is made between the practice of growing a new variety versus purchasing seed because farmers can also save seed from an improved variety, which means they have adopted the variety, but are not buying seed, which may reduce seed quality over time. Self-reporting remains tricky because farmers use different types of seed and can have a poor understanding of the type of seed they are using (Michelson et al., 2023; Wineman et al., 2020).

The defining feature of adoption in the context of market-driven seed sector development is the financial ability and willingness of farmers to pay (WTP) for quality seed. When it comes to WTP, a distinction is made between revealed and stated preferences (Morawetz et al., 2011). Stated preference methods reveal the behavioural intention of a respondent, which remains hypothetical. On the contrary, revealed preference methods show the actual behaviour of a respondent. In the case of market-driven seed sector development, companies seek to influence the real-time purchasing decisions of farmers. Common practice shows that this approach is not aligned with development interventions or experimental approaches. During many seed system interventions, free seed or subsidies are provided to farmers to promote adoption. However, seed companies want farmers to learn about the value of their products and are therefore generally opposed to such measures. Also, during many scientific experiments, monetary incentives such as 'cash-in-hand' or discount vouchers are provided to farmers resulting in unusually high adoption (Morawetz et al., 2011). Moreover, such incentives can become a leading determinant of adoption (McIntosh et al., 2013). In the case of market-driven seed sector development, no monetary incentives are provided: the point is to impact the seed purchasing decision of the farmer in a real market environment. Also, the objective of seed companies regarding adoption differs from public breeders: it extends beyond varietal adoption as repeated seed purchases over time are required for a viable business model, implying that farmers buy seed rather than rely on farm-saved seed.

Traditionally, technology adoption is considered as an individual decision-making process (Leeuwis & Aarts, 2021). These individualistic perspectives originate from the 'Diffusion of Innovations (DOI) theory' of Rogers (1962). Rogers' DOI theory defines technology diffusion as *"the process by which an innovation is communicated through certain channels over time amongst members of a social system"*, conceptualized as a largely linear process driven by information transfer and individual adoption decisions; during the adoption process, an individual moves through the five stages of knowledge, persuasion, decision, implementation and confirmation. Many new technology adoption theories and models build on the work of Rogers with one similarity: they continue to focus on the individual determinants of adoption behaviour (Leeuwis & Aarts, 2021). The usual suspects are demographic characteristics, personality traits and beliefs or social values. Kilwinger (2022) have explained how consistently disappointing adoption levels of quality seed amongst smallholders tend to result in an endless loop of more quantitative research: more household surveys, more determinants and more statistical models.

Novel theoretical perspectives on technology adoption have moved beyond linear and individualistic models of technological change (Kilwinger, 2022). Rogers (1995) substantially revised the DOI framework in response to critiques and accumulated evidence from development and agricultural contexts. While the core elements of diffusion framework (innovation, communication channels, time, and social system) and the five-stage decision process remained intact, Rogers shifted away from his linear, information-driven view of adoption. He explicitly acknowledged earlier biases, including a pro-innovation bias and a tendency to attribute non-adoption to individual deficits. The revised framework places emphasis on the social embeddedness of adoption. Leeuwis and Aarts (2021) have defined the concept of embeddedness as interdependencies between people whose interactions are oriented by formal and informal institutions. Rogers further refined his framework by distinguishing between different types of knowledge and by highlighting the importance of trial, reinvention, and experiential feedback. As a result, adoption is now portrayed as a dynamic process in which adoption, adaptation, and non-adoption are all meaningful outcomes. These revisions align more closely with the context of smallholder vegetable farming, which is characterized by risk, uncertainty, and heterogeneous user conditions.

While Rogers' DOI framework defines the stages through which adoption decisions unfold and the information required by individuals, it is less explicit about the learning mechanisms underpinning these stages. Stone's (2016) categories of didactic, social, and environmental learning can be used to operationalize Rogers' framework by clarifying how (smallholder) farmers acquire, evaluate, and validate information. Didactic learning refers to knowledge acquired through formal instruction and information transfer. This includes agricultural extension, demonstrations, labels, and advice from experts. Social learning occurs through observation, interaction, and communication with others, particularly peers perceived as similar or trustworthy. Farmers learn by watching neighbours, discussing outcomes, and interpreting shared experiences. Environmental learning refers to learning derived from direct engagement with the technology and its performance in the local environment. This includes learning-by-doing, experimentation, and the evaluation of outcomes such as yields or quality. Stone (2016) has argued that environmental

learning is often the most decisive form of learning for farmers, as it provides concrete feedback about whether a technology works under their conditions.

This thesis covers the different adoption stages and types of learning in the context of market-driven seed sector development. Chapter 2 focuses on the type of technologies that become available to farmers. Chapter 3 investigates how seed companies envision the adoption process and the different strategies through which these actors seek to create demand for their seed products. Chapter 4 and 5 focus on agricultural extension provided by a corporate foundation. The extension programme provides farmers with all three types of learning guiding them towards an adoption decision: farmers can learn about a technology at a demonstration, witness technology adoption by their peers, then experiment with the technology at their own farm. Chapter 5 specifically zooms in on the potential of social learning as a mechanism for technology diffusion as it focuses on the impact of the programme on untargeted farmers rather than the farmers who were directly targeted, as these farmers do not experience didactic learning themselves. Finally, Chapter 6 and 7 focus on seed purchasing decisions: one of the learning processes of farmers is which agrodealers and products they trust when sourcing quality seed. Leeuwis and Aarts (2021) define trust as "the expectation that others can be trusted to perform the necessary complementary behaviours and/or provide conducive conditions that enable the adoption of a technology or behaviour." In Rogers' terms, if seed quality is perceived to be unreliable the relative advantage of the technology becomes uncertain, and farmers may refrain from adoption. These chapters explore how farmers learn about quality seed in a market environment shaped by uncertainty. Market actors seek to remove these risks through packaging and retailers, but can they do so effectively?

1.5 Research design

The objective of this thesis requires the provision of both qualitative and quantitative explanations to examine market-driven vegetable seed sector development from the perspectives of seed companies, agrodealers, and farmers. To this end, the research design combines literature review, qualitative inquiry, impact evaluation, and experimental methods, with each approach addressing a separate component of the overarching objective. Applying these different methods, the chapters gradually move from describing mechanisms, to measuring impacts, to experimentation.

Chapter 2 and Chapter 3 both identify mechanisms that shape market dynamics. By combining insights from breeding science and business economics, Chapter 2 clarifies the crop-specific feasibility conditions that shape private investment decisions and positions vegetables within this broader landscape. Drawing on a structured review of the literature, the chapter identifies key biological and economic conditions that determine whether a hybrid breeding programme is considered technically and commercially feasible by seed companies. The analysis is illustrated through three crop-based case studies, maize, wheat, and potato, which together highlight how crop characteristics influence breeding strategies. The main output for Chapter 2 are the biological and economic factors which shape the investment decisions of seed companies in breeding programmes.

Chapter 3 then analyses the business models of leading vegetable seed companies operating in SSA and assesses how these models shape seed sector development in the region. Based on 18 in-depth

interviews with regional and commercial directors, the chapter examines how companies differ in their approaches to market development, farmer engagement, and risk management. Given the limited transparency of the private seed sector, the analysis moves from company-level information to the identification of broader patterns. Using ideal-type analysis, the chapter develops a set of seed company typologies, thereby advancing understanding of the heterogeneous strategies and perspectives of private-sector actors in vegetable seed systems. The main outputs for Chapter 3 are the seed company typologies, which explain the differences between private-sector strategies in SSA.

Quantitative methods are subsequently used in Chapters 4 and 5 to examine how private-sector-led market development strategies translate into farmer-level outcomes. Both chapters draw on a large-scale randomized controlled trial (RCT) implemented across 150 communities in Kano and Kaduna states in northern Nigeria. The intervention was a market-driven agricultural extension programme implemented by East-West Seed Knowledge Transfer. The RCT included three arms: a control group, a treatment group receiving agricultural extension, and a treatment group receiving extension combined with a test-based public certification of participants. Chapter 4 evaluates the direct impact of this intervention on targeted farmers. Using survey data from 1,498 farmers, the chapter estimates impacts on vegetable cultivation, adoption of quality seed, uptake of good agricultural practices, and selected livelihood indicators. By doing so, the chapter assesses whether knowledge provision translates into measurable changes in farmer behaviour and welfare. The main contribution of Chapter 4 is to quantify the effectiveness of a quasi-commercial extension model in supporting the emergence of a functional market for improved vegetable seed and consequential impacts on farmer livelihoods.

Chapter 5 shifts the focus from direct impacts to community-level diffusion dynamics. Rather than analysing target farmers in different treatment groups, the chapter examines spillover effects among untargeted farmers living in intervention communities. In particular, it investigates whether the certification treatment acts as a credible signal of 'qualification' to untargeted neighbouring farmers. Drawing on survey data from 1,302 untargeted farmers, the chapter evaluates indirect effects on vegetable cultivation and the adoption of quality seed and good agricultural practices. The main contribution of Chapter 5 is to show how signalling and social learning mechanisms shape the diffusion of agricultural technologies beyond directly supported farmers, thereby assessing how market-driven interventions can catalyse broader market formation.

Finally, Chapter 6 and 7 use qualitative and quantitative tools to understand the impact of trust on farmer seed purchasing decisions. Chapter 6 examines product-level and agrodealer-level factors that shape farmers' seed purchasing decisions in northern Nigeria. The chapter first maps the vegetable seed value chain, with particular attention to last-mile distribution through agrodealers. It then analyses seed quality challenges at the retail level and investigates factors that influence farmer trust when buying vegetable seed. Chapter 6 draws on 18 key informant interviews with seed companies, 78 structured agrodealer interviews, and 6 focus group discussions with farmers. It applies a thematic framework analysis to identify product- and agrodealer-level factors, particularly trust-related mechanisms that shape farmer seed purchasing decisions.

Subsequently, the experimental Chapter 7 quantifies the impact of trust-related factors on farmers' willingness to pay for maize and vegetable seed products supplied by different agrodealers. The chapter examines whether formal and informal quality signals mitigate asymmetric information problems in agricultural input markets. The analysis pursues two related objectives. First, it assesses whether farmers differentiate between more and less trustworthy agrodealers, and how perceived trustworthiness influences farmers' willingness to pay for seed inputs. Second, it analyses the relationship between actual seed quality and farmers' perceptions of quality, drawing on both formal and informal signals. Chapter 7 is a complex mixed-methods paper which uses six focus group discussions, 78 interviews, rankings, germination trials, two experimental auctions (n = 560 and n = 585), mystery shoppers and a dice rolling experiment to quantify the impact of trust on farmer willingness to pay for agricultural inputs. At the different stages of the experiment, different samples of farmers and agrodealers were used from Kano and Kaduna state in northern Nigeria.

Figure 1.3 presents an overview of the thesis structure, including key information for each chapter. For more information on the applied research methods, please refer to the methodology sections of Chapters 3-7.

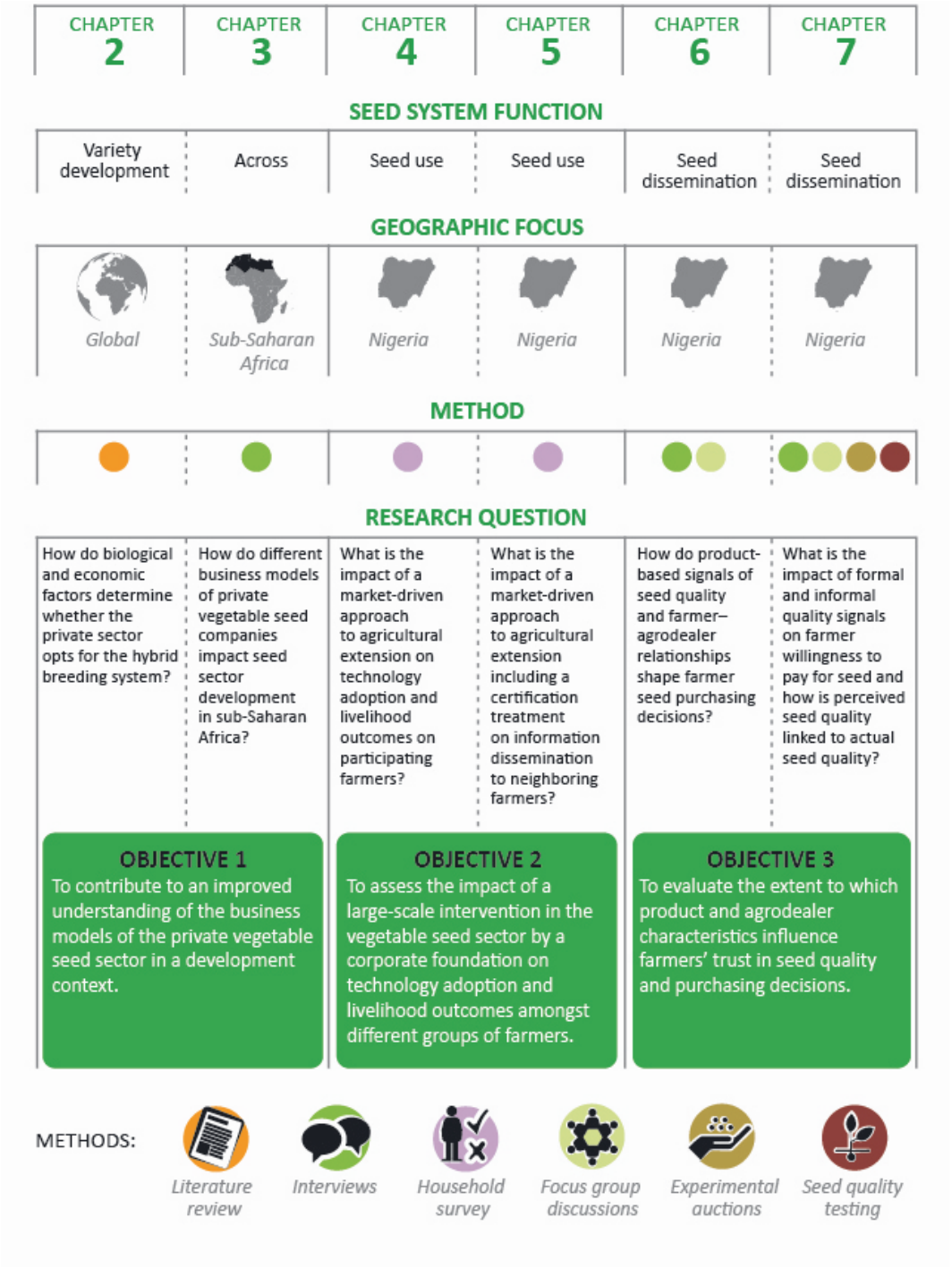


Figure 1.3: Thesis outline for Chapter 2-7.



2

Crucial factors for the feasibility of commercial hybrid breeding in food crops

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Abstract

There is an ongoing societal debate about plant breeding systems and their impact on stakeholders in food systems. Hybrid breeding and hybrid seed have become controversial topics as they are believed to mostly serve high-tech agricultural systems. This article focuses on the perspective of commercial plant breeders when developing new cultivars of food crops. Arguably, hybrid breeding is the most effective breeding system for genetic improvement of crops, enhancing yields, improving product quality and increasing resistance against (a)biotic stresses. Nonetheless, hybrid breeding is not commercially applied in all crops. We analyse how biological and economic factors determine whether a commercial plant breeder opts for the hybrid system or not. We show that the commercial feasibility of hybrid breeding depends on the crop and business case. In conclusion, the commercial application of hybrid breeding in crops seems to be hampered mostly by high costs of seed production. Case studies regarding the hybrid transitions in maize, wheat and potato are included to illustrate these findings.

2.1 Introduction

Hybrid breeding represents a technology with the potential to strengthen global food and nutrition security (Labroo et al., 2021; Mackay et al., 2021). The concept of hybrid breeding and hybrid cultivars (also referred to as F1 hybrids) is based on crossing two parent lines that usually are fixed for the most important traits and reside in two different gene pools (Mackay et al., 2021). There is an ongoing societal debate regarding the desirability of promoting this technology. The debate is shaped by conflicting narratives on global food security (Béné et al., 2019; Clapp, 2016; Lammerts van Bueren et al., 2018). While proponents associate hybrid breeding with scientific and genetic advancement, opponents associate hybrid breeding with unsustainable cropping systems, reduced biodiversity and market consolidation by multinational breeding companies (Kantar et al., 2019; Lammerts van Bueren et al., 2011; Lammerts van Bueren et al., 2018). This paper aims to contribute to the discussion by explaining the perspective of commercial plant breeders. To serve a diverse readership, we attempted to avoid technical jargon and details without compromising the content.

Plant breeding entails the art and science of changing the genetic composition of plants to improve their economic utility to humans (Chahal & Gosal, 2002). Four classic plant breeding systems can be distinguished: vegetative, open-pollinated, self-pollinated and hybrid. In this paper, we follow the principles outlined by Brown and Caligari, while excluding exceptions such as the development of synthetic and composite varieties, whereby mixtures of breeding systems are applied (Brown & Caligari, 2008). This classification is based on the reproduction processes of crop species. Breeders make crosses between individual plants and produce seeds or clonal propagules. The first three systems are based on the natural reproductive systems of plants. These systems have been used since the domestication of wild species and the onset of agriculture. Hybrid breeding was introduced only at the beginning of the twentieth century (Labroo et al., 2021). The hybrid system is based on human intervention in the natural reproductive systems of crop species.

The hybrid breeding system is arguably the most advanced of the four classic breeding systems, because it allows breeders to efficiently estimate and exploit genetic components of individual traits (Mackay et al., 2021). It remains challenging to distinguish between the impact of genetics and that of the environment or crop management on traits. Still, hybrid varieties are generally considered to enhance productivity and plant uniformity (Rijk et al., 2013; Rudolf-Pilih et al., 2019). Apart from yield, numerous other traits (such as resistance to biotic stresses, tolerances to abiotic stresses and product quality) are important drivers of breeding programmes. Such traits can be introduced much faster and can be efficiently combined in one variety thanks to hybrid breeding (Lindhout et al., 2011; Rudolf-Pilih et al., 2019). Moreover, breeding companies prefer to combine the best traits in hybrid varieties because these have 'natural' intellectual property protection based on the genetic segregation of harvested selfed seeds of hybrid plants (Labroo et al., 2021; Mackay et al., 2021).

Close to 400,000 plant species exist today, of which 6,000 are being cultivated and less than 200 are of substantial importance for global food production (Bélanger & Pilling, 2019; Priyadarshan, 2019). Only six crops account for 60% of global food production: sugar cane, maize, rice, wheat, potato and soybean (Food and Agriculture Organization of the United Nations, 2019). In this paper, we emphasize food crops. The hybrid breeding system has been applied to fewer than 50

food crops. The aim of this article is to identify prerequisites for the development of a hybrid cultivar from the perspective of the commercial plant breeder. The question arises: why has hybrid breeding been used for the improvement of some crops but not for others? First, we discuss the biological and legal frameworks of plant breeding. It is important to build an under-standing of the structures within which a commercial plant breeder is operating, imposing limits and providing opportunities. Second, we introduce the four plant breeding systems, describing features with regard to the process of making crosses and seed multiplication. Third, we discuss biological and economic characteristics that influence decision-making in the hybrid breeding process. Finally, we categorize existing hybrid crops where breeding systems are used, to identify determinants for commercial plant breeding programmes.

2.2 Basics of commercial plant breeding

In nature, plants evolve under natural conditions by mutations and natural selection (Acquaah, 2020; Brown & Caligari, 2008). Plant breeders change the genetic composition of plants to meet human preferences and match farming conditions. Domestication entails the process during which a plant is deliberately transitioned from a wild species, growing in a natural vegetation with many competing species, into a crop adapted to farming conditions in an artificial, species-poor environment and for human needs. Farmers started the process of domestication through the selection of individual plants of wild species from natural vegetation and turning these into manageable crops to feed themselves and their domesticated animals. This selective domestication process took thousands of years for the crops widely grown today (Priyadarshan, 2019). Directed selection by farmers may be considered the first act of plant breeding.

In the past 200 years, the process of directed selection developed into a process of genetic recombination, during which crosses are made between the most promising plants to 'combine' their genetic compositions. Plant breeding is a repetitive process during which breeders recombine genes by making deliberate crosses and select the best plants from the offspring. Genetic recombination by crossing is a random process. Until today, the breeder is bound to trial and error to generate superior cultivars. This process has been confounded by genotype-by-environment interactions. The genetic potential of a new cultivar can be reliably assessed only by repeated trials under the specific and variable conditions for cultivation. This process usually requires one or several rounds of crossing, repeated trialling and selecting the best plants. New cultivars are thoroughly tested by the breeder, often in collaboration with farmers.

Upon the commercialization of cultivars, starting materials for cultivation by farmers are produced on a large scale. This is realized generatively or vegetatively: generative multiplication is done via seed, while vegetative multiplication is done via plant parts such as roots, cuttings, tubers, bulbs, rhizomes, shoots or tissue culture. Starting materials are sold to farmers for agricultural production. Alternatively, companies specializing in young plant raising may buy seed and grow seedlings, which are then sold to the farmers. This is common practice in many vegetable crops. Commercial plant breeders obtain returns on their investments through seed sales and/or royalties by licensing others to sell seed. Costs entail research and development, seed production and processing, and commercialization (marketing and sales).

A successful cultivar has added value for the entire food chain. Upstream, farmers seek marketable crops that can be produced efficiently. Important characteristics are high yields, uniformity, resistance to biotic stresses, tolerances to abiotic stresses and minimal input requirements in terms of water, fertilizers and crop protectants. Downstream, processors, retailers and consumers prefer uniform crop products, good storability, high nutritional value, consistent quality and low prices. Plant breeders must therefore focus on a wide variety of traits. An additional requirement for breeders is efficient multiplication of starting materials, enabling seed to be produced and sold at a competitive price.

2.3 Biological framework

Plant breeding systems are based on natural processes. Opportunities for and limitations of plant improvement are therefore determined by the biological traits of a species. It is necessary to understand the biology underlying and defining breeding programmes before one can explain commercial feasibility. An explanation of the biological framework is provided below.

Genotype and phenotype

'Genotype' refers to the complete genetic composition of a plant; 'phenotype' refers to the entire set of observable traits. The same genotype can result in different phenotypes across environments, and, vice versa, different genotypes can show a similar phenotype. Generally, plant species have over 30,000 genes that are responsible for their traits (Sterck et al., 2007). Some genes can be directly linked to specific traits such as colour, while other 'polygenic' traits, such as quality or yield, are more complex and depend on many genes, which also show interactions (Crouch & Bodmer, 2020; Mackay et al., 2021). A breeder identifies preferred plant traits and designs experiments to assess the occurrence and inheritance of these traits (Bernardo, 2020). Subsequently, the breeder combines traits into one genotype through crossing. Selection is still mostly done on the basis of phenotypes. For qualitative traits, the number of genes is very high, and single genes have only a small impact on the phenotype (Bernardo, 2020). As the functions of most of the genes remain unknown and the phenotypic expression of genes may differ over locations, seasons and years, many trials are required to select the best cultivars. Molecular markers may facilitate and speed up breeding, being a diagnostic tool for genes that influence crop traits (Zhao et al., 2021). This process is designated 'marker-assisted selection' (Priyadarshan, 2019).

Cultivars

There are two types of cultivated varieties or 'cultivars'. Plant breeders aim to develop 'commercial' or 'modern' cultivars with a distinct, well-defined and stable genotype (Bélanger & Pilling, 2019). Modern cultivars are often preferred by farmers, as these reduce the risk of harvest failure thanks to their stable performance. Modern commercial cultivars tend to be legally protected because of their high economic value. By contrast, farmers' cultivars, also known as landraces or traditional cultivars, may be less uniform and contain high(er) levels of genetic diversity (Bélanger & Pilling, 2019; Priyadarshan, 2019). Farmers' cultivars may be well adapted to local dietary preferences and environmental circumstances.

Mating system

The mating system of a plant is defined by the sexual organs of its flowers (Barrett, 2003; Charlesworth et al., 2005). A plant may have hermaphrodite flowers with both female and male sexual organs. A plant can also have male flowers or female flowers on the same or different plants (Figure 2.1). The female organs of plants are the pistils, comprising an ovary with the ovules. The male organs of plants are the anthers, which release pollen. When a pollen grain lands on the female stigma, it grows through the style to the bottom of the pistil, where the ovules with egg cells are located; the egg cells are then fertilized. This results in an embryo that grows into a seed of the next generation: the progeny. In plant species, a distinction is made between self-pollinators and cross-pollinators (Barrett, 2003). In self-pollinators, seeds are the result of self-fertilization: a pollen grain fertilizes the egg cell of its own flower or of another flower on the same plant, generating 'selfed progeny'. By contrast, seeds may be generated via outcrossing, whereby a pollen grain fertilizes the egg cell of another plant with a different genotype, resulting in outcrossing and 'hybrid progeny'. Self-fertilization may be prohibited by a natural system, designated 'self-incompatibility', whereby the pollen growth is arrested (Charlesworth et al., 2005). The division between self-pollinators and cross-pollinators is a gross generalization: species show a continuum in mating types (Whitehead et al., 2018). Some self-pollinators are very strict, whereas others can occasionally outcross; some cross-pollinating species may also produce viable seed after selfing.

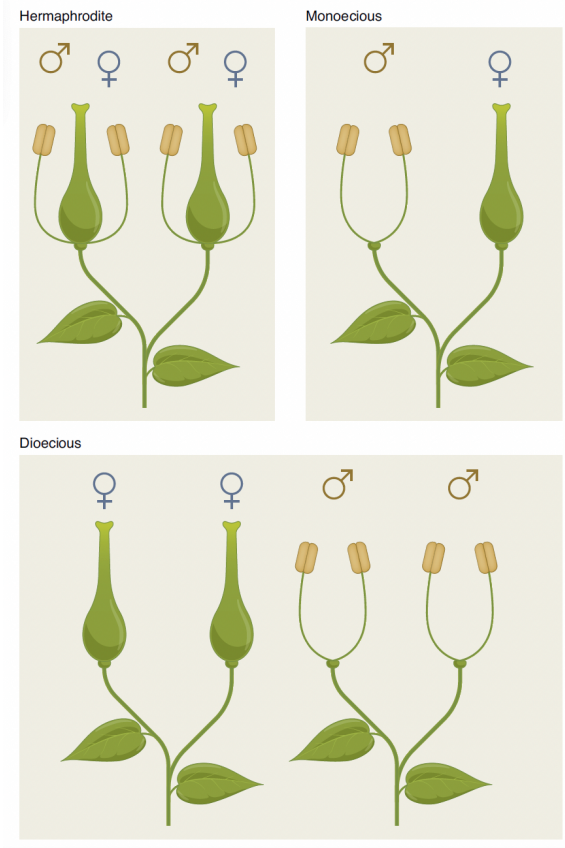


Figure. 2.1: Variation in the occurrence of sexual organs in plants. Species have different mating systems defined by the sexual organs of flowers on plants. Hermaphrodite plants have flowers with both female and male sexual organs. In monoecious species, separate female and male flowers are found on the same plant. In dioecious species, female and male flowers are present on different plants.

Homozygosity and heterozygosity

Zygosity refers to the degree of similarity of alleles of a particular gene. If the alleles for a gene on a chromosome pair are the same, a gene is fixed (Lande & Schemske, 1985). In homozygotes, all the alleles of each gene are identical. This means that a line is genetically pure, and all genes are fixed. In heterozygotes, alleles are different. There are dominant alleles, which show activity, and recessive alleles, which show activity only in the absence of dominant alleles. Homozygosity is the result of repeated self-fertilization, which leads to inbreeding and reduced genetic variation (Lande & Schemske, 1985; Porcher & Lande, 2005). Strict self-pollinators are natural inbreds, while non-strict self-pollinators and cross-pollinators vary in their level of inbreeding (Lande & Schemske, 1985). Reduced genetic variation often results in weak plants, a phenomenon called 'inbreeding depression' (Husband & Schemske, 1996). Some outcrossing species might not tolerate inbreeding at all, as the progeny plants obtained after selfing are too weak, non-flowering and/or sterile (Husband & Schemske, 1996).

Gene pools

Plant breeders use three types of gene pools for breeding (Harlan & Wet, 1971; Palmer & Hymowitz, 2016). The primary gene pool consists of the genotypes of a breeding programme, including modern cultivars ('active breeding germplasm'). The breeder uses these genotypes to generate new cultivars. The market constantly demands new traits, and these may not be present in existing marketed cultivars. Genetic variation is increased by making crosses with genotypes beyond the primary gene pool. The secondary gene pool includes older farmers' cultivars (landraces) and closely related species. The tertiary gene pool consists of other related species and wild relatives that are genetically more distinct. Important genetic improvements and traits are often derived from secondary and tertiary gene pools. These pools contain higher genetic variation; hence, more innovative and rare traits can be exploited. Still, breeders prefer to use germplasm from the primary gene pool, as this is the most adapted to the market needs. Moreover, using germplasm from the secondary or tertiary pool is challenging. The introduction of desired traits goes hand in hand with the introduction of numerous undesired traits, which must be removed through a lengthy process of repeated backcrossing (Tourrette et al., 2021).

Induced genetic variation

Additional technologies exist to improve plant genetics and induce genetic variation, such as artificially induced mutations, genetic transformation and gene editing (Priyadarshan, 2019). These tools should be separated from breeding systems, as they are not based on the recombination of natural genes that are present in the breeders' germplasm. Mutations are 'random' changes in DNA, which have been of crucial importance for evolution (Brown & Caligari, 2008). They can result in an altered plant, a mutant (for example, with a different flower colour or chemical composition of the seed). In nature, spontaneous mutations result in genetic variation and occur frequently. Mutations are induced by agents such as UV light, chemicals or random errors in DNA replication (Brock, 1971). Plant breeders can artificially trigger mutations using the same agents. In the past 70 years, over 2,000 mutant cultivars have been released, mainly in ornamental species, for which an altered flower colour can result in a new cultivar (Ahloowalia et al., 2004; Brock, 1971). Furthermore, technologies allow for the introduction of specific (trans)genes, resulting in the creation of genetically modified organisms. Innovations (such as CRISPR–Cas9) can induce site-specific mutations,

designated 'gene editing'. This article does not further discuss these tools but focuses on the four classic plant breeding systems (Figure 2.2).

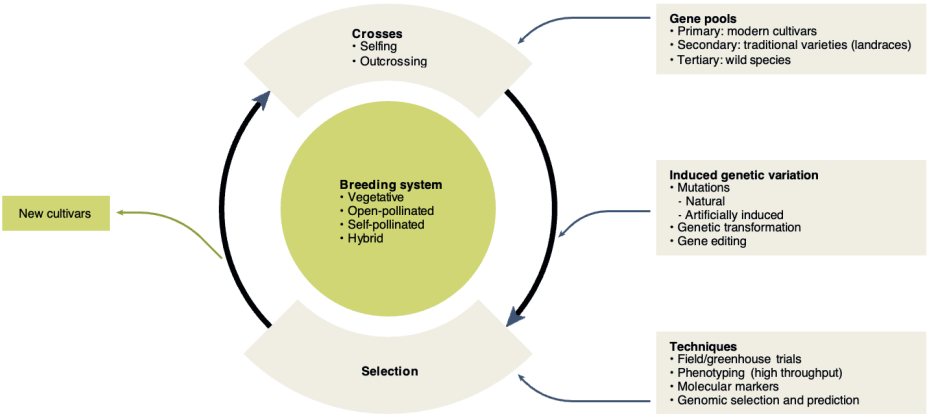


Figure 2.2: Plant breeding cycle for the development of new cultivars. The continuous cycle of plant breeding results in the development of new cultivars based on crosses and selections among plants of a crop species, whereby the breeder applies one of the breeding systems supported by biological techniques. Existing genotypes for breeding are derived from the gene pools, and new genotypes are created using tools to induce genetic variation.

2.4 Legal framework

The business of commercial plant breeding is based on a legal framework (Figure 2.3), through which a breeder can become the owner of new cultivars (Jamali et al., 2020; Louwaars, 2007). It is possible for a plant breeder to obtain plant breeder's rights (PBR) for newly developed cultivars, which meet the so-called DUS criteria: distinct from existing cultivars; uniform, meaning that individual plants look similar; and stable, meaning that the cultivar remains true to its description through generations and multiplications. PBR give a breeder the exclusive right for a fixed period (generally 25 years) to commercialize the cultivar by producing and selling propagation material; seeds, tubers and plants (Jamali et al., 2020). In Europe, the seeds of vegetable and field crop cultivars can be commercialized only if they have passed the DUS test. PBR application is voluntary, but plant breeders will usually obtain PBR to protect their varieties before commercialization.

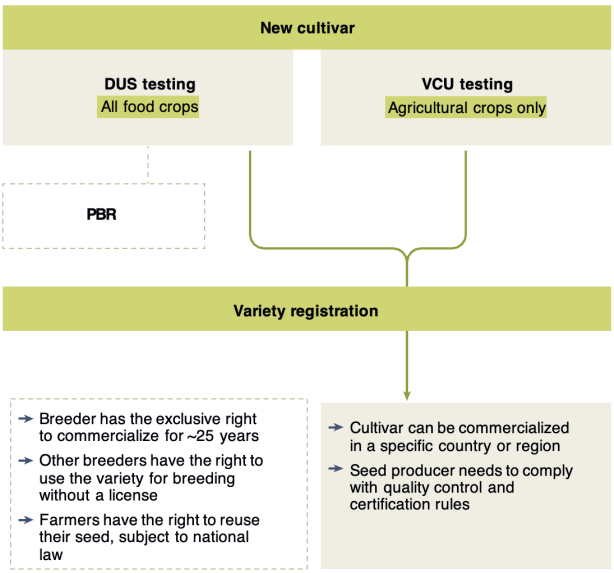


Figure 2.3: Formal legal framework guiding commercial plant breeding. In most seed regulatory systems, new cultivars of food crops are submitted to DUS and VCU tests for variety registration and release to the seed market. DUS means distinct, uniform and stable. VCU testing requires values similar to or better than existing varieties. DUS and VCU are required for variety registration of agricultural crops. Only DUS data are required for the registration of other food crops. Additionally, DUS data are used to apply for PBR, providing breeders with the exclusive right to commercialize the cultivar, commonly for 25 years. Application for PBR is voluntary.

There are two exceptions to the PBR rule. The first exception is farmers' privilege (also known as farm-saved seed) (De Jonge et al., 2022; Louwaars, 2007). It safeguards the right of farmers to save seeds from the plants they grow. Farmers have the right to use these seeds by themselves during the next season, but they are not allowed to sell them. In some countries, farmers need to pay a fee to the owner of PBR when saving seeds. The farm-saved seed exemption applies to field crops to support food security. It does not apply to vegetables or ornamentals, because these are considered to have a more commercial character. The second exception is the breeders' exemption, which allows for the use of protected varieties without authorization for further crossing, breeding and selection.

In most countries, there is an additional requirement to pass the test for Value for Cultivation and Use (VCU) for agricultural crops (Jamali et al., 2020). VCU concentrates on the agronomic characteristics and economics of a new cultivar, assessing features such as yield, disease resistance and (processing) quality (Jamali et al., 2020). Only cultivars that outperform existing cultivars already available in the country are placed on the 'National List'. This National List determines which cultivars are recommended to farmers in a country. In a few countries, VCU is not required, and plant breeders can sell their DUS varieties; it is up to breeders and farmers to do performance trials and decide which varieties to sell or grow (Jamali et al., 2020).

Plant breeding systems

Plant breeding systems are defined by processes of genetic recombination and reproduction. Four classic breeding systems can be distinguished: vegetative, open-pollinated, self-pollinated and

hybrid (Table 2.1) (Acquaah, 2020). All breeding systems start with the generation of new genetic combinations based on crosses between favourable genotypes and subsequent selection of the best plants in the consecutive progenies. They represent a continuous process of improvement through crossing, testing, selecting and fixing of genotypes. The four systems differ in terms of the breeding process, the type of starting material generated, the multiplication of the starting material and the speed of genetic improvement.

Table 1 | Overview of four plant breeding systems

Breeding system	Breeding process	Generation of new starting material	Starting material for cultivation	Speed of genetic improvement
Vegetative	Crosses and selection in consecutive vegetatively propagated progenies	Vegetative propagation	Clones	Slow[a]
Open-pollinated	Mass selection in open-pollinated populations	Mass pollination	Seeds of the population	Medium
Self-pollinated	Crosses, backcrosses and repeated selfings	Selfings	Selfed seeds	Fast
Hybrid	Crosses, backcrosses and repeated selfings to generate inbred parents and crosses between parents to generate the hybrid	Crosses between (homozygous) parent lines	Hybrid seeds	Fast[b]

[a]Vegetative breeding moves slowly for polygenic traits such as yield and drought resistance. It can be a fast way to introduce genetically simple traits such as flower colour in ornamental crops. [b]It may take a long time to develop inbred lines; once these exist, hybrid breeding is the fastest system to realize genetic improvement.

Table 2.1: Overview of four plant breeding systems

Vegetative breeding system

The vegetative breeding system is the most basic and empirical breeding system. Crosses are made to produce new genetic combinations, and the best plant is selected after repeated trials. It is the dominant system in genetically complex species (see below 'Ploidy level'). Cultivars are reproduced vegetatively: clones are made from selected plants. In this way, breeders ensure that the genetic composition of the plant remains constant. Examples are root and tuber crops, ornamental crops and fruit crops.

Open-pollinated breeding system

The open-pollinated system is based on population management. The breeding process is less controlled than in other breeding systems. Most crosses occur without the involvement of a breeder as plants within a selected population spontaneously outcross. Plant species often have a natural (self-incompatibility) system that prevents them from self-fertilization, and plants are randomly pollinated and fertilized by neighbour plants (Charlesworth et al., 2005). Seeds of a new (open-pollinated) cultivar are produced in the same way by open pollinations. Genetic variation in open-pollinated cultivars remains relatively high. Each plant represents a unique genotype, meaning that it has a unique genetic composition. Open-pollinated cultivars are not very uniform and may not be stable due to genetic drift during the multiplication process. The DUS criteria are less strict when seeking to obtain PBR for open-pollinated crops. Demand for highly uniform crops has resulted in a shift from the open-pollinated system to the hybrid system in many crops. Examples of crops in which a transition from the open-pollinated system to the hybrid system has occurred are maize, cabbage, carrot, leek, onion and sunflower. For major crops such as maize, hybrid cultivars are preferred by commercial farmers, although some open-pollinated cultivars are still being used, mainly by smallholder farmers (Almekinders, Hebinck, et al., 2021).

Self-pollinated breeding system

Self-pollinators reproduce via a natural system whereby their own pollen fertilizes flowers of the same plant. As explained previously, repeated selfing results in offspring in which all chromosome pairs are eventually identical. This phenomenon is called 'homozygosity'. Genetic variation within a self-pollinated population gradually decreases. In this system, the breeder starts by making manual crosses of parent plants with desired characteristics, and the progenies are selfed for many generations, whereby the best plants are selected. This results in a homozygous cultivar that can easily be reproduced by harvesting the selfed seeds.

Hybrid breeding system

Hybrid breeding is based on human interventions in natural reproductive systems. The system is based on the development of inbred lines and subsequent crossing of two selected inbred lines to generate the hybrid cultivar (Figure 2.4). Upon selfing, the offspring of homozygous genotypes remain homozygous, while the offspring of heterozygous genotypes segregate into homozygous and heterozygous genotypes. The eventual deliberate crossing of two homozygous parent lines results in heterozygous offspring, which usually leads to enhanced uniformity, stronger and more resilient plant growth and higher yields. This phenomenon whereby the progeny of crosses among parent inbred lines outperforms its parents is designated 'heterosis' or 'hybrid vigour' (Kaeppler, 2012).

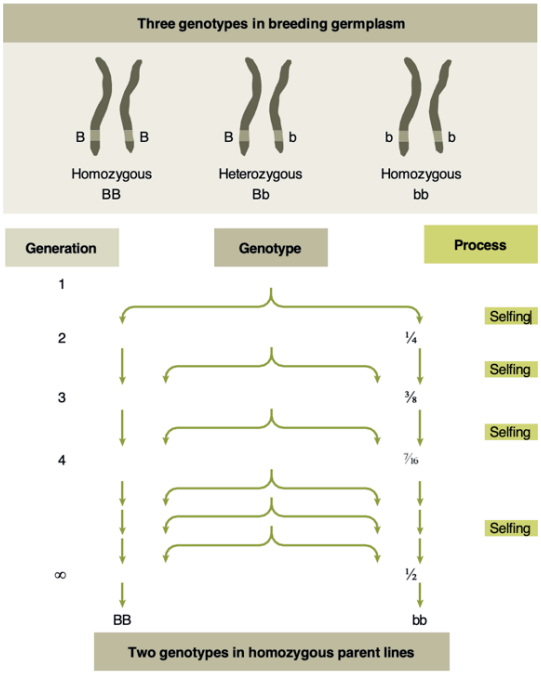


Figure 2.4: Development of homozygous inbred lines. The diploid breeding germplasm consists of three genotypes, 'BB', 'Bb' and 'bb', with B and b representing two different alleles of one locus. In the end, there are two homozygous parent genotypes left: BB and bb. A cross is made between two individual homozygous parents with different alleles to create a hybrid that is heterozygous (Bb).

The main advantage of hybrid breeding is the improved predictability of the outcomes of crosses. The homozygous character of inbred parent lines results in improved control over genetics.

Furthermore, inbred lines enable the breeder to use (marker-assisted) backcrossing to add new traits to existing cultivars while maintaining other traits. This process is called 'trait stacking' and is impossible in the vegetative and open-pollinated breeding systems. Another reason why commercial breeders prefer hybrid cultivars is the natural protection of intellectual property. Seeds harvested from a hybrid plant are genetically diverse and hence differ from the original hybrid. Plants raised from these saved seeds are inferior to the plants grown from the hybrid seeds. Farmers need to buy new hybrid seeds every season to maintain crop performance.

The multiplication of starting materials for hybrid cultivars is a resource-intensive and expensive process. It requires more resources than for the other three breeding systems because each hybrid seed is the product of a deliberate cross between two specific parent plants. Also, due to inbreeding depression, inbred lines tend to produce fewer seeds; thus, many plants are required to produce the desired amounts of seeds. Male parent lines produce no hybrid seeds at all and occupy a varying part of the field (5–40%), depending on the crop species (Virmani et al., 2003). The production of hybrid seeds can be done manually, or by wind or insects when male-sterile female plants are used. As a result of the development of parent lines and the labour required for seed production, the costs of hybrid seeds are usually higher than the seed production costs of open-pollinated or cross-pollinated crops.

2.5 Biological and economic characteristics of crops

Breeding programmes are shaped by economic and biological feasibility. Below, we discuss biological and economic characteristics of crops that influence the commercial feasibility of a hybrid breeding programme. Certain characteristics are identified as determinants from the perspective of the plant breeder.

Mating system: inbred lines and heterosis

The preferred breeding system is largely determined by the mating system of a crop (Chahal & Gosal, 2002). Mostly, it is directly linked to the feasibility of generating inbred lines. The hybrid breeding system was easily applied to (strict) self-pollinators such as tomato, pepper and eggplant. A natural inbreeding process had already been completed, resulting in the selection of alleles with an evolutionary advantage. The mating system of (strict) self-pollinators is optimal because all genetic combinations can be made: selfings and (back)crosses. The mating system of cross-pollinators often prevents self-fertilization, and crosses are made between different genotypes. This results in genetically diverse and highly heterozygous crops, in which alleles with a negative effect on plant performance can remain hidden, especially in polyploid crops (Lindhout et al., 2018). Upon selfings, deleterious alleles may pop up in homozygous loci. This is the main reason for inbreeding depression observed in such crops. The development of inbred lines poses a great challenge, especially in cross-pollinators. Parent lines are generally weak and, in particular, too weak to support commercial seed production. This is why the degree of inbreeding for parent lines of hybrid cultivars may differ. When seed yields of pure inbreds are too low, breeders prefer 'impure' parent lines. A lower degree of uniformity is then accepted. Once viable inbred parent lines have been developed, applying the hybrid breeding system is straightforward: the inbred parents are improved through intercrosses and backcrosses (Lindhout et al., 2018).

Furthermore, the mating system may also determine the level of heterosis. Some breeders link the magnitude of heterosis to genetic diversity: combining more genetically distinct parent plants leads to a greater manifestation of heterosis (Brown & Caligari, 2008). Among selfers, a degree of heterosis can be found, but it is generally more erratic (Nienhuis & Sills, 1992). Maize, an outcrossing species, shows an enormous degree of heterosis, incentivizing breeders to pursue hybrid breeding (Singh et al., 2012). However, it must be stressed that the cause of heterosis is still disputed (Kaeppler, 2012). At this point, plant breeders simply benefit from the manifestation of heterosis without knowing the scientific cause underlying the phenomenon. Breeders can develop heterotic pools of contrasting parents to maximize the heterosis effect. Such pools have been very important for some cross-pollinators such as maize and pearl millet (Singh & Gupta, 2019). For self-pollinating vegetables such as tomato, breeders use inbred lines with high general combining ability rather than heterotic pools.

Ploidy level

In nature, plants may have two, four or more copies of all chromosomes. This is referred to as a plant being 'diploid' (two copies), 'tetraploid' (four copies) and so on. A wide variation in ploidy level occurs in plants. In polyploid species, a high number of disadvantageous alleles accounting for a particular gene can be tolerated thanks to alternative advantageous alleles on the sister chromosomes. Simply put, good sister alleles compensate for the deleterious effects of bad sister alleles (Allard, 1999). The unfavourable alleles become a problem only during the development of inbred lines, which is a prerequisite for hybrid breeding. This explains why the great majority of hybrid crops are diploids. Polyploid crops can be converted into diploids, but this is a lengthy process that requires a lot of resources (Lindhout et al., 2011).

Plant generation time

Plant generation time refers to the duration of the life cycle of a plant, which is the cycle from seed to seed. It is possible to distinguish among annual, biennial and perennial crops. Annual crops have a life cycle of one year in which they germinate, flower, set seed and die. The world's main staple foods (wheat, rice, maize, potato and beans) are all annual crops. Biennial plants take two years to complete their life cycle. Perennial species, such as trees, grow and flower for many years and have a long generation time. Plant generation time influences the speed of the breeding programme. From a plant breeders' perspective, shorter generation times are preferred because the breeding programme can move faster in developing inbred lines and selecting offspring. Breeders may attempt to reduce the generation time through the use of artificial environments, which speed up plant development.

Seed production and male sterility

Seed production costs of hybrid cultivars depend on crossing efficiency and labour costs. The crossing efficiency of a crop refers to the number of seeds produced per pollination of a single flower or per crossing. If the crossing efficiency is low, many crosses are required to produce a certain number of seeds, resulting in higher costs. Large differences exist between the crossing efficiencies of plant species. For some crops, such as lettuce, cereals and beans, a few seeds are produced per cross. For other crops, such as tomato, potato and pepper, one cross can result in over 100 seeds. Seed production costs are an important reason why hybrid cultivars have not been developed for certain crops, such as wheat (Gupta et al., 2019). A prerequisite for commercial

feasibility is the capability of the plant breeder to manipulate the plant in such a way that it efficiently produces hybrid seed, reducing labour costs. Costs depend on the ability to pollinate via wind or insects instead of manual pollination. Male and female plants can then be placed in specific designs in isolated fields to maximize the success of natural crosses via wind or insects. Plants can also be placed in isolated cages in greenhouses where insects pollinate the flowers. In case of wind or insect pollination, crossing efficiency is less critical because labour costs are low. By contrast, manual hybrid crosses are economically feasible only if the crossing efficiency and the commercial value of the harvested hybrid seeds are also high (Xiao et al., 2019). Moreover, breeders can use male sterility to reduce the costs of seed production. Male-sterile plants do not produce fertile pollen; hence, the seeds produced are by definition obtained by outcrossing. Male sterility exists in nature and is frequently used in hybrid breeding programmes. Labour costs are significantly reduced when manual emasculation (the removal of the male sexual organs of a plant) is no longer needed. Alternatively, male flowers can be mechanically removed from monoecious plants, as is done in maize. A challenge in the usage of male sterility is the maintenance and reproduction of the female lines that are male sterile. Genetic systems for the restoration of male fertility are being used to reproduce male-sterile female lines through selfings. This further complicates the breeding and seed production of hybrid crops (Chen & Liu, 2014).

Value of the harvested product per plant

The output of a breeding programme is commercial seeds (or plants), which are used by farmers to cultivate a crop. The commercial output of farmers is the harvested product per plant, such as staple foods, fruits and vegetables. The price of commercial seed is connected to the market value of the harvested product per plant. A high market value per plant means that the price of commercial seed can be higher: farmers are willing and able to invest in expensive seed when expecting returns on the investment. A hybrid cultivar should enable a farmer to obtain sufficient added value in terms of quantity and quality (such as shelf life and uniformity). A greenhouse tomato is an example of a crop with an extremely high value of harvested product per plant. A tomato seed may produce a plant that grows year-round in a greenhouse with a production value per plant of dozens of euros (Peet & Welles, 2005). This means that the price of commercial tomato seed may exceed one euro. By contrast, a field-grown industry tomato plant may have a production value of only five to ten eurocents. Commercial seed of an industry tomato cultivar must therefore be at least 10 to 20 times cheaper than the seed of a greenhouse tomato cultivar. In summary, industry tomatoes are a low-margin, high-volume product, whereas greenhouse tomatoes are a high-margin, low-volume product.

Market size

Investments in breeding programmes are linked to the size of the local, regional or global market. The market for hybrid seeds needs to be sufficiently large to cover the investments in breeding, production and commercialization. The effect is twofold. First, plant breeders will invest more money in global crops with a large global market (such as maize). Second, breeders will seek to develop cultivars suited for diverse climatological conditions, maximizing their potential market per cultivar. It is less attractive for commercial plant breeders to focus on niche markets, meaning local crops, specific consumer preferences and climatological conditions, because the costs of such breeding programmes are not easily returned by the limited seed sales. Figure 2.5 shows the major global seed markets for some food crops.

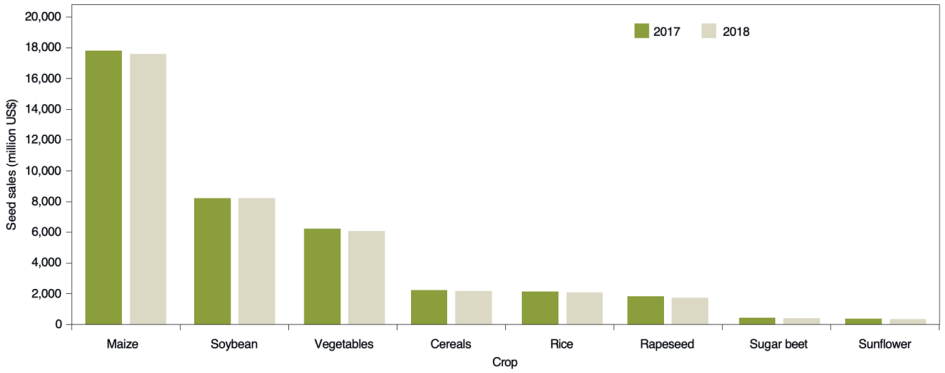


Figure 2.5: Global seed markets. Formal global seed market by food crop, excluding informal sales and farm-saved seed. Figure adapted with permission from IHS Markit (2019).

2.6 Case studies

Below, three examples are outlined: maize, wheat and potato. Maize is a cross-pollinator and is the first crop for which a hybrid breeding programme was launched, over 100 years ago. Nowadays, most modern maize cultivars are hybrids, and these are also bred and grown in developing countries (Erenstein & Kassie, 2018). Wheat is a self-pollinator for which the self-pollinated system is still being used. Breeding companies have shifted between investing and divesting in hybrid wheat (Gupta et al., 2019). Hybrid breeding has only recently been applied to potato, for which a shift from the tetraploid potato to a diploid potato was required (Lindhout et al., 2011). These cases illustrate the impacts of the different biological and economic factors, which are described above.

Hybrid maize

The hybrid breeding system was developed and implemented for maize at the beginning of the twentieth century (Crow, 1998). Maize is a diploid cross-pollinator but also has limited self-fertilization, allowing for the development of inbred lines (Duvick, 2005). It took several decades to overcome inbreeding depression and develop well-performing inbred parent lines and hybrids. The first commercial hybrid cultivars were released in 1930. Initially, maize hybrids were generated through 'double crossing', whereby commercial seed was produced by crossing two pure F1 hybrids. This was required because the seed production costs of true hybrids were too high. Later on, three-way crosses were made. 'True' hybrid maize was commercialized only from 1960 onwards, meaning crosses were made between highly homozygous parent lines. Maize is a monoecious species with separate female and male inflorescences (Figure 2.1). This has been highlighted as one of the main reasons why maize became the first hybrid cultivar (Andorf et al., 2019). Plants only containing viable female reproductive organs can be generated (manually or mechanically) by the removal of male inflorescences or tassels before flowering. Hybrid seeds can then easily be collected from female plants, which are naturally pollinated by the male plants, that are placed in between female plants. This is still the main way in which hybrid maize seed is produced, as it results in relatively low seed production costs. Maize is now the crop with the highest economic value in the world. Maize became the major global crop only after the

development and application of hybrid breeding, which resulted in a wide variety of hybrid cultivars that were well adapted to lower temperatures and suitable for the production of biofuels (Allard, 1999). Since the first hybrid varieties were introduced, yields in commercial maize production have increased by a factor six, of which approximately half is thanks to genetic improvement and the other half to improved cultivation techniques (Figure 2.6) (Duvick, 2005; Troyer, 2006).

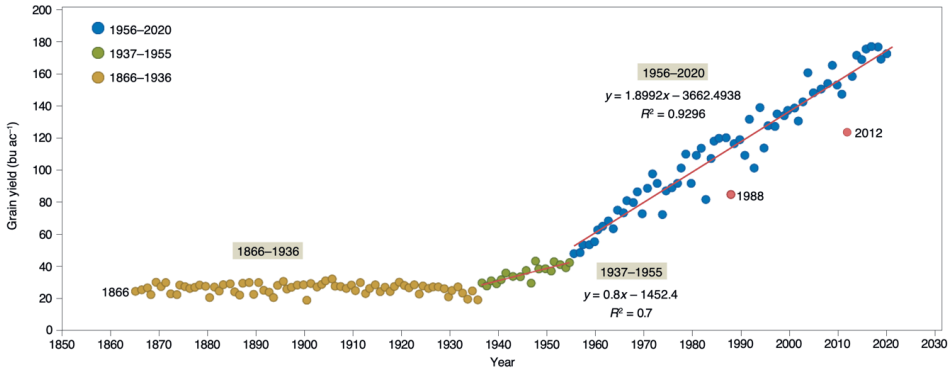


Figure 2.6: Maize yield increases in the United States since 1866. Since the introduction of hybrid cultivars, maize yields have increased more than five times thanks to breeding progress and improved cultural practices. Note that 100 bushels per acre is equivalent to 6.73 t ha⁻¹. Three phases can be distinguished. From 1866 to 1936, the use of open-pollinated varieties resulted in stagnant yields of about 26 bushels per acre (1.75 t ha⁻¹). From 1937 to 1955, the adoption of double-cross hybrid maize resulted in grain yield improvement of about 0.8 bushels per acre per year (0.05 t ha⁻¹). From 1956 to 2020, single-cross hybrids combined with the adoption of nitrogen fertilizer, higher plant densities, pesticides and mechanization resulted in grain yield improvement of 1.9 bushels per acre per year (0.13 t ha⁻¹). Figure adapted with permission from Nielsen (2021).

Hybrid wheat

Like maize and potato, wheat is one of the most important food crops in the world. Wheat is an allohexaploid or amphidiploid self-pollinator, which means that the lines are highly homozygous, and it is not difficult to develop inbred lines. There have already been two waves of interest in hybrid wheat breeding, in the 1960s and 1990s (Gupta et al., 2019). However, the success of hybrid breeding programmes has been limited, and hybrid wheat has not been commercialized on a large scale. The key obstacle blocking a hybrid transition for wheat is that the low added value of hybrid varieties is insufficient to cover the high costs of seed production (Gupta et al., 2019; Longin et al., 2014). Also, the market for wheat is segmented, with strong quality preferences for bread making. Reported performance differences between pure line and hybrid wheat cultivars vary and remain small (Jiang et al., 2017; Longin et al., 2014; Zhao et al., 2021). The heterosis effect has been small, as wheat is a selfer with limited genetic variation. Hybrid wheat offers a yield increase of about 10% (Gupta et al., 2019; Jiang et al., 2017). Pure line cultivars produced via the self-pollinated system also improve each year (Voss-Fels et al., 2019). As line cultivars enter the market two years earlier, hybrids may be outdated upon variety release. Most importantly, seed production costs for hybrid wheat are too high. Wheat produces only one seed per crossed flower, and its pollen is heavy, which limits the success of natural pollination by wind (Boeven et al., 2018). Hence, manual pollination is far too expensive, and wind pollination may be less effective. Moreover, it has been difficult to introduce male sterility. At this point, a hybrid wheat transition remains

uncertain due to the remaining biological and economic challenges linked to seed production, heterosis and a fragmented market. The transition will require a significant reduction in seed production costs and identification of heterotic pools to obtain strong heterosis effects (Boeven et al., 2016). The development of heterotic pools is a costly, lengthy process, which can now be accelerated using modern breeding tools such as big data and markers to improve prediction abilities (Zhao et al., 2021). Attempts to realize male sterility genetically or chemically have not yet resulted in commercial usage of wheat hybrids over large acreages (Gupta et al., 2019).

Hybrid potato

Traditionally, potato breeding is 'empiric' due to the complex genetic structure of the potato (Douches et al., 1996; Jansky et al., 2016). The cultivated potato is tetraploid: it has four sets of chromosomes. In the past century, the vegetative breeding system has been the dominant system, and yield increases were based on improved cultivation practices rather than real genetic improvement (Douches et al., 1996). While maize cultivars are usually replaced after five to ten years, two of the most prominent potato cultivars, Bintje and Russet Burbank, which were introduced over 100 years ago, are still grown on large acreages in Europe and the United States (Jansky et al., 2016; Zhang et al., 2021). There was a longstanding conviction that it is impossible to apply the hybrid breeding system in potato (Lindhout et al., 2011). A reduction in ploidy level from tetraploid to diploid made it possible to produce inbred lines more efficiently than when using tetraploids (Lindhout et al., 2018). However, the diploid potato is a strict cross-pollinator, and it seemed unfeasible to create inbred lines due to potato's self-incompatibility and strong inbreeding depression. After these challenges were overcome, it became possible to systematically combine genes and exploit heterosis, introducing desirable traits such as disease resistance (Su et al., 2020). Moreover, diploid potato can be grown from hybrid true seed, through either direct sowing or transplanting seedlings. Tetraploid potatoes are multiplied via the vegetative system with a multiplication rate of a factor of ten (Jansky et al., 2016; Lindhout et al., 2011). By contrast, one diploid potato plant may produce thousands of seeds per season. The potential of diploid potato has now been generally recognized, and hybrid breeding programmes have been launched by the public and private sectors in Europe, the United States and China (Jansky et al., 2016; Lindhout et al., 2011; Zhang et al., 2021). After ten years, yield trials have demonstrated that the potential of the diploid hybrid potato is similar to that of the traditional tetraploid potato (Hutten, 1994; Stockem et al., 2020). The question is now when hybrid potatoes will start outperforming tetraploid varieties. This timeline reflects the large initial investment required for a hybrid breeding programme for a new crop.

2.7 Synthesis

The decision of commercial plant breeders to launch a hybrid breeding programme depends on the biological and economic characteristics of a crop. The hybrid breeding system is the preferred system for commercial plant breeders. First, it enables breeders to most effectively and efficiently develop and produce new cultivars tailored to human needs and preferences. Second, it offers breeders natural protection of intellectual property and the opportunity to obtain return on investments. History has shown that once hybrid breeding is successfully applied in a crop, it becomes the dominant breeding system for commercial plant breeders (Priyadarshan, 2019). Representative crop species are listed in Table 2.2 with qualifications for relevant characteristics.

What are the economic and biological determinants to breed or not to breed? Table 2.2 highlights several determinants, among which seed production costs are the most crucial. These costs can be high for hybrid cultivars due to the required labour and land. The value of the harvested product and the seed market size are other important economic factors defining potential returns on investment. It should be stressed that profitability for the farmer is always a prerequisite for a breeding programme: farmers will invest in expensive seeds only if they can obtain a return on this investment. Scientific breakthroughs in breeding show how biological limitations imposed by the mating system and ploidy level of a crop can be overcome. The limits of biological feasibility are constantly shifting; for example, potato used to be considered one of the least suitable crops for hybrid breeding, but hybrid breeding is now being applied in potato. The question arises whether hybrid breeding programmes should be launched for crops with commercially disadvantageous or discouraging characteristics. Breeding has been limited for indigenous leafy vegetables and fruit trees, but these crops are very important for global food security (Steenhuijsen Piters et al., 2021). The same applies to cassava, sweet potato and quinoa. How can stakeholders work together to improve the performance of these crops? In the absence of an immediate business case, public–private partnerships may offer a way to organize the required resources to achieve shared goals. Collaboration is necessary to mobilize funding and technologies. Food systems around the world are under unprecedented pressure due to population growth and climate change. Through collaboration, we can ensure that the potential impact of plant breeding, and hybrid breeding in particular, will materialize. The common objective should be to breed robust, resilient and constantly high-yielding cultivars to contribute to food and nutrient security for the future world population.

Table 2.2: *The economic data included in this table are based on the experience of the authors and senior experts from the commercial plant breeding industry and the Access to Seeds Index (WBA, 2016, 2019a, 2021) refer to self-pollinators and cross-pollinators, respectively.* [a]*Traditionally, rice cultivars are self-pollinated. Male sterility has been introduced, reducing the costs of hybrid seeds (Charlesworth et al., 2005). Commercial production of hybrid rice started in China in 1976 (Charlesworth et al., 2005; Cheng et al., 2007; Yuan, 1986). Barley and rye are more successful hybrid crops thanks to the application of male sterility. No hybrid system has been developed for oats. Successful rye hybrids have been developed on the basis of male sterility and self-incompatibility66.* [b]*Hybrid sugar beet varieties were introduced in the 1950s. Initially, hybrid sugar beet varieties were tetraploid. Triploid varieties were used from the 1970s onwards, and from the 2000s onwards, diploid varieties were introduced (McGrath & Panella, 2018). Ever since, yields have increased by 60%, and the lifetime of cultivars has been reduced to two to three years.* [c]*Asparagus and spinach are dioecious species, allowing separation into female and male plants for hybrid seed production (see also Figure 2.1).* [d]*Most cucurbitaceous crops are monoecious, with separate female and male flowers on the same plant. Male flowers of the male parent line are used to pollinate the female flowers of the female parent line.* [e]*The value of a spinach plant from one seed is low. Still, hybrids are used because the production costs of hybrid seeds are equally low.* [f]*In pepper and tomato, male sterility is available, but it is not yet of crucial economic importance because of the high number of seeds per cross and the high market value per plant. Nonetheless, male sterility in hot pepper is of increasing importance to avoid the difficult and time-consuming practice of emasculation of its small flowers.*

Table 2 | Biological and commercial characteristics of examples of crop species and their dominant breeding systems

	Mating system used by breeder	Ploidy level	Plant generation time	Efficiency of hybrid seed production		Market value per plant for crop cultivation	Current value of the global seed market	Breeding system			
				Number of seeds per manual crossing	Male sterility applied			Vegetative	Self-pollinated	Open-pollinated	Hybrid
				Low, <10 Medium, 10–60 High, >60 (seeds per crossing)		Low, <0.05 Medium, 0.05–1 High, >1 (euros)	Low, <50 Medium, 50–500 High, >500 (million euros)	1, dominant system 2, secondary system			
Field crops											
Barley, oat, rice, rye, wheat[a]	Selfer	2*n*	Annual	Low	yes[a]	Low	High		1		2
Cassava, sweet potato, yam	Outcrosser	2*n*	Annual	Low		Low	Low	1			
Maize	Outcrosser	2*n*	Annual	High	yes	Low	High			2	1
Millet, sorghum	Selfer	2*n*	Annual	Low	yes	Low	High			1	2
Mustard, rapeseed	Outcrosser	2*n*	Annual	Low	yes	Low	High			2	1
Potato	Outcrosser	2*n*, 4*n*	Annual	Medium	No	Medium	High	1			2
Sesame	Outcrosser	2*n*	Annual	High		Medium	Low			1	
Sugar beet[b]	Outcrosser	2*n*	Biennial	Low	yes	Medium	Medium			2	1
Sunflower	Outcrosser	2*n*	Annual	Low	yes	Low	Medium			2	1
Legumes											
Bean, pea, peanut	Selfer	2*n*	Annual	Low		Low	Medium		1		
Soybean	Selfer	2*n*	Annual	Low		Low	High		1		
Vegetables											
Asparagus[c]	Outcrosser	2*n*	Perennial	Low	Dioecy[c]	High	Low		2		1
Brassicaceae (broccoli, Brussels sprout, cabbage, cauliflower)	Outcrosser	2*n*	Biennial	Low	yes	Medium	High			2	1
Carrot	Outcrosser	2*n*	Biennial	Medium	yes	Low	Medium			2	1
Onion, leek	Outcrosser	2*n*, 4*n*	Annual/biennial	Medium	yes	Low-Medium	Medium			2	1
Cucurbitaceae (cucumber, gourd, melon, watermelon, squash)[d]	Selfer	2*n*	Annual	High	Monoecy[d]	High	High		2		1
Eggplant	Selfer	2*n*	Annual	High	No	High	Medium		2		1
Lettuce	Selfer	2*n*	Annual	Low	No	Medium	Medium		1		2
Okra	Selfer	2*n*	Annual	High	yes	Medium	Low			2	1
Spinacia (spinach)[e]	Outcrosser	2*n*	Annual	Low	Dioecy[c]	Low[e]	Medium			2	1
Tomato, sweet/hot pepper[f]	Selfer	2*n*	Annual	High	yes[f]	High	High		2		1
Other											
Fruits, berries, banana, palm	Outcrosser	2*n*–8*n*	Perennial	Low		Medium	Medium	1			
Coffee, tea, cacao	Outcrosser	2*n*	Perennial	Low		Medium	Low	1		2	



3

Market-driven transitions in the vegetable seed sector in sub-Saharan Africa

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Abstract

Quality vegetable seed has the potential to significantly impact nutrition security in sub-Saharan Africa, as the region has the world's lowest per capita production and consumption of vegetables. Moreover, seed companies might have an important role to play, as in Asia; there, vegetable production and consumption increased rapidly following the expansion of the private seed sector. However, market-driven seed sector development remains contentious, with some celebrating technological advancements and others raising concerns. This paper contributes to seed systems literature by focusing on the role of vegetable crops and diversity within the private sector. It explores the heterogeneous character of the private sector by studying how different business models of leading vegetable seed companies jointly contribute to sector development in sub-Saharan Africa. Eighteen in-depth interviews were conducted with leading vegetable seed companies operating in the region. Qualitative tools were selected to translate individual company data into general findings, while thematic analysis was used to pinpoint a private sector perspective and ideal-type analysis was used to construct business model typologies. The results show that seed companies collectively view seed sector development as a linear trajectory involving public and private investments to enable farmers to adopt increasingly advanced seed types, especially hybrids. In this trajectory, different companies take on different roles based on specialization in seed system functions: variety development, seed production, seed dissemination, and seed use. The coexistence of and collaboration between different (private) actors in the vegetable seed sector contribute to plurality and integration in line with the concept of integrated seed sector development. However, it is not a static condition as company roles evolve with expanding business models in terms of system functions and market segments. A general objective of (national) seed policies is to increase farmers' access and choice in terms of quality seed of improved varieties. Seed sector development interventions can enhance inclusivity by focusing on viable and innovative business models for niche markets in terms of farming systems and crop types.

3.1 Introduction

Seed companies play a critical role in providing farmers with access to quality seed of improved varieties, which is vital for achieving Sustainable Development Goal (SDG) 2: Zero Hunger. Vegetables are a crucial component of healthy diets and often represent an important income source for smallholder farmers (Schreinemachers et al., 2017). In Asia, the private sector's combined approach of breeding, distribution, demonstration, and capacity building triggered a major increase in the use of quality vegetable seed as well as vegetable production and consumption levels (Schreinemachers et al., 2021; Scoones & Thompson, 2011). This trajectory projects an important role for seed companies in sub-Saharan Africa (SSA), as the region has the world's lowest vegetable production and consumption levels, and development of the private seed sector has moved slowly (Schreinemachers et al., 2021; Steenhuijsen Piters et al., 2021). At the same time, the role of seed companies in achieving global nutrition security has grown controversial. While proponents associate seed companies with technological advancement, opponents tend to associate them with market consolidation and farmer dependency (Béné et al., 2019; Clapp, 2020; Westengen et al., 2023). Considering the urgent need to realize SDG 2, there is an equally urgent need to assess how business models of leading vegetable seed companies are contributing to development trajectories in SSA.

Large amounts of development funding have been spent to drive market-driven seed sector development (Scoones & Thompson, 2011; Westengen et al., 2023). The Alliance for a Green Revolution in Africa had an approximate budget of USD 1 billion between 2007 to 2020, focusing on staple crops (Wise, 2020). The Dutch government spent approximately EUR 214 million on seed sector development between 2018-2022, focusing on vegetables and potato amongst other crops (WCDI, 2023). However, the exact impact of these interventions remains unclear. Some quantitative studies show positive results in terms of the adoption of improved varieties and subsequent livelihood outcomes in a specific context (Deutschmann et al., 2021; Ruzzante et al., 2021; Takahashi et al., 2020). Similarly, qualitative research underlines that the level and impact of the adoption of improved varieties depend on contextual factors (Almekinders et al., 2019; Kilwinger, 2022). There remains an absence of scientific data (Nabuuma et al., 2022), and for vegetables there is less information than on staples, as the focus of academics, policymakers and development practitioners remains on the latter, especially maize (Louwaars & de Boef, 2012; Louwaars et al., 2013; Nabuuma et al., 2022).

The Access to Seeds Index, published in 2016, 2019, and 2021, "measures and compares the efforts of the world's leading seed companies to enhance the productivity of smallholder farmers" (WBA, 2016; 2019a; 2021). Through benchmarking and publicizing the efforts of companies, the Index seeks to incentivize companies to do better. Most seed companies obtain low scores and the conclusion drawn by the Access to Seeds Index team is that the performance of companies is "concerning" (WBA, 2022). An alternative interpretation could be that while the smallholder segment is commercially interesting for some companies, it does not represent a "sufficiently profitable market" for others (Beumer & Stemerding, 2021). The Index represents the first attempt to increase transparency in the seed sector by ranking business models and promoting best practices. However, it focuses exclusively on smallholder farmers without defining this concept and does not consider the different ways in which companies can contribute to seed sector

development, or whether companies use external (public) funds to implement certain activities (WBA, 2021).

Our paper seeks to contribute to the seed systems literature and address this evidence gap by focusing on vegetable seed systems and diversity within the private sector. Specifically, we focus on the role of leading vegetable seed companies in seed sector development in SSA because vegetable seed companies are frontrunners in terms of innovation and farmer outreach. It explores the heterogeneous character of the private sector by studying how different business models impact seed sector development in SSA through 18 in-depth interviews with the (regional) commercial directors of companies operating in the region, using qualitative tools to translate individual company data into general findings. The results indicate that seed companies collectively view sector development as a linear trajectory in which professionalizing farm systems and produce markets are associated with rising standards for seed quality and genetics, and in which companies take on different roles specializing in seed system functions. In our discussion and conclusion, we reflect on the approaches of leading vegetable seed companies and evaluate how policies might enhance the positive impact of market-driven seed sector development.

3.2 Conceptual framework

Quality seed

Quality seed is a subjective term for which farmers, seed companies and governments all have their own definition. A distinction should be made here between legal and farmer perceptions of quality. In formal systems, quality standards are defined by law and controlled via seed certification and testing schemes (Louwaars & de Boef, 2012). Additionally, every seed company can have its own standards that move beyond the regulatory minimum. Farmers have individual preferences and look for seed which matches their farming system, dietary preferences and/or market demands. Almekinders and Louwaars (1999) have listed four aspects of seed quality: genetic, physiological, sanitary, and analytical quality. Genetic quality refers to varietal adaptation, identity, and purity; physiological quality refers to seed germination and vigour; sanitary quality refers to the absence of seed-transmitted disease, and analytical quality refers to the percentage of 'good seed' as opposed to inert matter or 'other' seeds. Genetic quality can be improved through breeding, while physiological quality can be improved through multiplication and conditioning techniques (Kilwinger, 2022). Quality levels are often linked to the origins of seed, referring to the conditions under which a variety was generated and seed was produced. Indeed, quality differences exist between formally-produced and farm-saved seed, but these may not always lead to significant differences in crop performance in prevailing farming systems (Almekinders & Louwaars, 1999). Moreover, other factors such as the availability and cost of seed may also play a decisive role for farmers (Louwaars & de Boef, 2012).

In terms of vegetable seed type, it is possible to distinguish between four categories, based on seed source and variety: farm-saved seed, open-pollinated variety (OPV) seed, standard hybrid seed and advanced hybrid seed. All types could be considered quality seed when meeting the standards of a government, company, or farmer. The first type is produced by farmers themselves and referred to as 'farm-saved seed'. The varieties may be landraces, also called 'traditional varieties'; 'farmers' new varieties', resulting from farmer selection; or reproduced modern varieties (Salazar et al.,

2007). Farm-saved seed becomes available to farmers by saving on-farm, through local exchanges or through local produce markets (Lipper et al., 2009). The three remaining types are obtained via formal channels like seed shops or distribution by the government or NGOs. We use the term OPV to refer to purchased seed of a defined variety that is reproduced through open pollination. These varieties may exist for a long time or have been recently bred; they may be protected by plant variety protection, or be unprotected and part of the public domain. OPVs of self-pollinating crops like tomato, beans and lettuce are genetically stable and suitable for re-use, while OPVs of cross-fertilizing crops like onion, squash and melons require more care to maintain varietal identity and purity when farmers save seed for the next season. Hybrids (also called F1-hybrids) are the product of crossing two distinct parent lines combining important traits (see Chapter 2). Generally, hybrids are more uniform than OPVs in cross-fertilizing crops. However, hybrids are genetically unstable when reproduced, which means that farmers should not save seed if they want to maintain varietal qualities. We distinguish between two types of hybrids: 'standard hybrids' which are improved varieties that combine more useful traits and are bred for a higher yield potential, versus 'advanced hybrids' which are developed for high-end farm and market systems. Advanced hybrids are expensive and require more horticultural skills of farmers to gain a return on their investment. Practices such as using seedling trays, mulching, or trellising can increase germination rates, yields and product quality substantially. In developed markets, vegetable seed companies almost exclusively sell advanced hybrids except for crops for which hybrid seed cannot be produced profitably such as lettuce and beans. In seed markets in low and middle-income countries in SSA, companies tend to have OPVs, standard hybrids and advanced hybrids in their product portfolios.

Seed systems

Seed systems represent the set of activities affecting access to and use of seeds (Tripp, 1997). A well-functioning seed system provides "sufficient access to adequate quantities of good quality seed and planting materials of preferred crop varieties at all times" (FAO, 2016). Traditionally, a distinction has been made between formal and informal seed systems (Louwaars, 2007; Louwaars & de Boef, 2012). Informal seed systems are also referred to as farmer or local seed systems. In informal systems, farmers save seeds themselves or obtain seeds via their (social) network or markets based on processes of exchange, gifts, or payment (Sperling & Almekinders, 2023). Variety development, seed production, and dissemination are integrated in the farming system and farmer communities. In formal seed systems, farmers buy seeds (or seedlings), which are produced and supplied through a specialized and regulated value chain (Almekinders & Louwaars, 1999). In the formal system, farmers may also receive seeds 'for free' via development or government distribution programmes. Nowadays, seed systems are usually placed along a spectrum ranging from informal to formal, with several intermediary forms (Westengen et al., 2023).

Some scholars prefer to focus on seed system functions instead, looking at variety development, seed production, seed dissemination and seed use (Figure 3.1) (Christinck et al., 2018; Westengen et al., 2023). Seed system functions are similar in informal and formal systems, but the actors and techniques involved, and agents with the power to make decisions, are different. In informal systems farmers will take on more (if not all) seed system functions, while they are often considered to be 'seed users' in the formal system. Seed system functions are shaped by and operate in the legal framework, sociocultural system and agroecological system (Borman et al., 2022; Christinck et al., 2018; Westengen et al., 2023). The legal framework may affect seed systems intentionally,

regulating varieties and seed quality in the formal systems, or unintentionally, affecting informal or intermediate system functions (Louwaars et al, 2013). Seed systems are also embedded in sociocultural systems, notably regarding gender roles in selection, storing and purchasing of seeds. Finally, seeds must fit in the agroecological system which define farming conditions.

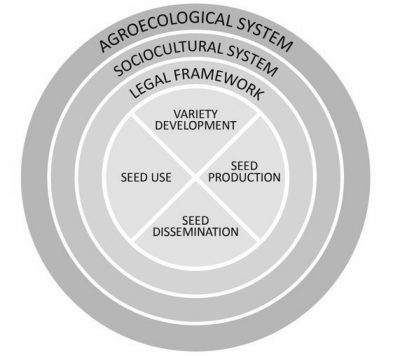


Figure 3.1: The four basic seed system functions embedded in the legal framework, sociocultural and agroecological system (adapted from Christinck et al., 2018).

Integrated seed sector development

Integrated seed sector development has been defined by Louwaars and de Boef (2012) as the integration of formal and informal seed systems at the technical and institutional levels. The two fundamental principles of an integrated approach to seed sector development are plurality and interaction. Firstly, seed sector development should be looked at in a pluralistic manner. An integrated approach recognizes that no single system, actor, or intervention can meet the diverse needs of farmers. Seed system diversity enhances farmers' ability to access their preferred variety and type of seed (Nabuuma et al., 2020). Individual farmers use different seed systems to obtain seed for different crops as well as the same crop: one tomato farmer may plant farm-saved seed, OPV seed, and advanced hybrid seed in adjacent plots (Sperling & Almekinders, 2023; ter Steeg & Gildemacher, 2023). Secondly, the interaction between formal and informal seed systems strengthens both. It is essential for breeders that genetic material and information on local conditions flow from the informal to the formal system (Almekinders & Louwaars, 1999). It is also clear that varieties and traits which flow from the formal to the informal system can reach more farmers through local dissemination (De Jonge et al., 2022; Schreinemachers et al., 2017). Similarly, methods for seed storage and marketing can flow from the formal sector to improve those used in the informal system.

Market-driven seed sector development

The aim of seed companies is to produce and sell quality seed of improved varieties that match the needs of farmers. They often create demand for their products by showcasing varieties on demo-plots and distributing seeds via a network of agrodealers. Moreover, companies may provide extension services alongside standard marketing and sales activities. To facilitate adoption, a 'bundled' or 'multi-component' approach tends to be required that provides farmers with simultaneous access to quality inputs, training, and credit (Deutschmann et al., 2021; Nabuuma et al., 2022). Capacity building or extension services might also be required because the simultaneous adoption of improved varieties and good agricultural practices is generally needed to generate a

return on the investment in quality seed (ter Steeg & Gildemacher, 2023). However, there are difficulties associated with companies' outreach to farmers. Riungu et al. (2021) found that the commercial set-up of demonstrations or field days may inhibit social learning and adoption, while Miehe (2023) found that some farmers may refrain from investing in seed once they are better informed regarding risks and costs associated with improved varieties.

It should be stressed that globally the public sector is not absent in market-driven seed sector development. When it comes to variety development, breeding and seed research are largely managed by universities and research institutes for most crops. Precompetitive research is supported in many countries through public-private partnerships (Beumer & Stemerding, 2021; Dhillon et al., 2020). The private sector is, however, dominant in vegetable breeding as the public sector tends to focus on major food crops (see Chapter 2; Schreinemachers et al., 2017). The World Vegetable Center, with stations in Benin and Tanzania, is an important exception in this respect. Regarding seed production and dissemination, the public sector has key responsibilities in terms of quality assurance and monitoring compliance. In terms of seed use, the public sector commonly (co-)funds development projects, for example to incentivize private actors to provide extension and capacity building services (Scoones & Thompson, 2011); but as market-driven seed sector development aims at long-term financial sustainability, public funding is usually limited after a kickstart.

3.3 Contextual framework

Vegetable crops

Vegetables are often used as exemplary crops for which formal seed systems work (Almekinders et al., 2019; Louwaars & de Boef, 2012; Mausch et al., 2021). Vegetable seed systems differ markedly from those of major food crops such as cereals and pulses where the harvested product is botanically identical to the seed. For vegetables, seed production is a separate activity; the seeds commonly appear after the harvest of the vegetable crop, which requires selected plants to be kept in the field longer (Pandita et al., 2023). Some vegetable crops may not produce seeds due to unsuitable climatic conditions, which means that farmers must buy seed. In addition to the separate seed production process, the small amounts of seed required and high market value of produce probably raises the willingness and ability of farmers to invest in quality vegetable seed (Steenhuijsen Piters et al., 2021). As a result, farmers are generally more willing to purchase seed for vegetable than field crop production.

A distinction can be made between local and global vegetables. Local vegetables are indigenous to or have been naturalized in a particular region and are embedded in the sociocultural system (Towns & Shackleton, 2019). In SSA, local vegetables include amaranth, African eggplant, African kale (collards) and okra. Seed for local vegetables is mostly saved or sourced via the informal sector. Meanwhile, seed for global vegetables is mostly sourced via the formal system. Global vegetables (also called exotic vegetables) like tomato, onion, cabbage, cucumber, pepper, and eggplant, are consumed around the world and often considered 'commercially important' (Towns & Shackleton, 2019). For certain crops like cabbage and onion, seed production in the tropics is challenging because low temperatures and specific day-length regimes are required for optimal flowering and seed set (Motoki et al., 2019; Tesfay et al., 2011). In summary, the informal system is dominant for

local vegetables; the formal system is dominant for global vegetables; but many intermediary systems exist.

However, the distinctions between local versus global crops, and informal versus formal seed systems seem to be shifting. A literature review by Ayenan et al. (2017) identifies a private-sector model as the most financially sustainable system to raise seed quality and availability for local vegetables. Whenever the value of harvested products increases thanks to improved logistics and the rise of urban markets, farmers are incentivized to invest in quality seed (ter Steeg & Gildemacher, 2023). The 2021 edition of the Access to Seeds Index showed that 25 out of 67 seed companies include local crops in their portfolio (WBA, 2021a). Some companies have launched hybrid breeding programmes for local crops like African eggplant (Dinssa et al., 2015). The main determinant seems to be whether a vegetable is a commercial or subsistence crop.

Gender considerations are important throughout, whether carrying out extension activities to improve vegetable cultivation, or marketing quality seeds of improved varieties (Kramer & Trachtman, 2024). This is because vegetable production – like the general agricultural system – is shaped by gender norms (Brearley & Kramer, 2020). The distinction between commercial and subsistence crops also has a gender dimension. Kramer and Trachtman (2024) describe how home gardens for vegetable production often remain "a women's domain" in SSA, but stress that reinforcement of stereotypes is undesirable, and that local context is especially important, as across SSA gender norms significantly differ so that gender-intentional designs will have different impacts.

Revolution of Greens

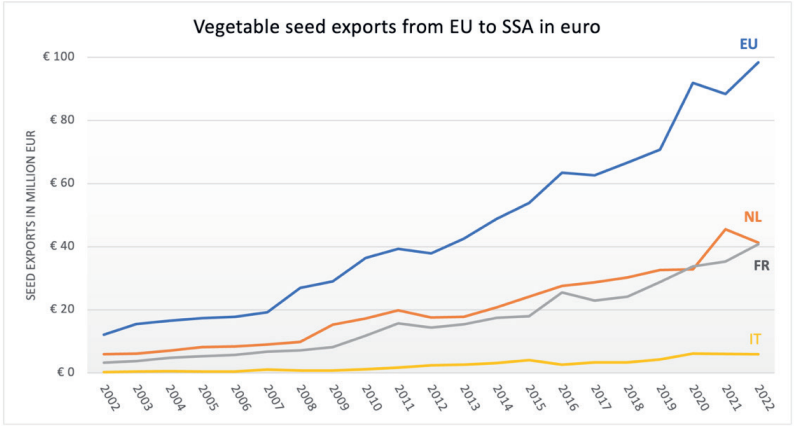
Vegetable seed companies have had a major impact on seed systems in developed and developing countries. Schreinemachers et al. (2021) describe how the public-driven Green Revolution of the 1960s and 1970s focused on major food crops. They show that in contrast, the 'Revolution of Greens' in Asia in the 1990s was market-driven and led to a tremendous increase in vegetable production and consumption, following regulatory reform under which local and global seed companies realized a large market expansion, investing in the capacity building of farmers and demonstration to promote the adoption of quality inputs and good agricultural practices. Furthermore, they point out that at the beginning of the 1990s vegetable consumption levels were similar in Asia and SSA, but that while levels have greatly increased across Asia, hardly any change can be observed in SSA. Thus, Asia's trajectory suggests that the private seed sector could have an important role to play in SSA.

The vegetable seed sector in sub-Saharan Africa

Seed sector development has moved slowly in SSA: technology adoption remains low while yield gaps generally remain high (Bold et al., 2017; Gaffney et al., 2016; Suri & Udry, 2022). Like Asia, several countries implemented reforms to liberalize the seed sector from the 1980s onwards (Schreinemachers et al., 2021). However, this did not lead to the rise of formal seed systems or large-scale establishment of global and local seed companies in SSA except for hybrid maize (Erenstein & Kassie, 2018). The reforms did lead to the founding of some vegetable seed

companies in East and Southern Africa, but less so in West and Central Africa. Local seed companies have mostly focused on seed trade and distribution (WBA, 2022).

Export data can be used as an indicator of formal seed sector development. Increasing European vegetable seed exports to SSA indicate that local and global seed companies are successfully creating demand for their products (Figures 3.2a and 3.2b). Vegetable seed exports from Europe to SSA increased from less than 20 million euros in 2002 to close to 100 million euros in 2022. The Netherlands and France are the largest exporters, both accounting for around 40 percent of the European vegetable seed exports to SSA in terms of value in 2022. Moreover, the value of seed exports increased from 19 euros per kg of seed in 2002 compared to 49 euros in 2022. The rising value of seed exports per kg differs greatly within the EU, with Italy exporting relatively cheap seeds while the Netherlands exports more expensive seeds. While the export value per kg has stayed relatively similar over the years in Italy, the export value per kg has risen for Dutch vegetable seed.



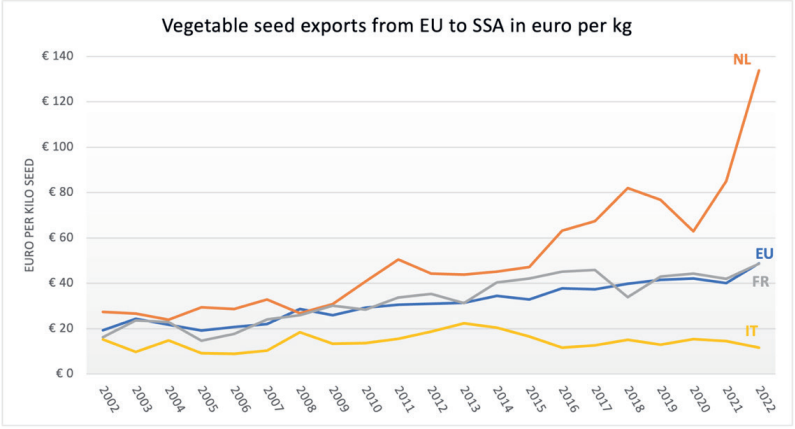


Figure 3.2a: Vegetable seed exports from EU to SSA (including South Africa), in constant (2022) EUR millions, 2002-2022 (source: Eurostat (2023); World Bank, 2024).
Figure 3.2b: Vegetable seed exports from the EU to SSA (including South Africa) in constant (2022) EUR per kilogram, 2002-2022 (source: Eurostat, 2023; World Bank, 2024).

3.4 Material and methods

This article combines thematic and ideal-type analysis to define a private sector perspective and build an understanding of how leading vegetable seed companies are currently contributing to seed sector development in SSA. The core of this paper comprises 18 key informant interviews with (regional) commercial directors of leading vegetable seed companies active in SSA. The commercial lead for SSA was targeted as an interviewee because this person is most likely to have an in-depth understanding of the current and future business of the company in the region. In the absence of a regional commercial lead, the Chief Commercial Officer (CCO) or Chief Executive Officer (CEO) was targeted. This qualitative dataset is unique thanks to the insider status and community membership of the authors (Dwyer & Buckle, 2009). Insider research builds on a shared language and experience, which tends to result in increased trust and openness of participants vis-à-vis the researcher. Moreover, the vegetable seed companies were reassured that no references would be made to individual company data in publications. Therefore, the methodology focuses on the identification of trends and patterns, with data analysis tools chosen accordingly.

Data collection

Our sample was based on the Access to Seeds Index (WBA, 2021a) and covers a significant share and diverse range of the companies. It includes 10 out of all 13 global companies (Advanta, BASF (Nunhems), Bejo, East-West Seed, Enza Zaden, Limagrain, Rijk Zwaan, Sakata, Syngenta and Takii). All 13 global companies were initially targeted, but one company did not respond. Corteva Agriscience was excluded because they do not focus on vegetable crops. KWS was included but it reported to not be active in SSA for vegetables; KWS sold its OPV vegetable portfolio to Zasco, which was then included in the sample. Furthermore, it includes four local and regional seed companies (SeedCo, Agriscope, Kenya Highland Seed, and Victoria Seeds). Additionally, four smaller global seed companies were interviewed that specialize in seed production or dissemination (Bakker Brothers, EASI Seeds, SUBA, and Zasco). In total, the sample consists of 18 vegetable seed companies active in SSA. We included a diversity of actors in terms of company size, crop type, seed type, ownership structure and business operations in sub-Saharan Africa.

The interview questions focused on the four seed system functions discussed previously. For variety development, questions were asked about breeding activities and product portfolio in terms of crops and seed types. For seed production, questions focused on production, processing, and trade. For seed dissemination, questions addressed country priorities, the preferred market entry model, partnerships with distributors and responsibilities of local teams. For crop production and use, questions addressed the support provided to (smallholder) farmers in the form of extension services or capacity building. Finally, questions were asked about partnerships with public, private or development actors to zoom in on potential collaborations and role divisions. The main objective was to find out which seed system functions the companies prioritized in their strategy. Interviews were conducted in-person (if possible), or virtually, and lasted approximately two hours.

Data analysis

The two qualitative methods (thematic analysis and ideal-type analysis) were selected to subtract general results from the data without referring to individual companies. Firstly, thematic analysis

was used to develop a shared perspective of the leading seed companies on vegetable seed sector development in SSA. The focus was on themes as meaning-based patterns: "reflecting a pattern of shared meaning, organized around a core concept or idea" (Braun et al., 2019). Secondly, ideal-type analysis was used to define typologies to categorize leading vegetable seed companies active in the region. The ideal type, which was introduced by Max Weber, has evolved over time as a conceptual tool in sociology (Swedberg, 2018); for instance, Stapley et al. (2022) explain how ideal-type analysis serves to understand interviewees based on within-group similarities and between-group differences.

For both thematic and ideal-type analysis, two steps of data analysis were taken; familiarization with the data and reconstruction of the cases. During the reconstruction step, we prepared summaries which were shared with respondents for validation. For thematic analysis, the next steps were reflexive coding and constructing themes (Braun et al., 2019). For the ideal-type analysis, we formulated the ideal types, identified optimal cases, wrote ideal type descriptions, checked credibility, and carried out comparisons (Stapley et al., 2022), evaluating whether the competitors listed by companies were placed in the same group.

3.5 Results

3.5.1 The private sector perspective

The thematic analysis highlights three general patterns. The seed companies focused on the following: commercial farmers and crops; seed types; and hybrid transitions.

Commercial focus

The companies reported that they sell seed to 'commercial farmers' who produce for the market and that this can include smallholders. They explained that the extent to which the produce of farmers is meant for the market varies, but that farmers can start investing in seed if they can sell at least part of their harvest. The companies often work with farmer typologies, which they usually define based on the technology level of the farm system and intended market for the harvested produce; these factors determine which seed type a farmer is encouraged to buy. This commercial lens is also applied to crops. All crops, both global and local vegetables, are interesting for seed companies if they are produced commercially. Currently, most seed companies are mainly focused on tomato and onion. In SSA, these are the only vegetable crops for which large, stable markets exist, meaning that farmers purchase seed frequently. Several companies reported that tomato and onion seed sales account for over half of their revenues. However, some companies specialize in other crops groups like brassicas or pumpkins, building on existing breeding programmes and a strong market position.

Seed types and hybrid transitions

Hybrid transitions in vegetable crops are witnessed, anticipated, and promoted by seed companies. The statements were varied, but they were all rather similar: "we are transitioning", "farmers are learning", "the future is hybrid" and "it can go fast." These statements were made in response to different questions about company business strategy. Companies mention hybrid transitions being a raison d'être, market entries requiring a certain level of hybridization, product portfolios explaining why OPVs were phased out, and capacity building to enable farmers to adopt hybrids.

Companies distinguished between farm-saved seed and OPVs; OPVs and hybrids; and standard hybrids and advanced hybrids. As one company representative explained it: "in low-tech markets, you start with OPVs, continue with low-value hybrids and slowly introduce high-value hybrids." Another company stated: "we used to have OPVs and super hybrids. Now we are demonstrating the benefits of cheap hybrids." These statements show that seed companies try to create a step-by-step product portfolio for farmers. There is a major gap between OPVs and super hybrids in terms of pricing and skills and this is the reason why the aforementioned company stated that they had learned that it is necessary to have cheaper hybrids in their product portfolio as a stepping stone. Most companies aim to offer farmers the full spectrum of seed types and ensure farmers can work their way up through the product portfolio.

Companies seem willing and able to invest in the creation of demand for hybrid seed, while investing in OPVs seems unpopular. Some companies reported that margins on hybrid seed are higher than margins on OPVs, others stressed the quality difference between OPVs and hybrids. OPVs are considered 'gateway products' for most crops, after which farmers transition to hybrids with more beneficial traits. Companies reported that they do not invest in promotional activities for OPVs because the varieties are well-known, often old, and similar to their competitors' products. Hybrids are company-specific varieties and hence, others cannot leach on marketing campaigns selling the same product. Vegetable seed companies have successfully created seed markets for some self-fertilizing crops like yardlong beans, but the success of the yardlong bean was deemed the result of the popularity of hybrid varieties of other crops sold under the same brand: hybrids allow a seed company to distinguish itself by increasing brand awareness. Please note that seed companies generally put self-fertilizing crops like beans in the same category as open-pollinated varieties of cross-fertilizing crops because they may have to compete with farm-saved seeds, which reduces commercial seed prices unless plant variety protection is effective in such markets.

Several companies explained that demand for hybrids is driven by improved resistance to pest and disease pressures. They stated that it is key to create added value for farmers in the form of resistances (or marketability), because farmers will not buy hybrids if they are not clearly better than OPV alternatives. Intensification of production plays a role here because it increases such pressures. One respondent explained how it has become impossible to grow traditional tomato varieties in certain areas in Kenya because the disease pressure has become too high. Moreover, the improved resistance of hybrids allows for off-season production during which market prices are much higher. Farmers can make more money if they produce during these challenging circumstances. In this case, farmers might use 'ordinary' seed during the peak season when they fetch low prices and invest in 'extraordinary' seed during the off-season.

Vision for seed sector development

The private sector's perspective on vegetable seed sector development follows a linear trajectory in which farmers adopt increasingly technologically advanced seed types as they become increasingly market oriented. Figure 3.3 illustrates the conceptualization of seed sector development that we derived from the company interviews. The horizontal axis shows commercial formalization of the seed, farm and market systems. The vertical axis shows the technical support

that companies need to supply to farmers. The level of commercial formalization represents a decisive factor: companies focus on commercial crops including local crops like African eggplant, African kale, and okra if there is a growing market matching their product profiles and business strategies.

Our analysis of interviews with companies clarified that they need to provide a growing amount of resources as the farmers move from OPV, to standard hybrid, to advanced hybrid seed. These transitions, for example from OPV to hybrid, require variety development, awareness raising and capacity building. We have illustrated this in Figure 3.3; the fluctuating line indicates the resources needed to realize transitions between seed types. Some companies allocate significant resources in the form of long-term investments, but companies also point at the responsibility of the public sector to finance or implement interventions such as extension services and pre-competitive research. The two dotted lines in the background indicate rising seed prices and a decreasing number of customers of seed companies. Not all farmers transition to more technologically advanced seed types, which means that the number of customers of seed companies in the advanced segment is lower than in the earlier phases.

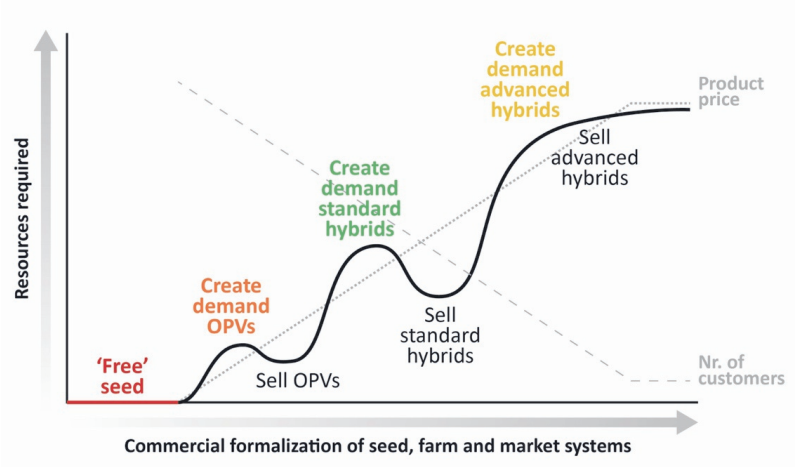


Figure 3.3: Seed company perspectives on seed sector development based on the authors' conceptual representation based on analysis of the 18 key informant interviews.

Furthermore, Figure 3.3 illustrates how companies distinguish between four phases of market-driven seed sector development based on seed type: the phases represent transitions to new seed types. In phase zero, farmers use farm-saved seed and/or free seed supplied by NGOs or the government. Transitioning to the first phase, demand is created for OPVs, meaning that farmers are willing to pay. Once demand has been established, seed companies can sell their products via agrodealers. Transitioning to the second phase, demand is created for standard hybrids. Companies may invest in capacity building of farmers to enable them to earn a return on the investment in hybrid seed. Again, after demand creation, fewer resources are required to sell standard hybrids. In the final phase, the transition to advanced hybrids is made. Seed companies in this segment continuously need to provide tailored services that focus on a more limited number of farmers. For this reason, they pursue integrated value chains in which they build strong customer relationships and maintain strict quality control. Hence, Figure 3.3 illustrates that in the interviews

the companies reported a more selective customer base for advanced hybrids, which require a higher technology level and ability to invest.

It is important to note that these phases can run in parallel while demand for all seed types co-exists: the same farmer can use different types of seed for different vegetables. Farmers also switch back and forth between seed types as they have different preferences and face different (financial) conditions in each season. They may also buy combinations of seed types for the same crop to serve different market segments during the same season or grow the same crop in different seasons. Still, many seed companies are convinced that once farmers reach a certain level of professionalism in terms of production and market orientation, they stick with hybrids. Moreover, they are convinced that the vegetable sector in SSA is generally moving in this direction.

3.5.2 Company typologies

Using ideal-type analysis, four types of vegetable seed companies were identified. The indicators selected to define these are shown in Table 3.1: four distinct company profiles with different business models. These business models are based on their primary specialization in a particular seed system function (variety development, seed production, seed dissemination, or seed use). This does not imply that the company has not taken on other system functions.

Table 3.1: Four vegetable seed company typologies in low-tech markets.

	Variety development (1)	**Seed production (2)**	**Seed dissemination (3)**	**Seed use (4)**
Breeding programme	Yes	No	No	Yes
Seed type	Hybrid	OPV	Hybrid and OPV	Hybrid and OPV
Seed production	Own seed	Own seed and others	Own seed or none	Own seed
Crop type	Vegetables	Mixed	Mixed	Vegetables
Packaging	Per seed	Per gram	Mixed	Mixed
Seed tenders	No	Yes	Yes	No
Local team	No	No	Yes	Yes

Variety development
Variety development companies are research and development (R&D) companies with breeding programmes as the backbone of their company. As high-tech companies, they focus on the development of advanced hybrids and usually do not have any OPVs in their portfolios except for certain self-fertilizing crops like lettuce. Variety development companies consider OPVs to be a separate type of business focused on price rather than quality competition. High-value hybrid seed is usually sold per seed (rather than per gram or kg) to ensure the farmer knows the investment and profit made per plant. Companies explained that hybrids are better-performing varieties with more beneficial traits. Some explained that their R&D investments are very high, and it is necessary to gain a return on this investment: it is easier to do this via hybrids, which provide natural

intellectual property protection. Breeding programmes are usually global but allow for the generation of varieties for specific environments and markets. The focus lies on global crops, for which markets are sufficiently large to gain a return on R&D investments. Moreover, focus lies on a limited number of core crops in which the company has specialized. Specialization creates opportunities; companies can sell licenses to each other. After the company selects its products, there may be plenty of varieties left for licensing. Variety development companies have integrated seed value chains and control the seed production in-house or through licensed multipliers. Seed production is done all over the world in climatic zones that are suitable for the crop, while seed processing is usually done in one or few central locations: a degree of decentralization is essential to cope with environmental or policy risks, but it bears scale disadvantages. Variety development companies do not partake in seed tenders and are often outspoken opponents of tenders because farmers should get access to quality seed and learn the value of quality seed. Their customers tend to be professional commercial farmers. Generally, the SSA market is not a top-priority for these companies because the number of farmers able to invest in and make use of their high-tech high-value products is limited. Some companies frame their presence in the region as part of their corporate social responsibility (CSR) agenda or as a long-term investment.

Seed production

For the formal system, vegetable seed production is concentrated in regions with optimal agroecological conditions rather than in the target market where the seed sales occur. Seed production companies do not invest in R&D but access older 'free' or public sector varieties to produce OPV seed. Also, they may receive parental lines from other seed companies to contract-produce OPV or (hybrid) seed for them. Therefore, companies specialized in seed production sell their own branded seed but also produce seed for other companies or NGOs/IGOs. In case of the latter, the seed packaging often carry the logo of their customer and not theirs. Also, they produce seed of a variety and quality level chosen by their customer. The general trend of land scarcity and increasing quality demands makes it more difficult to identify trusted producers in optimal seed production locations. Seed production companies require a certain scale of production and sufficient distance between them and other seed (or agricultural) producers. Many seed companies struggle to scale their own production facilities because it requires considerable financial resources and a large customer network. Moreover, predicting demand can be difficult, so contracting out seed production is a risk mitigation strategy: companies are willing to pay more for such contracts because they can avoid producing too much and ending up being stuck with perishable seed in storage. Some seed production companies have seed tenders as their main business model. Tenders are instigated by NGOs or IGOs like the Food and Agricultural Organization (FAO) and the choice of bid is usually price-driven provided that standard quality and packaging requirements are met. Seed production companies are only responsible for producing the seed in bulk and their buyer is responsible for delivery. Companies that specialize in seed production benefit from the tenders because of profit margins, large quantities, and low business risks.

Seed dissemination

Seed dissemination companies focus on the development of a distribution network: they usually do not invest in R&D or produce their own seed. Variety development is deemed too expensive and/or unnecessary as there is an abundant supply of varieties available in the public domain or

accessible via licensing agreements. Dissemination companies can be exclusive representatives of other seed companies, or can sell under their own brand. Their product portfolio includes OPVs; public (usually older) varieties; and standard hybrids bought or produced under licence from other companies. Seed production can be contracted to specialized (local) multipliers. The focus is on trade, delivery, and sales; their distributor and/or farmer network provides them with an understanding of local demand. The companies explained that short feedback loops with farmers allow them to select varieties, which match their needs. A distribution company stressed that they mostly compete by bringing the product close to farmers "at the right price, at the right time." These companies may move beyond standard sales channels and set up innovative distribution systems, working with tuk-tuks, motorcycles or mobile shops to resolve last-mile challenges. Dissemination companies tend to also sell seed for field crops and other agricultural inputs to build sufficient scale for a profitable business. They also sell in quantities that fit the needs of a variety of farmers using small package sizes. Seed dissemination companies may participate in seed tenders as well.

Seed use

Companies specialized in seed use support farmers throughout the crop cycle, offering technical advice and organizing trainings. They have OPVs and hybrids in their portfolio and sell some varieties per seed and others per gram. In comparison to variety development companies, their portfolio might not include the most advanced varieties. This is because they spread their efforts and have local and global crops in their portfolio rather than focusing on core crops. Hybrid seed production is usually done in-house, while OPV production can be outsourced. Creating demand for more advanced products requires 'seed use' companies to work closely with the farmers. The companies explained that farmers often need to develop their horticultural skills to unlock the full potential of quality seed and gain a return on their investment. This support can be offered by the company's extension agents or corporate (not-for-profit) foundations. The creation of a separate entity marks the division between commercial and pre-commercial capacity building activities more clearly. Besides capacity building regarding seed use, companies may provide farmers with support in terms of marketing, linking them with traders or processors to improve market access for their products. Seed use companies do not participate in seed tenders because these do not result in financially sustainable seed systems. They may receive external (public) funds to provide extension services to (smallholder) farmers who might become their customers in the future.

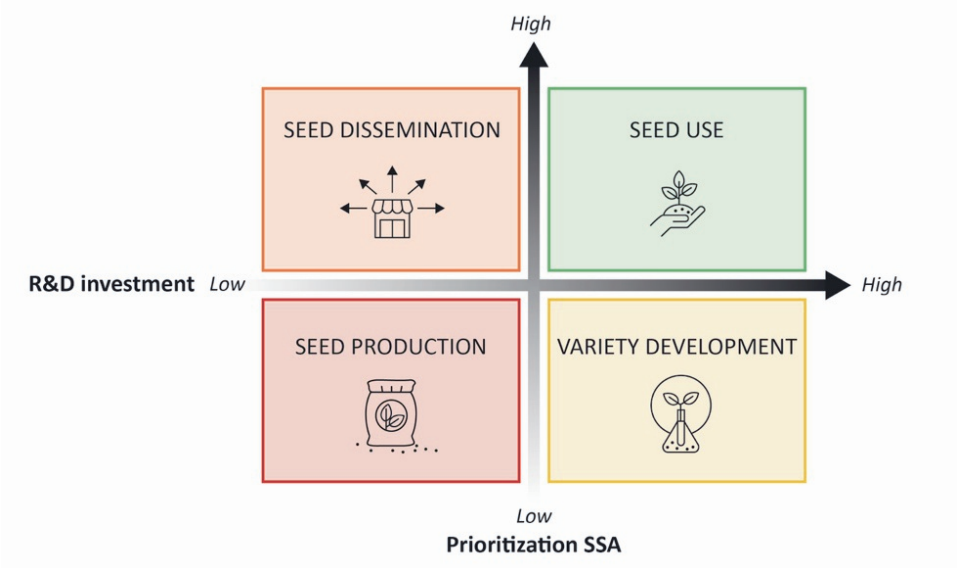


Figure 3.4: Two-by-two matrix of company typologies based on key indicators.

3.5.3 Evolving business models

The four company types play different roles in market-driven seed sector development. Seed production and dissemination companies are both involved in the provision of free seed via seed tenders. Demand creation for OPVs is mostly done by seed dissemination and seed use companies. Transitions to standard hybrid seed is realized by companies with mixed product portfolios including OPVs and hybrids, which are dissemination and seed use companies. Variety development companies will compete to supply select groups of farmers that can transition to advanced hybrids. As seed sector development progresses in SSA, companies start to invest in seed system functions beyond their specialization and move into new segments. Variety development companies invest in local teams for distribution, and local adaptation of core crops or local commercial crops. A company focused on advanced hybrids might add a standard hybrid to their portfolio to reach a new group of customers building brand awareness earlier on. Seed dissemination companies seek to invest in variety development, launching breeding programmes, often in collaboration with organizations like the World Vegetable Center or global partner companies. Rather than distributing brands of other companies, they now start to sell their own varieties under their own brand. Moreover, they want their own hybrids to ensure future competitiveness. Variety development companies seem to enjoy an advantage here in terms of human and technological resources. The ability of seed dissemination companies, often local companies, to shift gears and take on additional seed system functions seems more limited. Growth can occur through expanding one's own business or mergers and acquisitions. For example, an international company may prefer to take over a local company with a strong distribution network and local product portfolio rather than developing their own.

3.6 Discussion

Most narratives on seed sector development start with smallholders, but the 'smallholder farmer' is an ambiguous concept in vegetable farming systems, and the focus of market-driven vegetable seed sector development is on commercial farmers, whether small or large. The FAO defines smallholders as those cultivating up to 10 hectares (2013). While this definition can be useful for field crops, it seems out of place when it comes to vegetable seed sector development; ideally, a vegetable farm is small and highly productive. Thus, smallholders may be better defined based on the level of subsistence versus market orientation rather than in terms of land sizes or other resources (Fan et al., 2013; Murphy, 2010).

The focus of seed companies is also on commercial crops, both global and local. Seed companies tend to initially direct their attention to tomato and onion, the main commercial vegetables, and worldwide production has a similar trend; tomato is the most important vegetable, with 16 percent of global production, followed by onion (including shallots) with 9 percent (FAO, 2022). However, a variety of vegetables is needed to support agrobiodiversity and diverse diets (Nabuuma et al., 2022). In terms of policy interventions, Afari-Sefa et al. (2012) point at the need to develop new, nutrient-dense varieties of local and global vegetable for which (smallholder) farmers can find urban and rural markets. For (local) niche crops, interventions could focus on strengthening informal commercial seed systems (Sperling & Almekinders, 2023).

Vegetable seed companies are primarily focused on hybrids. While companies seem willing and able to fund the transition from OPVs to hybrids, the transition from farm-saved seed to the purchasing of quality seed of OPVs seems a less commercially appealing investment. Companies seem reluctant to invest in the breeding and marketing of OPVs, seeing them as difficult investments on which to earn returns. However, public-private partnerships can offer a solution in this regard: the World Vegetable Center is developing open-source OPVs (and hybrids) of global and local vegetables, which companies can start producing directly or use in their own breeding programmes. Interventions could also provide support to emerging (local) companies focused on OPVs to facilitate this transition (Kugbei & Bishaw, 2002).

Meanwhile, market demand for hybrid vegetable seed is driven by food systems. Seed companies stress that farmers only buy expensive hybrid seed if there is added financial value. In the vegetable sector, this value is often created by off-season production during natural peaks in disease pressure. It is also created by peaks in disease pressure resulting from intensified production, as is the case with tomato in Kenya (Avedi et al., 2022). Additionally, climate change has already altered weather patterns, increasing biotic and abiotic stress levels. Together these developments will fuel demand for technologically advanced seed. A future challenge will be to develop viable business models for niche markets in terms of farming systems and crop types (Dinssa et al., 2015).

Figure 3.3 shows a reduced number of customers for seed companies selling advanced hybrids. In line with the private sector's vision, Fan and Rue (2020) argue that smallholders should move up or move out: they should raise farm productivity or find off-farm employment. Similarly, seed companies anticipate rising farm productivity for a select group of farmers following the professionalization of seed, farm and market systems, which all goes hand-in-hand. However,

some contest this view, pointing out that there is a lack of off-farm jobs in SSA if moving out, and a lack of incentives for local market production if moving up (Giller et al., 2021). A plurality of seed systems is needed to serve a diversity of farmers, for those who move up, but also for those who cannot move up or out.

Most vegetable seed companies seek to expand their businesses by moving into new market segments or seed system functions. In Europe, such dynamics have reduced the number of seed companies in the past 50 years (Schenkelaars et al., 2011). Still, in OECD countries, start-ups also continue to emerge, and challenge established players, while in Asia, global companies fuelled vegetable seed sector development after which both local and global companies benefitted from an established market (Schreinemachers et al., 2021). In the Netherlands, for instance, new companies have been founded focusing either on specific vegetable crops, such as Limseed (asparagus) and Novisem (celeriac, endive, and others) or specific markets for main crops such as Axia (tomato) and Westland Seed (peppers). Therefore, besides a plurality of seed systems, a range of seed companies may continue to serve different farmers and market segments.

3.7 Conclusion

In this paper, we have zoomed in on market-driven transitions, investigated how business models of leading vegetable seed companies contribute to seed sector development in SSA, and discussed several interventions aimed at enhancing the positive impact of market-driven vegetable seed sector development. We found that companies foresee a linear trajectory in which public and private investments are made to enable farmers to adopt increasingly technologically advanced seed types. Their perspective resembles the view of Douglas (1980), that seed system development moves from informal to formal systems. In this shared vision, vegetable seed companies play different roles and specialize in different seed system functions. The current coexistence of and collaboration between different (private) actors in the vegetable seed sector contribute to plurality and interaction, which is in line with an integrated approach to seed sector development. However, it is not a static condition; company roles appear to evolve with expanding business models in terms of system functions and market segments. Furthermore, while the dominant focus of seed companies on commercial farmers, commercial crops and hybrid varieties maintains the plurality of seed systems, this focus does not encourage interaction between seed systems. The general objective should be to increase farmers' access and choice in terms of quality seed of improved varieties through innovative and inclusive business models. In this way, the contribution of vegetables to healthy diets and farmer incomes can be enhanced in the work towards Zero Hunger.



4

Market-driven agricultural extension for smallholder vegetable farmers: evidence from a randomized controlled trial in northern Nigeria

Emily ter Steeg, Stellamaris Aju and Marrit van den Berg

Abstract

Low adoption of agricultural technologies among smallholder farmers in sub-Saharan Africa continues to constrain productivity and livelihood improvements. While agricultural extension services (AES) are widely promoted to address this challenge, evidence on their effectiveness remains mixed. This study evaluates the impact of a market-driven AES programme focused on commercial vegetable production in northern Nigeria. We conducted a randomized controlled trial involving 1,498 households across 150 communities in Kano and Kaduna state to measure the impact of market-driven AES on technology adoption and livelihood outcomes. An add-on treatment tested whether test-based certification of trained farmers enhanced impacts. We found robust evidence that the programme increased commercial vegetable cultivation, the adoption of improved vegetable varieties and uptake of good agricultural practices. We also observed higher vegetable revenues among treated farmers, but no effects were detected for food and nutrition security. Finally, we found that test-based certification does not lead to consistent gains in technology adoption. These findings demonstrate that market-driven AES can meaningfully contribute to technology adoption and livelihoods, even in the absence of other measures to lift farmer constraints. By focusing on vegetable crops and a quasi-commercial extension model, this study contributes new evidence to the literature on technology adoption and agricultural extension in sub-Saharan Africa, highlighting the potential and the limitations of market-driven approaches to improving smallholder livelihoods.

4.1 Introduction

There is rising concern about the low level of technology adoption by smallholder farmers in sub-Saharan Africa (SSA). Prevalence of undernourishment in the region continues to rise, with 22.3% of the population being undernourished in 2024 (FAO et al., 2025). Meanwhile, the adoption of agricultural technologies can improve farm productivity as well as marketability of harvested crops (Abdulai, 2023; Gollin et al., 2021; Schreinemachers et al., 2021). In return, this can yield significant improvement in livelihood outcomes across various dimensions, including food and nutrition security and overall poverty reduction (Nabuuma et al., 2022). The review of Takahashi et al. (2020) suggests that agricultural technologies are accessible and profitable for smallholders. Still, smallholders in SSA often refrain from adoption: Suri and Udry (2022) have even concluded that technological advancement in the region has largely stagnated.

An explanation for this trend is offered by Giller et al. (2021) who have described the economic lock-in of smallholder farmers in SSA with shrinking land sizes and a lack of capital. They stressed that enhancing productivity and diversifying into high-value crops is important to strengthen smallholder livelihoods. Contrary to staple crops, vegetables offer a way out of poverty for smallholders because they can profitably be cultivated on small plots and are less suitable for mechanization (Schreinemachers et al., 2021). However, cultivation also requires more labour and farm management skills (ter Steeg & Gildemacher, 2023). Also, vegetable production requires market access, as crops are perishable, and access to water to irrigate crops in the absence of rain. If these conditions are met, vegetables can raise land productivity and provide a regular income stream (Schreinemachers et al., 2021). Nonetheless, most research, policies, and development projects have continued to focus on maize or other staple crops (Nabuuma et al., 2022; Mwangi et al., 2021).

Meanwhile, vegetable seed companies seek to create demand for their products in SSA (see Chapter 3). To this end, some companies invest in farmer capacity building, which takes the form of agricultural extension services (AES) as farmers need new skills to unlock the potential of improved vegetable varieties (ter Steeg & Gildemacher, 2023; Schreinemachers et al., 2021). AES are widely implemented to diffuse new technologies amongst smallholder farmers (Ruzzante et al., 2021; Takahashi et al., 2020). In many developing countries, a major part of government expenses is attributed to cover these costly services (Akroyd & Smith, 2007). Pure private-sector models are generally deemed infeasible in a development context due to market failures, but hybrid models in which the public sector finances private actors to deliver AES are increasingly viewed as promising, albeit not without risks (Feder et al., 2011). Involving the private (seed) sector in AES ensures access to specialized technical knowledge and alignment with market demand. However, it may also skew advice toward commercial crops and inputs, and risks undermining advisory neutrality.

We therefore conducted a study to analyse the impact of a hybrid, market-driven approach to AES to promote technology adoption for commercial vegetable production. We focused on a one-year training programme implemented by the East-West Seed Knowledge Transfer (EWS-KT) Foundation, which is linked to the seed company East-West Seed (EWS). While EWS sells seed, EWS-KT focuses on capacity building and provides AES to smallholder farmers. It uses a contact farmer approach in which 'entrepreneurial' farmers with irrigated and centrally located plots are

selected to host a demonstration plot. Throughout the season the team of EWS-KT trains the demo host and a group of other farmers from the community. The training of EWS-KT focuses on good agricultural practices (GAP), variety selection, planning and marketing. By enabling farmers to earn a return on their investment in quality vegetable seed, EWS-KT creates a viable market for EWS and potentially, other seed companies. A mix of public and private funds is used to finance the activities of EWS-KT.

The EWS-KT programme was implemented in northern Nigeria in Kaduna and Kano states. In these states agriculture remains the dominant livelihood with a large share of the population engaged in farming (Plaisier et al., 2019). Kaduna is the country's largest production region for tomatoes and onions in terms of quantity, and Kano is the second largest producer (Plaisier et al., 2019). A large share of the vegetables produced in the North is transported to major cities in the South. Despite the importance of both states as vegetable-producing regions, overall sector development has been slow, mostly due to the limited adoption of improved agronomic practices, which continues to depress productivity and contributes to widespread food insecurity (Ogunbo et al., 2015; Plaisier et al., 2019). In collaboration with EWS-KT, we designed and implemented a randomized controlled trial (RCT) providing AES in treatment areas, while refraining from entering control areas. In half of the treatment areas, we tested farmers after completing the programme and certified during a public ceremony. EWS-KT started working in Nigeria in 2015, but for this RCT we specifically targeted newly reached communities for whom AES implementation started in March 2023 and ended in June 2024. Using our baseline and endline data, we then assessed whether the training activities and/or test-based certification affected vegetable production, technology adoption, and livelihood outcomes.

The aim of our RCT was two-fold. Firstly, to understand how an information treatment in the form of market-driven AES influences smallholder farmers' decisions to grow new crops and adopt new technologies. Secondly, to study the impact of these decisions on livelihoods. Our hypotheses were as follows. First, the activities of EWS-KT were expected to lead to more farmers growing vegetables. Second, these activities were expected to have a positive impact on the uptake of agricultural technologies, specifically the use of quality vegetable seed and the GAPs covered during the trainings. Third, we hypothesized that the uptake of these technologies would improve livelihood outcomes such as household income and food security. Fourth, we expected that testing and certifying farmers who complete the training programme would enhance their motivation and, consequently, boost impact. Our results provided evidence in support of our first hypothesis: commercial vegetable production greatly increased in the treatment areas. We also found support for our second hypothesis, namely that the uptake of agricultural technologies increased among treatment farmers. Specifically, we observed higher adoption rates of improved vegetable varieties and nearly all GAPs. The evidence for impacts on livelihoods was less robust: while we observed higher vegetable incomes, we did not detect improvements in food and nutrition security. Only one of the income measures remained significant after correcting for multiple hypothesis testing (MHT). Finally, we did not find support for our fourth hypothesis, that test-based certification of trained farmers increases technology adoption.

Many studies have discussed vegetable production in the context of home consumption and nutrition (Depenbusch et al., 2021; Merchant et al., 2023; Nguyen et al., 2025). Also, several studies

indicate the potential of horticultural commercialization to alleviate poverty in the context of export markets (Ashraf et al., 2009; Muriithi & Matz, 2015) and supermarkets (Rao & Qaim, 2011). This study contributes to the body of literature on technology adoption and AES in two ways. Firstly, it focuses on vegetable, which continue to represent an understudied topic. To date, most academic research regarding AES or other seed system interventions has focused on staple crops and particularly maize (Nabuuma et al., 2022). As discussed earlier, vegetable crops have distinct economic advantages over staple crops and represent the shift to high-value crops, which has been highlighted by Giller et al. (2021) as a solution to the economic lock-in of smallholders. Thanks to these advantages, farmers might be better able to adopt technologies which could result in a greater magnitude of impact.

Secondly, we contribute to the literature on AES by examining a quasi-commercially motivated model. The AES are provided by a corporate foundation engaged in precommercial activities that prepare markets for the parent seed company as well as its competitors. The model balances between public-good objectives and private-sector incentives. Even though some authors qualify AES as a "local public good" (Takahashi et al., 2020), private and public-private models warrant closer scrutiny in the context of shrinking development budgets and a changing agricultural sector (Feder et al., 2011). Moreover, while the effectiveness of AES has been widely studied, results remain mixed, and methodological differences require further investigation (Ruzzante et al. 2021). Since the publication of Kondylis et al. (2017), experimental work has focused on unpacking these differences (Buehren et al., 2025; Ragasa et al., 2025; Yitayew et al., 2021). The commercial character of the AES provided may influence adoption amongst farmers. While Dar et al. (2024) found that commercial interests motivate extension officers and fuel uptake, Riungu et al. (2021) found that these can limit impact if commercial motives reduce trust and hinder social learning.

Furthermore, a key characteristic of such a market-driven approach is that farmers are only provided with training, an information treatment, without lifting other constraints. In many intervention studies, farmers have been also provided with other incentives such as free seed (Buehren et al., 2025; Nguyen et al., 2025; Ragasa et al., 2025) or credit (Ashraf et al., 2009; Deutschmann et al., 2025). Seed companies tend to be opposed to providing free seed or subsidies because they want farmers to become familiar with the value of their products (see Chapter 3). The effectiveness of stand-alone information treatments has sometimes been questioned, as farmers face multiple, interlinked constraints (Ragasa et al., 2025; Suri & Udry, 2022). When no additional incentives are offered, some authors have found that information treatments have no impact on farmer demand for quality seed (Morgan et al., 2020; Pan et al., 2018). Despite these constraints, we found a positive effect of market-driven AES on technology adoption including improved vegetable varieties.

4.2 Study design and data

We conducted a clustered RCT with 150 communities from eight local government areas (LGAs) in Kano and Kaduna states in northern Nigeria. Our RCT included two treatment arms and one control; the first treatment arm exclusively focused on AES, while the second treatment arm added a certification element for farmers who completed the programme and successfully passed an

exam. Treatment was assigned at the community level to account for spillover effects within communities while data were collected at the household level.

Ethical clearance for this study was obtained via the Wageningen University & Research (WUR) Research Ethics Committee (Approval Number: 2024-083), the state governments (Kano state: NHREC/17/03//2018 and Kaduna state: NHREC/17/03/2018), and IFPRI (MTI-23-0521). The study's pre-analysis plan was registered in the American Economic Association's RCT Registry (AEARCTR) prior to endline data collection in June 2024 (ID: AEARCTR-0013489). Deviations are listed in Appendix 4.1.

4.2.1 Context

The EWS-KT programme was implemented in northern Nigeria in Kaduna and Kano states. In 2019, 80% of the population of Kaduna was reported to work in agriculture while at the country level employment in agriculture had fallen to 36% (Plaisier et al., 2019). Progress in the vegetable sector remains limited, with challenging environmental conditions and suboptimal farming practices undermining productivity (Ogunbo et al., 2015; Plaisier et al., 2019). Farmers in Kaduna and Kano cultivate many cash and food crops, such as maize, ground nuts, and cotton during the rainy season (May–October) and/or dry season (November–April). Tomato yields are around 7 t/ha and align with or fall slightly below yields reported elsewhere in the region (Plaisier et al., 2019). Kaduna and Kano are key vegetable production hubs in Nigeria whereas the consumption centres for vegetables are the large cities in the South of Nigeria. In recent years, Kaduna and Kano have suffered from rising conflict and insecurity, disrupting both agricultural production and the transportation of produce to the South. This has contributed to the major increases in food prices, with tomato prices increasing by 106% between March 2023 and 2024 (Mathew & Ayo, 2024).

4.2.2 Intervention

Technical field officers provided training on demonstration plots in each treatment community during the two vegetable seasons between May 2023 and April 2024. Before the start of the training year, EWS-KT selected one farmer per community to host the demo plot on their farm based on their targeting criteria (see section 2.4). These farmers were required to mobilize approximately 25 other farmers to participate in the trainings, which continued throughout the crop cycles. Men and women were trained in separate groups. The groups systematically follow all the key stages of crop production for two crop cycles at the demo plots. Farmers select two of eleven vegetable crops for training: one in the wet season and one in the dry season. The training programme included both general modules and crop-specific modules. All modules were standardized and delivered uniformly across farmer groups. During the training seasons, demo hosts received free inputs for the demo plot, and they got to keep the harvest. No free inputs (or discounts) were provided for other plots of the demo host or other participants in the training. EWS-KT also trained agrodealers in the communities to answer agronomic questions of farmers, especially those related to EWS varieties. In about half of the treatment communities, farmers were offered the opportunity to do a practical test after completing the training programme. Farmers who completed the test successfully received a certificate specifying the technologies that they mastered. The certificates were awarded in public village-level ceremonies at the end of the season. The purpose of these

ceremonies was to stimulate awareness of and demand for the new knowledge and technologies among the non-targeted farmers in the community.

4.2.3 Outcome indicators

We used four sets of indicators to address the research questions and estimate treatment effects. The intervention was expected to increase farmers' knowledge, thereby raising vegetable cultivation and the adoption of improved technologies and practices. These changes should, in turn, positively impact farm productivity. Higher productivity was expected to translate into financial gains, reflected in increased production values and revenues. Finally, improved economic outcomes may strengthen household food and nutrition security. As noted above, this study focused on commercial vegetable production: vegetables grown on farm plots are primarily produced for sale as opposed to vegetables grown in home gardens. We therefore expected effects on food and nutrition security to operate mainly through income-related channels.

The first group of indicators pertained to the prevalence of vegetable cultivation. The goal here was to study the impact of the AES programme on the overall number of farmers producing vegetables on farm plots and in home gardens. We introduced two dummies: one for vegetable production on the farm and one for home garden production. These indicators were linked to the shift of smallholders into high-value crops and represented diversification of their livelihood.

The second group of indicators focused on technology adoption. Agricultural technology can refer to "equipment, genetic material, farming techniques, and agricultural inputs that have been developed to improve the effectiveness of agriculture" (Ruzzante et al., 2021). We studied the adoption of improved varieties and other farming techniques, also called GAPs. The adoption of 'quality seed' can be difficult to measure because farmers sometimes have a poor understanding of the type of seed they are using (Michelson et al., 2023; Wineman et al., 2020). We used a binary variable to distinguish between the use of improved and traditional varieties for vegetable cultivation. We did not ask whether farmers bought seed, and hence, farmers might have used recycled seed from an improved variety, which is unadvisable in case of hybrids (Van Campenhout et al., 2025). Also, we used a binary variable regarding the use of government certified vegetable seed, which implies the seed was certified and hence, bought.

For the GAPs, we looked at adoption using aggregated GAP indicators such as the total number of practices adopted and the number of farmers using more than five GAPs. In addition, we used dummies to look at the adoption of specific techniques. The latter represented an explorative analysis which was not part of our pre-analysis plan. EWS-KT educates farmers regarding ten different GAPs: crop rotation, seedling transplanting, use of shade houses, staking, thinning, pruning, trellising, mulching, use of biopesticides (neem oil), and record keeping. Some practices, like crop rotation and record keeping, are relevant for all crops. Other practices like seedling production are most relevant for vegetables, whereas direct sowing is generally used for cereals and legumes. Moreover, practices like staking, pruning and trellising are only relevant for specific crops such as tomatoes.

The third group of indicators focused on livelihood outcomes: the value of production, and food and nutrition security. We examined the estimated total values of production for all vegetables

combined as well as the top three most produced vegetables. These values were calculated based on the total quantity produced and the market price received. Moreover, we looked at the revenue for all vegetables combined based on the actual quantity sold and market price. Finally, we calculated total crop income. We could only calculate income aggregated across crops because the use of inputs was reported at the plot rather than the crop level. We relied on these monetary measures rather than quantity data, as they offer a more consistent basis for comparison and compilation across different crops. Our approach also helped to avoid common challenges with yield data quality and reliability, especially in smallholder settings (recording and harmonizing plot sizes and outputs is tricky, as this is prone to mistakes because of the use of different measurement units).

We also looked at food and nutrition security, which we measured using the Household Food Insecurity Access Prevalence (HFIAP) and Food Consumption Score (FCS). HFIAP is commonly applied as an indicator to quantify food (in)security (Jones et al., 2013). The HFIAP categorizes households into four levels of food insecurity (food secure to severely food insecure) based on predefined thresholds. In our analysis we used a dummy, which indicates whether households are categorized as food secure according to HFIAP. The FCS is a proxy indicator developed to assess dietary diversity, food frequency, and nutritional value of a household's diet over the past 7 days (WFP, 2024; Jones et al., 2013). The highest possible FCS is 112, which means each of the 8 food groups was consumed on all 7 days. A 35.5-score threshold is generally considered as 'acceptable' (WFP, 2024).

The fourth and final group of indicators looked at the intensification of production, which represents a second explorative analysis. We assessed whether the treatment influenced the use of other agricultural inputs, namely chemical fertilizer, organic fertilizer, herbicides, and chemical pesticides. EWS-KT teaches farmers how to apply these in an informed manner, but this does not imply an increase or decrease in amounts used. The use of such inputs, apart from organic fertilizer, generally signals intensification of production.

4.2.4 Sample

For this study, EWS-KT selected 150 new target communities in Kano and Kaduna, expanding its operations in northern Nigeria. The organization selected communities based on potential for vegetable production as well as security threats, which continue to pose a serious problem in both states. In Kaduna, 70 communities were selected across four local government areas (LGAs). In Kano, 80 communities were selected across four LGAs. Stratified by LGA, the 150 communities were randomly assigned to one of two treatment groups or the control group: 52 communities were assigned to treatment group 1 (TG1) only receiving AES, 50 communities were assigned to treatment group 2 (TG2) receiving AES plus test-based certification and 48 communities were assigned to the control group (CG). The geographic distance between communities was deemed sufficient to prevent spillover effects between treatment and control groups.

In both treatment and control communities, EWS-KT selected the demo hosts based on a combination of individual capabilities, social status, and economic conditions. Eligible farmers were required to own an appropriate plot of land with reliable access to water for irrigation and good accessibility. Candidates were also expected to occupy a recognized position within the

community (e.g. village or sub-village leader, traditional authority, or an active member of a farmer group) and to demonstrate verbal and written communication skills. Furthermore, selected farmers needed to show an entrepreneurial attitude and willingness to engage with others.

In the treatment communities, demo hosts were requested to invite and mobilize a group of about 25 farmers for participation in the training. The research team randomly selected 9 of these farmers per community to be part of our sample. In control communities, demo hosts were informed that the AES would be implemented with a year's delay. They were not asked to mobilize other farmers, since this would lead to expectations that would not be met in the short run. Therefore, the research team randomly selected twelve farmers in each control community to be part of the sample instead. We used a larger sample size for the control villages to allow for (propensity score) weighing to compensate for potential systematic differences between treatment and control farmers resulting from the different selection processes.

4.2.5 Data collection

Data were collected at two points in time: at the start of the project and at least three months after the end of the intervention. Crop production data covered the previous two seasons, hence the last two seasons before the AES intervention for the baseline survey and the second intervention season and the first post-intervention season for the endline survey. The timing of the endline survey was chosen to accommodate reflection and small-scale experimentation before actual adoption. Our final total sample consisted of 1,498 smallholder farmers (Table 4.1) During the baseline, the sample consisted of 1,683 farmers, while at endline we tracked and re-interviewed 1,498 farmers.

Table 4.1:Sample structure distinguishing between different farmer types and showing treatment arms.

	TG1: AES-only	**TG2: AES + Certification**	**CG: Control**	**Total**
Demo hosts	50	47	40	137
Farmers invited for training	444	421	-	865
Other farmers	-	-	496	496
Total farmers*	494	468	536	1498

* This row shows the total number of farmers sampled per community across the three groups: demo hosts, invited farmers, and other farmers.

We used a structured questionnaire developed based on stakeholder consultations, a review of project documents, existing survey tools, secondary data, and an exploratory survey among demo hosts. The questionnaire covered questions about household composition, farm activities, and food consumption and security. All questions about agricultural activities were asked per season, parcel, and crop. The questionnaires were translated into the local language (Hausa) to avoid misinterpretation (cross-translation errors) by the enumerators and to facilitate easy administration. All respondents provided informed consent prior to their participation. Baseline data was collected using KoboCollect, while endline data was collected using ODK. Data cleaning and analysis were performed using Stata.

4.2.6 Attrition analysis

We had an attrition rate of 11% with an overall dropout of 185 farmer during the endline. Considering the insecurity issues in the area, a key reason for attrition was migration with many households relocating to safer, more stable areas. Long-term residency was not a criterion during baseline sampling, so moving households were also included. Attrition levels were examined using balance tests based on the baseline control and outcome variables. We looked at attrition comparing all those receiving treatment, with the control group (Appendix 4.2); then, comparing the two treatment groups (Appendix 4.3). Only one difference was found, as households in one of the treatment groups were more likely to have a household member in a farmer group ($p<0.10$), suggesting minimal bias in our sample.

4.2.7 Balance tests

We conducted balancing tests using the baseline data. We did this in two parts: for the full sample, comparing both treatment arms (AES only and AES plus certification) to the control arm (Appendix 4.4) and comparing the two treatment groups (Appendix 4.5). For the full sample, we also tested for balance between treatment and control households excluding the demo hosts (Appendix 4.6) to isolate the potential effects of the different sample selection procedures for the non-host farmers in treatment and control areas. We compared the subsamples on our covariates and all outcome variables. All tests resulted in the same conclusion, that the data are well-balanced with minor differences between treatment and control households.

When comparing the two treatment groups, two variables exhibited a statistically significant difference: gender at 5% and >1 household member part of farming group at 1%. In addition, we found that control households were somewhat more likely to use improved vegetable varieties (5%, share of vegetables grown with improved varieties 10%) and to apply homemade biopesticides (5%) or mulch (5%). Yet treatment households on average used more chemical fertilizers (10%) and had higher vegetable revenues (10%). While these differences are few given the large number of variables tested, they could be indicative of differences between the differently selected non-host samples. Yet, when dropping the demo-hosts, the only imbalances left were for the use of mulching at 5% and for the value of chemical fertilizer and the use of homemade biopesticides at 10%. Hence, there were some small, unsystematic differences regarding outcome indicators, but our empirical strategy controlled for these.

Based on the above observations, our selection procedures did not bias the sample. Demo hosts in treatment areas were required to invite relatively large groups of around 25 farmers to compensate for high expected non-compliance. We selected our treatment group from the invited or 'targeted' farmers rather than compliers (farmers completing the training). This explains why the invited farmers in the treatment areas are highly comparable to the randomly selected farmers in the control group. Because of this similarity, we did not use propensity score weights in our impact estimates.

4.3 Empirical strategy

ANCOVA regressions are used to measure the impact of the two treatments on the outcome indicators. We define two different equations to answer our research questions. In our primary specification, we assess the impact of the market-driven AES treatment - with and without certification - on technology adoption and livelihood outcomes. We do this by comparing households of demo hosts and invited farmers in treatment communities with households of demo hosts and other farmers in control communities. The resulting regression model for the outcome vector *Y* for household *i* in community *c* is:

$$Y_{lci} = \alpha_0 + \alpha_1 \mathrm{T}_{lc} + \alpha_2 K_{lci} + \alpha_3 Y^0_{lci} + \alpha_4 X^0_{lci} + \alpha_l + \varepsilon_{lci} \quad (1)$$

In this equation, *T* is a dummy variable indicating treatment status, *K* is a dummy for key farmers, Y^0 is the baseline outcome, X^0 are baseline controls, and α_l are LGA (or strata) fixed effects. The key coefficient vector of interest is α_1, which captures the estimated impact of the treatment on our outcome vector. The dummy *K* merely accounts for systematic differences in farmer characteristics between key farmers and the broader sample and limited power does not allow us to also estimate treatment effects for this subgroup. Standard errors ε are clustered at the community level.

With our second specification, we test for the potential additional impact of the testing and certification treatment on technology adoption and livelihood outcomes. This intervention was mainly designed to stimulate the diffusion of technologies within communities signalling skills and knowledge to neighbouring farmers who are not trained themselves. Still, the treatment may also solidify training resulting in higher adoption and triggering higher livelihood outcomes. Therefore, we add a dummy for participation in the certification treatment *T2*:

$$Y_{lci} = \alpha'_0 + \alpha'_1 \mathrm{T}_{lc} + \alpha_{11} \mathrm{T2}_{lc} + \alpha'_2 K_{lci} + \alpha'_3 Y^0_{lci} + \alpha'_4 X^0_{lci} + \alpha'_l + \varepsilon'_{lci} \quad (2)$$

The key parameter vectors of interest in this specification are α'_1, which shows the effect of training only and α_{11}, which shows the additional effect of certification on top of training. The controls used in both models are age of the respondent, gender of the respondent, education level, total land owned, household size, the household dependency ratio and farmer group membership.

To control for MHT, we choose the Romano-Wolf procedure (2005a, 2005b) as our outcome indicators are part of the same theory of change and hence, correlated (see section 2.4). Adjusted p-values in line with Bonferroni (1935) can be found in Appendixes 4.7- 4.10.

4.4 Descriptive statistics at baseline

Our sample consisted almost exclusively of male respondents (93%) from Islamic households (98%), which is in line with the demographics in Kano and Kaduna (Table 4.2). The average household size was approximately 10 people with on average half within the working age population (15-60). About half of the respondents had completed primary or higher education (52%). Average land size was 2.8 acres, which exceeds the national estimates for smallholders of

1.2 acres (FAO, 2018). About half of the respondents had at least one household member who was part of a farming group.

Table 4.2: Socioeconomic characteristics of survey households at baseline (N=1498)

Variable	Mean	Std. Dev.	Min	Max
Farmer gender (dummy, male = 1)	.931	.254	0	1
Age of respondent (years)	37.77	11.296	15	80
Religion (dummy, Islam = 1)	.981	.138	0	1
Education level respondent (dummy, finished secondary or higher = 1)	.464	.499	0	1
Primary or lower education	.536	.499	0	1
Secondary education	.338	.473	0	1
Higher education	.126	.331	0	1
Education level head of household (finished primary or higher = 1)	.434	.496	0	1
Total land owned (acres)	2.802	2.634	0	26.705
Household size (count)	9.887	5.772	0	35
Household dependency ratio (scale 0-1)	.439	.211	0	1
>1 household member part of farming group (dummy)	.507	.5	0	1

Standard deviations are in parentheses. Endline data is used for total land owned and religion as there was an issue with the baseline data.

Most respondents cultivated cereals and/or legumes (97%) with a smaller group cultivating vegetable crops (35%) (Table 4.3). The average number of vegetables cultivated in our sample was 0.56, while it was 1.6 for vegetable farmers. Only a small group of households reported cultivating vegetables in a home garden (15%). The use of improved varieties was limited for cereals and/or legumes at 12%. The use of improved varieties for vegetables was limited across farmers at 6%, while it was 16% amongst vegetable farmers. 11% of farmers reported cultivating government certified cereals and legumes seeds, while 5% reported using government certified vegetable seeds. The average number of GAP applied was 1.6, ranging from 0 to 10, with only 4% of farmers in the sample applying more than 5 practices. Zooming in on technology adoption, we also looked at individual practices. While some practices like thinning and crop rotation were widely practised, others like record keeping, trellising and pruning were practised by few. Chemical fertilizers were used by almost all farmers (90%) with slightly fewer farmers (83%) using organic fertilizer. Herbicides and pesticides were used by 10% and 17% of the farmers in our sample. The average farm income was ₦453,000 (approximately $310 based on the average exchange rate in 2024). The value of production for the top three vegetables was ₦61,000, comparable to the combined value of all vegetables (₦63,000) as the diversity of vegetables grown was low. Revenue from vegetable sales averaged ₦37,000. Looking at vegetable farmers specifically, both the value of production for the top three vegetables and total value for all vegetables produced equalled ₦175,400, whilst the revenue equalled ₦100,300. The large standard deviations indicate considerable heterogeneity in these outcomes. With regards to food security, 62% of the households were qualified as food secure, 8% were qualified as mildly food insecure, 17% as moderately food insecure, and 16% as severely food insecure. FCS scores were 44 on average, which is acceptable using the 35.5-score threshold, but still rather low (WFP, 2024).

Table 4.3: Descriptive statistics outcome variables for full sample based on the baseline data (N=1498 for full sample and N=524 for vegetable farmers only)

Variable	Mean	Std. Dev.	Min	Max
Vegetable production				
Cereal and/or legume production (dummy, yes =1)	.971	.169	0	1
Vegetable production (dummy, yes = 1)	.350	.477	0	1
Home garden with vegetable production (dummy, yes =1)	.152	.359	0	1
Number of vegetables cultivated (count)	.556	.897	0	10
Number of vegetables cultivated – veg. farmers only (count)	1.59	.81	1	10
Quality seed				
Used improved vegetable variety (dummy, yes =1)	.057	.233	0	1
Used improved vegetable variety – veg. farmers only (dummy, yes =1)	.164	.371	0	1
Used improved cereal and/or legume variety (dummy, yes =1)	.116	.321	0	1
Used government certified vegetable seed (dummy, yes =1)	.045	.208	0	1
Used government certified cereal/legume seed (dummy, yes =1)	.109	.312	0	1
Good agricultural practices				
Total number of GAP applied (count)	1.573	1.568	0	10
Applied 5 or more GAP (dummy, yes =1)	.036	.186	0	1
Staking (dummy, yes =1)	.065	.247	0	1
Crop rotation (dummy, yes =1)	.429	.495	0	1
Thinning (dummy, yes =1)	.164	.370	0	1
Pruning (dummy, yes =1)	.041	.199	0	1
Trellising (dummy, yes =1)	.035	.185	0	1
Record keeping (dummy, yes =1)	.044	.205	0	1
Homemade biopesticide (dummy, yes =1)	.145	.352	0	1
Mulching (dummy, yes =1)	.162	.368	0	1
Transplanting (dummy, yes =1)	.427	.495	0	1
Shade house (dummy, yes =1)	.061	.239	0	1
Crop income				
Total value of top 3 commonly produced vegetables (100k Naira)	.614	1.218	0	7.5
Total value of top 3 commonly produced – veg. farmers only (100k Naira)	1.754	1.497	0	7.5
Total value of all vegetables produced (100k Naira)	.632	1.226	0	7.5
Total value of all vegetables produced – veg. farmers only (100k Naira)	1.754	1.497	0	7.5
Total revenue for all vegetables sold (100k Naira)	.370	.787	0	4.83
Total revenue for all vegetables sold – veg. farmers only (100k Naira)	1.03	1.03	0	4.83
Total crop income (total value minus cost) (100k Naira)	4.528	5.345	-10.386	29.183
Food security				
Food secure (HFIAP, dummy, yes =1)	.62	.486	0	1
Mildly food insecure (HFIAP, dummy, yes =1)	.083	.277	0	1
Moderately food insecure (HFIAP, dummy, yes =1)	.166	.372	0	1
Severely food insecure (HFIAP, dummy, yes =1)	.156	.363	0	1
Food Consumption Score (FCS score, 0-112)	44.182	18.747	0	112
Other agricultural inputs				
Used chemical fertilizer (dummy, yes =1)	.902	.298	0	1
Chemical fertilizer quantity applied (kg)	485.724	575.621	0	5225
Chemical fertilizer value of amount bought (100k Naira)	1.716	2.000	0	18.435
Used organic fertilizer (dummy, yes =1)	.834	.372	0	1
Used chemical pesticides (dummy, yes =1)	.102	.186	0	1.62
Used herbicides (dummy, yes =1)	.173	.292	0	4.51

Values are expressed in Naira (₦), Nigeria's currency. Monetary values are scaled (divided by 100,000).

4.5 Results

4.5.1 Impact of treatment on core outcome variables

In line with our first hypothesis, our results in Table 4.4 indicate that the training programme of EWS-KT significantly increases vegetable cultivation. The number of farmers cultivating vegetables increases by 16% point in treatment areas, corresponding to a 50% increase relative to the control mean. The effect is significant at the 1% without and at 5% level with MHT corrections. This increase refers exclusively to vegetable cultivation on farm plots; there appears to be no effect of the treatment on the prevalence of vegetable cultivation in home gardens. Adjusted p-values in line with Romano-Wolf are included in the table, while those in line with Bonferroni (1935) can be found in Appendix 4.7.

Table 4.4: Average treatment effect on vegetable cultivation on farm plots, in home gardens, use of quality seed and GAP

	(1)	(2)	(3)	(4)	(5)	(6)
	Farmer cultivated vegetables	Home garden vegetable cultivation	Used improved vegetable variety	Used gov. certified vegetable seed	Total number of GAP applied	Adopted more than 5 GAP
Variables						
	Without controls					
Treatment	0.165***	0.003	0.074***	0.075***	0.620***	0.115***
	(0.000)	(0.677)	(0.001)	(0.001)	(0.000)	(0.000)
Constant	0.341***	0.026*	0.037	0.044	2.335***	0.082**
	(0.000)	(0.077)	(0.313)	(0.255)	(0.000)	(0.033)
R-squared	0.134	0.008	0.107	0.102	0.123	0.076
With controls						
Treatment	0.158***	0.008	0.070***	0.071***	0.590***	0.114***
	(0.000)	(0.299)	(0.001)	(0.001)	(0.000)	(0.000)
	[0.001]	[0.680]	[0.013]	[0.010]	[0.001]	[0.001]
Constant	0.137	0.125***	-0.137**	-0.114*	1.398***	0.009
	(0.177)	(0.001)	(0.049)	(0.099)	(0.000)	(0.895)
Control mean	0.315	0.017	0.084	0.086	2.446	0.080
R-squared	0.176	0.053	0.124	0.115	0.171	0.089
Obs.	1,498	1,498	1,498	1,498	1,498	1,498

Notes: Treatment effects are estimated using ANCOVA, all regressions include a key farmer dummy and control for the baseline value of the outcome. Standard errors are clustered at the community level, p-values are shown in parentheses with *** p<0.01, ** p<0.05, * p<0.1. Adjusted p-values (Romano-Wolf) are shown in square brackets.

Furthermore, these results show that the EWS-KT training programme significantly increases the share of farmers adopting improved vegetable varieties and government-certified vegetable seeds with 7 percentage points (1% significance level without and 1-5% with MHT). The estimated effects imply more than an 80% increase relative to the control mean. The increases are lower than the percentage point increase in vegetable farmers, suggesting that not all new vegetable farmers use improved or certified seeds. The programme also increases the adoption of GAPs: farmers apply on average 0.59 more GAPs across crops. In addition, the training induces an 11%-point increase in the share of farmers adopting more than five GAPs, corresponding to a 140% increase relative to the control mean. This suggests that a select group of farmers in the treatment areas

adopted a substantial package of technologies. Both GAP effects remain statistically significant at the 1% level with MHT corrections. These findings provide strong support for our second hypothesis, that the training increases the used of improved seeds and the adoption of GAPs.

Regarding our third hypothesis, the results in Table 4.5 show some indication of small positive treatment effect on household incomes but no impact on household food or nutrition security based on HFIAP scores and the FCS. The treatment increases the total value of the top three vegetables (tomato, onion, and chili), and of all vegetables combined, by ₦40,100, representing a 34% increase relative to the control mean. The effect on vegetable revenue is ₦31,100, a 39% increase compared to the control mean. The effect on vegetable revenue remains significant after MHT at the 10% level, whilst the other effects do not. For total crop income, the coefficient is positive, but it is small and not statistically significant.

Table 4.5: Average treatment effect on the value of vegetable production, crop income and food security:

	(1) Total value of 3 commonly produced vegetables	(2) Total value all vegetables produced	(3) Revenue for all vegetables produced	(4) Total crop income	(5) Food Consumption Score (FCS)	(6) Food secure (HFIAP)
Variables						
Without controls						
Treatment	0.421**	0.419**	0.312***	0.206	1.700	-0.010
	(0.013)	(0.014)	(0.010)	(0.631)	(0.108)	(0.759)
Constant	1.402***	1.421***	1.306***	7.590***	47.620***	0.505***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R-squared	0.160	0.162	0.169	0.172	0.021	0.048
With controls						
Treatment	0.401**	0.401**	0.311**	0.176	1.560	-0.013
	(0.023)	(0.023)	(0.012)	(0.667)	(0.122)	(0.672)
	[0.156]	[0.156]	[0.095]	[0.892]	[0.477]	[0.892]
Constant	0.256	0.275	0.521	2.716**	39.845***	0.513***
	(0.578)	(0.553)	(0.141)	(0.012)	(0.000)	(0.000)
Control mean	1.179	1.189	0.797	5.136	49.19	0.524
R-squared	1,498	1,498	1,498	1,498	1,498	1,498
Obs.	0.185	0.187	0.193	0.221	0.064	0.061

Notes: Treatment effects are estimated using ANCOVA, all regressions include a key farmer dummy and control for the baseline value of the outcome. Standard errors are clustered at the community level, p-values are shown in parentheses with *** p<0.01, ** p<0.05, * p<0.1. Adjusted p-values (Romano-Wolf) are shown in square brackets. Monetary values are scaled (divided by 100,000).

4.5.2 Impact of testing and certification treatment on core outcome variables

In addition to the AES, half of the treatment sample was provided with an add-on treatment involving the testing and certification of participants. Tables 4.6 and 4.7 show that after controlling for this add-on treatment in the regressions, the certification coefficients for the production and income related variables are positive and quite large, even larger than the training coefficients, which are rendered insignificant. This seems to suggest that certification strengthened the effects of the training. Yet the certification coefficients are also statistically insignificant. Adding the

certification treatment, there is a positive effect of training on the FCS with a 1.8 increase and a positive effect of certification with a 7.7 percentage point increase in food secure households. However, the effect of training is not robust as it does not show in the previous regressions (Table 4.5) and the effect of certification cannot be explained without underlying changes in the production chain. Overall, we therefore conclude that certification did not significantly strengthen the effects of the training. Adjusted p-values in line with Bonferroni (1935) can be found in Appendix 4.8.

In addition to the AES, half of the treatment sample was provided with an add-on treatment involving the testing and certification of participants. When controlling for this add-on treatment in the regressions, the certification coefficients for the production and income related variables are positive and quite large, even larger than the training coefficients, which are rendered insignificant. This seems to suggest that certification strengthened the effects of the training. Yet the certification coefficients were statistically insignificant (Table 4.6 and 4.7). Adding the certification treatment, we detected a positive effect of training on the FCS with a 1.8 increase and a positive effect of certification with a 7.7 percentage point increase in food secure households. However, the effect of training was not robust as it did not show in the previous regressions, and the effect of certification cannot be explained without underlying changes in the production chain. Overall, we therefore conclude that certification did not significantly strengthen the effects of the training. Adjusted p-values in line with Bonferroni (1935) can be found in Appendix 4.8.

Table 4.6: Average treatment effect of training and certification on vegetable cultivation on farm plots, in home gardens, and on the use of quality seeds.

	(1)	(2)	(3)	(4)	(5)	(6)
	Farmer cultivated vegetables	Home garden vegetable cultivation	Used improved vegetable variety	Used gov. certified vegetable seed	Total number of GAP applied	Adopted more than 5 GAP
Variables						
	Without controls					
Training	0.166***	0.004	0.083***	0.079***	0.597***	0.101***
	(0.000)	(0.730)	(0.003)	(0.003)	(0.000)	(0.000)
Certification	-0.004	-0.001	-0.018	-0.007	0.046	0.030
	(0.940)	(0.953)	(0.560)	(0.824)	(0.753)	(0.342)
Constant	0.341***	0.026*	0.036	0.044	2.337***	0.084**
	(0.000)	(0.078)	(0.331)	(0.260)	(0.000)	(0.029)
R-squared	0.134	0.008	0.108	0.102	0.123	0.077
With controls						
Training	0.168***	0.004	0.082***	0.078***	0.593***	0.100***
	(0.000)	(0.688)	(0.001)	(0.002)	(0.000)	(0.000)
	[0.002]	[0.915]	[0.020]	[0.021]	[0.001]	[0.001]
Certification	-0.020	0.010	-0.025	-0.013	-0.006	0.031
	(0.047)	(0.008)	(0.031)	(0.030)	(0.136)	(0.031)
	[0.968]	[0.855]	[0.855]	[0.968]	[0.969]	[0.855]
Constant	0.134	0.126***	-0.141**	-0.116*	1.397***	0.014
	(0.185)	(0.001)	(0.046)	(0.095)	(0.000)	(0.841)
Control mean	0.315	0.017	0.084	0.086	2.446	0.080
R-squared	0.176	0.054	0.125	0.116	0.171	0.090
Obs.	1,498	1,497	1,498	1,498	1,498	1,498

Notes: Treatment effects are estimated using ANCOVA, all regressions include a key farmer dummy and control for the baseline value of the outcome. Standard errors are clustered at the community level, p-values are shown in parentheses and adjusted p-values (Romano-Wolf) are shown in square brackets. *** p<0.01, ** p<0.05, * p<0.1.

Table 4.7: Average treatment effect of training and certification on value of top three vegetables, total value of vegetables produced, total actual crop income, total expected crop income, FCS and food security

	(1) Total value 3 commonly produced vegetables	(2) Total value all vegetables produced	(3) Revenue for all vegetables produced	(4) Total crop income	(5) Food Consumption Score (FCS)	(6) Food secure (HFIAP)
Variables						
Without controls						
Training	0.261	0.259	0.227	-0.032	1.900*	-0.046
	(0.167)	(0.173)	(0.103)	(0.947)	(0.095)	(0.210)
Certification	0.328	0.329	0.174	0.490	-0.411	0.075**
	(0.155)	(0.153)	(0.310)	(0.261)	(0.742)	(0.040)
Constant	1.418***	1.436***	1.314***	7.609***	47.595***	0.509***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R-squared	0.162	0.165	0.170	0.173	0.021	0.051
With controls						
Training	0.247	0.247	0.222	-0.040	1.843*	-0.050
	(0.185)	(0.188)	(0.107)	(0.930)	(0.081)	(0.166)
	[0.563]	[0.563]	[0.452]	[0.944]	[0.423]	[0.563]
Certification	0.320	0.320	0.186	0.450	-0.589	0.077**
	(0.168)	(0.168)	(0.286)	(0.274)	(0.622)	(0.042)
	[0.725]	[0.725]	[0.855]	[0.855]	[0.968]	[0.317]
Constant	0.303	0.322	0.550	2.785**	39.739***	0.525***
	(0.512)	(0.490)	(0.127)	(0.011)	(0.000)	(0.000)
Control mean	1.179	1.189	0.797	5.136	49.19	0.524
R-squared	0.187	0.189	0.194	0.222	0.064	0.064
Obs.	1,498	1,498	1,498	1,498	1,498	1,498

Notes: Treatment effects are estimated using ANCOVA, all regressions include a key farmer dummy and control for the baseline value of the outcome. Standard errors are clustered at the community level, p-values are shown in parentheses with *** p<0.01, ** p<0.05, * p<0.1. Adjusted p-values (Romano-Wolf) are shown in square brackets. Monetary values are scaled (divided by 100,000).

4.5.3 Explorative analyses

To gain a better understanding of the changes underlying our core impact estimates, we looked at programme impact on individual GAPs. We found significant effects for six out of ten practices. Table 4.8 and 4.9 show that at the seedling stage, the use of shade houses and transplanting of seedlings into the field increases. In the field, more farmers apply mulching, use of homemade pesticides, pruning and trellising. All but the results for pruning remain significant after MHT. The effects generally represent large increases in comparison to the control means. In comparison to the control mean, the adoption of pruning increase with 33%, shade houses with 87%, mulching with 99%, homemade pesticide with 111%, and trellising with 159%. There is no effect on crop rotation, record keeping, staking or thinning; however, it should be noted that we also found that crop rotation and thinning are common practices which are widely adopted already. Adjusted p-values in line with Bonferroni (1935) can be found in Appendix 4.9.

Table 4.8: Average treatment effect on the adoption of shade houses, transplanting, mulching, crop rotation and homemade pesticides.

	(1) Shade houses	(2) Transplanting	(3) Mulching	(4) Crop rotation	(5) Homemade biopesticide
Variables					
Without controls					
Treatment	0.102***	0.166***	0.123***	0.037	0.088***
	(0.000)	(0.000)	(0.000)	(0.120)	(0.000)
Constant	0.004	0.357***	0.017	0.714***	0.101***
	(0.927)	(0.000)	(0.696)	(0.000)	(0.003)
R-squared	0.121	0.100	0.095	0.055	0.078
With controls					
Treatment	0.094***	0.156***	0.118***	0.029	0.093***
	(0.000)	(0.000)	(0.000)	(0.211)	(0.000)
	[0.001]	[0.001]	[0.001]	[0.641]	[0.001]
Constant	-0.189**	0.111	-0.125	0.498***	0.155**
	(0.015)	(0.326)	(0.128)	(0.000)	(0.014)
Control mean	0.108	0.360	0.119	0.778	0.084
R-squared	0.152	0.148	0.119	0.095	0.083
Obs.	1,498	1,498	1,498	1,498	1,498

Notes: Treatment effects are estimated using ANCOVA, all regressions include a key farmer dummy and control for the baseline value of the outcome. Standard errors are clustered at the community level, p-values are shown in parentheses with *** p<0.01, ** p<0.05, * p<0.1. Adjusted p-values (Romano-Wolf) are shown in square brackets.

Table 4.9: Average treatment effect on the adoption of record keeping, staking, trellising, pruning and thinning.

	(1) Record Keeping	(2) Staking	(3) Trellising	(4) Pruning	(5) Thinning
Variables					
Without controls					
Treatment	0.008	0.004	0.027***	0.049**	0.018
	(0.608)	(0.747)	(0.008)	(0.014)	(0.522)
Constant	0.122***	0.053**	0.028	0.151***	0.784***
	(0.001)	(0.016)	(0.242)	(0.000)	(0.000)
R-squared	0.029	0.002	0.039	0.081	0.146
With controls					
Treatment	0.010	0.007	0.027***	0.051**	0.009
	(0.503)	(0.587)	(0.006)	(0.014)	(0.725)
	[0.890]	[0.890]	[0.067]	[0.106]	[0.890]
Constant	0.244***	0.086**	-0.001	0.172***	0.451***
	(0.000)	(0.046)	(0.989)	(0.005)	(0.000)
Control mean	0.082	0.037	0.017	0.157	0.703
R-squared	0.044	0.008	0.041	0.089	0.178
Obs.	1,498	1,498	1,498	1,498	1,498

Notes: Treatment effects are estimated using ANCOVA, all regressions include a key farmer dummy and control for the baseline value of the outcome. Standard errors are clustered at the community level, p-values are shown in parentheses with *** p<0.01, ** p<0.05, * p<0.1. Adjusted p-values (Romano-Wolf) are shown in square brackets.

As a second explorative analysis, we assessed whether the treatment influenced the uptake of other agricultural inputs, as the use of these inputs signals the intensification of production. Table 4.10 shows statistically significant effects on the quantity and value of chemical fertilizers used, the use of organic fertilizer and the use of chemical pesticides. The effects on the quantity of chemical fertilizer bought and the use of organic fertilizer remain statistically significant at the 5-10% level with MHT corrections. These results indicate that although EWS-KT does not necessarily promote the increased usage of these agricultural inputs, but rather better-informed usage, the treatment seems to contribute to intensification. The p-values seem dependent on the inclusion of covariates. Adjusted p-values in line with Bonferroni (1935) can be found in Appendix 4.10.

Table 4.10: Average treatment effect on the use of chemical fertilizer, organic fertilizer, chemical pesticides and herbicides

Variables	(1) Chemical fertilizer quantity applied	(2) Chemical fertilizer Value	(3) Organic fertilizer use	(4) Chemical pesticide use	(5) Herbicide use
Without controls					
Treatment	25.757	0.285**	0.045**	0.081**	0.025
	(0.115)	(0.018)	(0.027)	(0.019)	(0.426)
Constant	127.390***	0.749***	0.835***	0.479***	0.640***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
R-squared	0.228	0.229	0.173	0.066	0.209
With controls					
Treatment	20.752**	0.226***	0.051**	0.075**	0.017
	(0.046)	(0.004)	(0.011)	(0.031)	(0.582)
	[0.117]	[0.019]	[0.057]	[0.109]	[0.605]
Constant	-126.038***	-1.059***	0.865***	0.303***	0.500***
	(0.000)	(0.000)	(0.000)	(0.010)	(0.000)
Control mean	272.897	1.912	0.791	0.529	0.666
R-squared	0.572	0.543	0.189	0.090	0.243
Obs.	1,498	1,498	1,498	1,498	1,498

Notes: Treatment effects are estimated using ANCOVA, all regressions include a key farmer dummy and control for the baseline value of the outcome. Standard errors are clustered at the community level and p-values are shown in parentheses with *** p<0.01, ** p<0.05, * p<0.1. Adjusted p-values (Romano-Wolf) are shown in square brackets. Monetary values are scaled (divided by 100,000).

4.6 Discussion

We found robust evidence that the EWS-KT training programme resulted in increased prevalence of vegetable cultivation, the adoption of improved varieties and the adoption of GAPs. Moreover, we found some evidence for its positive effect on revenues, but not for impact on food and nutrition security. Future research should examine the long-term impact of the training programme beyond our one-year timeline. It could be the case that farmers are still experimenting with the newly adopted technologies on a small scale, which would reduce the effect on livelihood outcomes. Alternatively, they may abandon the technologies if they perceive the benefits to be too small. In this section, we reflect on explanations for our findings and discuss additional factors that may have shaped both the implementation of the intervention and the quality of the data collected.

The measured effect sizes of the AES-treatment are even more meaningful when we take into account several factors. Firstly, the intervention and our sample included non-vegetable farmers, which allowed us to measure a 16% increase in the number of farmers cultivating vegetables. However, this also meant the number of vegetable farmers in our sample was relatively small: 639 out of 1,498 at endline. Except for some of the GAPS, the treatment effects were concentrated among these farmers. Zooming in on the vegetable farmers only, the effect of the training was an increase of 16 percentage points, compared to 7 percentage points overall, in the adoption of improved vegetable seed and an increase in vegetable revenues of ₦72,325 instead of ₦31,100 at an average value of crop income for control farmers ₦513,600. Secondly, we focused on the intention-to-treat (ITT) effect rather than the treatment effect on fully trained farmers. EWS-KT estimates that 70-80% of invited farmers actually participate in most trainings, which implies that the effect on farmers completing the programme is about 1.33 times stronger. Therefore, we found that the AES programme of EWS-KT had a substantial impact on the production practices and returns of a select group of trained farmers.

As outlined in the introduction, this study contributes to the agricultural extension literature by focusing on vegetable production rather than staple crops and by evaluating a market-driven AES approach that relies on information provision only, without relaxing other constraints faced by farmers. Direct comparisons between the impacts of the EWS-KT programme and those of other interventions are challenging, as study contexts, designs and interventions differ. Nevertheless, situating our results within the existing literature helps to contextualize its impact. The adoption levels of improved varieties are logically lower than those recorded for AES interventions that relax farmer constraints other than knowledge: adoption rates of improved varieties are higher if researchers offer farmers cash-in-hand to spend on inputs (Matsumoto, 2014), free seed (Buehren et al., 2025; Ragasa et al., 2025; Wanyama et al., 2023) or they go door-to-door to sell the seed (Emerick & Dar, 2017). Two studies examine bundled approaches for export horticultural crops (Ashraf et al., 2009) and maize (Deutschmann et al., 2025) combining information treatments with loans and input provision (and product offtake). Ashraf et al. (2009) find a similar increase in the production of export horticulture crops of 15.9%, but no significant increase in household incomes across treatment groups, while Deutschmann et al. (2025) report a 18% increase in profits.

However, the impacts observed for the EWS-KT programme were achieved without credit provision or input distribution and thus, notable. Our findings are comparable to those of Yitayew et al. (2021), who find no effect of traditional extension, and a 5% increase in the adoption of a wheat variety following a combined communication treatment for extension agents and demonstration plots. Other studies find no impact of information treatments on adoption. Pan et al. (2018) show that while farmers adopt low-cost practices following an information treatment, high seed prices prevent adoption of improved maize varieties. Morgan et al. (2020) find no impact of extension treatments on farmers' willingness to pay for improved bean seed. Among existing studies, the research design of Riungu et al. (2021) is closest to ours, as it evaluates commercial demonstrations. In their study, adoption of improved maize and bean varieties remains below 1%, leading the authors to conclude that commercial orientation of the demonstrations discourages uptake. This contrasts with our findings, which show a market-driven AES intervention for vegetables did lead to substantial increases in technology adoption.

Regarding food and nutrition security, we detected no impact. While increased vegetable production may affect food and nutrition outcomes directly via own production or indirectly via higher household income, neither pathway was observed in this study. Our findings confirm that interventions focused on agricultural production do not necessarily translate into food and nutrition security outcomes (Garbero & Jäckering, 2021; Girard et al., 2012). Similarly, Merchant et al. (2023) measure no impact of a production intervention focused on traditional African vegetables, while a combined nutrition and production intervention is effective. The EWS-KT intervention clearly impacts commercial vegetable production, but we did not find an impact on production in home gardens.

The question remains how a market-driven approach can balance public-good objectives with private-sector incentives, particularly in light of the risks noted in the introduction, such as advice being skewed toward commercial crops and inputs and concerns about advisory neutrality. First, market-driven approaches may indeed concentrate advice on commercially attractive crops. However, this pattern partly reflects farmer preferences. As farmers selected two crops for the training of EWS-KT, impacts were naturally concentrated on the most market-oriented vegetables. Thus, the observed concentration on commercial crops was not solely supply-driven but also demand-driven. The average number of vegetables produced by vegetable farmers was only 1.6 and vegetable incomes seemed mostly generated by growing tomato, onion and chili (Table 4.3).

Second, the issue of advisory neutrality arises when assessing whether market-driven AES stimulate a broader market for quality seed or primarily increase demand for the products of a specific company. In the EWS-KT training programme, improved varieties from EWS were used for demonstration. Endline data included 463 tomato-variety observations from 455 farmers. Of these, 202 varieties were unidentified, while the remainder included 101 Griffaton, 76 Jubailee, 58 EWS varieties, and 26 other varieties. These figures suggest that EWS maintains a strong market presence, but not a dominant one. Although research on seed branding remains limited, Rutsaert et al. (2024) highlight the importance of brand loyalty in the Kenyan maize seed market. Therefore, market-driven AES may prove a profitable long-term investment for seed companies.

We did not find a meaningful impact of the test-based certification treatment on vegetable production and technology adoption, which is unsurprising given that the certification was originally designed to facilitate knowledge diffusion by signalling proficiency to peer farmers rather than to directly influence adopters' own behaviour. However, the sizes of the coefficients were unexpectedly large. While we cannot draw any strong conclusions from these findings, they offer a starting point for future research. So far, most research has focused on (non-monetary) incentives to motivate the providers of AES (Balew et al., 2023; Shikuku et al., 2019; BenYishay & Mobarak, 2018). Balew et al. (2023) find that both material and symbolic 'social prestige' awards can be effective motivators for lead farmers to stimulate diffusion. A certificate handed out during a public ceremony could also serve as a social prestige award and might enhance the effectiveness of AES at a low cost. Future research could hence explore the role of 'micro-credentials' for AES participants in greater depth.

Finally, we want to point out that the implementation of the intervention and the research occurred in a challenging political and economic context. Both Kano and Kaduna states have experienced

persistent insecurity, which affected farmers' access to inputs at the time of our study. Inflationary pressures during the study period also sharply increased the cost of food and agricultural inputs. Moreover, while most vegetables in the northern states are produced for the Southern states, due to security issues such transports continued to be severely hampered. These contextual factors also impacted the research team: the Wageningen-based researchers were unable to travel to the field due to institutional security restrictions.

4.7 Conclusion

This study examines whether market-driven AES can stimulate technology adoption and strengthen smallholder livelihoods focusing on vegetable production in northern Nigeria. Using a RCT, we assessed the impact of a one-year training programme implemented by the corporate foundation EWS-KT. We found strong and consistent evidence that the training programme led to substantial increases in vegetable cultivation and in the uptake of improved vegetable seed and GAPs. Evidence on livelihood outcomes was more mixed. While we observed an impact on vegetable revenues, an impact on food and nutrition was absent. We did not find evidence that test-based certification of trained farmers enhances technology adoption. By focusing on vegetable crops and a quasi-commercial extension model, this study contributes to the literature on agricultural extension in several ways. First, it shows that AES can be effective even when other farmer constraints are not directly alleviated. Likely, this requires stronger economic incentives, which are in place for high-value crops like vegetables. Second, it provides empirical evidence on a market-driven extension model that balances commercial incentives with public-good objectives, suggesting that such arrangements can support technology adoption without undermining farmer trust. Taken together, our findings indicate that market-driven AES can have positive impacts, suggesting that public–private partnerships may represent a win–win scenario for seed sector development, albeit with a limited scope.

Appendix

Appendix 4.1: Deviations from our pre-analysis plan

Original outcome indicator	Adjustment
Total value of vegetable production from the home garden	We used a home garden dummy rather than the total value of vegetable production from the home garden because of the low prevalence of home gardens among the survey farmers.
Share of vegetable crops of improved variety.	As the share of farmers growing vegetables is limited and the average number of vegetables cultivated per vegetable farmer is only 1.6, we decided to remove the percentage of vegetables grown with improved varieties as an outcome indicator.

Appendix 4.2: Attrition analysis comparing the attritted sample for the two treatment groups (TG1 and TG2) and the control group (CG) on baseline control and outcome variables.

	(1)	(2)	(3)
Variable	**All farmers (treatment)**	**All farmers (control)**	**Diff/ (p-value)**
Socioeconomic characteristics			
Farmer gender (dummy)	0.924	0.877	-0.047
	(0.267)	(0.330)	(0.338)
Age of the respondent (years)	37.354	36.991	-0.364
	(10.666)	(11.425)	(0.830)
Education level respondent (dummy, finished secondary or higher = 1)	0.405	0.377	-0.028
	(0.494)	(0.487)	(0.739)
Total land owned (acres)	7.162	7.544	0.381
	(8.388)	(7.441)	(0.771)
Household size (count)	9.797	9.868	0.070
	(5.539)	(5.432)	(0.935)
Household dependency ratio (scale 0-1)	0.417	0.427	0.009
	(0.198)	(0.201)	(0.756)
≥1 household member part of farming group (dummy)	0.468	0.330	-0.138*
	(0.502)	(0.473)	(0.084)
Vegetable production			
Vegetable production (dummy, yes = 1)	0.278	0.302	0.023
	(0.451)	(0.461)	(0.755)
Vegetable production in a home garden (dummy, yes =1)	0.165	0.123	-0.042
	(0.373)	(0.330)	(0.469)
Quality seed			
Used improved vegetable variety (dummy, yes =1)	0.089	0.047	-0.041
	(0.286)	(0.213)	(0.248)
Used government certified vegetable seed (dummy, yes =1)	0.063	0.028	-0.035
	(0.245)	(0.167)	(0.249)
Good agricultural practices (GAP)			
	1.316	1.453	0.136
Total number of GAP applied (count)	(1.751)	(1.346)	(0.618)
	0.063	0.028	-0.035
Applied 5 or more GAP (dummy, yes =1)	(0.245)	(0.167)	(0.328)
Crop income			
Total value of top 3 commonly grown vegetables (Naira)	0.655	0.570	0.085
	(1.321)	(1.164)	(0.645)
Total value of all vegetables produced (Naira)	0.655	0.570	0.085
	(1.321)	(1.164)	(0.645)
Revenue for all vegetables produced (Naira)	0.253	0.358	-0.105
	(0.635)	(0.771)	(0.352)
Total crop income (Naira)	5.051	4.214	0.837
	(4.877)	(5.620)	(0.338)
Food security			
Food secure			
(HFIAP, dummy, yes =1)	41.101	42.967	-1.866
	(17.033)	(16.298)	(0.485)
Food Consumption Score (FCS score, 0-112)	0.633	0.679	-0.046
	(0.485)	(0.469)	(0.561)
Observations	106	79	185

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG1+TG2 mean - CG mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 4.3: Attrition analysis comparing the attritted sample for the two treatment groups (TG1 vs. TG2) on baseline control and outcome variables.

	(1)	(2)	(3)
Variable	**All farmers (AES only)**	**All farmers (AES + Certification)**	**Diff/ (p-value)**
Socioeconomic characteristics			
Farmer gender (dummy)	0.872	0.975	0.103
	(0.339)	(0.158)	(0.174)
Age of the respondent (years)	38.667	36.075	-2.592
	(11.904)	(9.277)	(0.279)
Education level respondent (dummy, finished secondary or higher = 1)	0.410	0.400	-0.010
	(0.498)	(0.496)	(0.932)
Total land owned (acres)	7.536	6.798	-0.738
	(10.113)	(6.387)	(0.708)
Household size (count)	9.949	9.650	-0.299
	(5.553)	(5.591)	(0.810)
Household dependency ratio (scale 0-1)	0.443	0.392	-0.051
	(0.213)	(0.181)	(0.286)
≥1 household member part of farming group (dummy)	0.564	0.375	-0.189
	(0.502)	(0.490)	(0.144)
Vegetable production			
Vegetable production (dummy, yes = 1)	0.333	0.225	-0.108
	(0.478)	(0.423)	(0.281)
Vegetable production in a home garden (dummy, yes =1)	0.179	0.150	-0.029
	(0.389)	(0.362)	(0.762)
Quality seed			
Used improved vegetable variety (dummy, yes =1)	0.128	0.050	-0.078
	(0.339)	(0.221)	(0.196)
Used government certified vegetable seed (dummy, yes =1)	0.103	0.025	-0.078
	(0.307)	(0.158)	(0.135)
Good agricultural practices (GAP)			
	1.436	1.200	-0.236
Total number of GAP applied (count)	(1.997)	(1.488)	(0.606)
	0.103	0.025	-0.078
Applied 5 or more GAP (dummy, yes =1)	(0.307)	(0.158)	(0.226)
Crop income			
Total value of top 3 commonly grown vegetables (Naira)	0.807	0.506	-0.301
	(1.537)	(1.069)	(0.267)
Total value of all vegetables produced (Naira)	0.807	0.506	-0.301
	(1.537)	(1.069)	(0.267)
Revenue for all vegetables produced (Naira)	0.330	0.179	-0.151
	(0.777)	(0.456)	(0.290)
Total crop income (Naira)	5.107	4.997	-0.111
	(5.126)	(4.687)	(0.926)
Food security			
Food secure			
(HFIAP, dummy, yes =1)	39.833	42.338	2.504
	(16.990)	(17.198)	(0.491)
Food Consumption Score (FCS score, 0-112)	0.590	0.675	0.085
	(0.498)	(0.474)	(0.468)
Observations	39	40	79

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG2 mean – TG1 mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 4.4: Covariate balance tests for full sample using the baseline data.

	(1)	(2)	(3)
Variable	**All farmers (treatment)**	**All farmers (control)**	**Diff/ (p-value)**
Socioeconomic characteristics			
Farmer gender (dummy)	0.903	0.944	0.041
	(0.296)	(0.230)	(0.241)
Age of the respondent (years)	38.160	37.512	-0.648
	(11.030)	(11.267)	(0.449)
Education level respondent (dummy, finished secondary or higher = 1)	0.442	0.476	0.034
	(0.497)	(0.500)	(0.460)
Total land owned (acres)	2.809	2.797	-0.012
	(2.649)	(2.627)	(0.959)
Household size (count)	9.912	9.846	-0.066
	(5.547)	(5.789)	(0.879)
Household dependency ratio (scale 0-1)	0.455	0.430	-0.024
	(0.207)	(0.212)	(0.126)
≥1 household member part of farming group (dummy)	0.470	0.528	0.058
	(0.500)	(0.499)	(0.191)
Vegetable production			
Vegetable production (dummy, yes = 1)	0.351	0.349	-0.001
	(0.478)	(0.477)	(0.971)
Vegetable production in a home garden (dummy, yes =1)	0.142	0.157	0.015
	(0.349)	(0.364)	(0.571)
Quality seed			
Used improved vegetable variety (dummy, yes =1)	0.026	0.049	0.022**
	(0.142)	(0.196)	(0.048)
Share vegetables grown with imp. variety (dummy, yes = 1)	0.041	0.067	0.025*
	(0.199)	(0.249)	(0.097)
Used government certified vegetable seed (dummy, yes =1)	0.041	0.048	0.007
	(0.199)	(0.213)	(0.601)
Good agricultural practices (GAP)			
	(1.571)	(1.534)	(0.529)
Total number of GAP applied (count)	1.507	1.609	0.102
	(1.610)	(1.545)	(0.447)
Applied 5 or more GAP (dummy, yes =1)	0.032	0.038	0.007
	(0.175)	(0.192)	(0.624)
Staking (dummy, yes =1)	0.058	0.070	0.012
	(0.234)	(0.255)	(0.553)
Crop rotation (dummy, yes =1)	0.424	0.431	0.008
	(0.495)	(0.496)	(0.838)
Thinning (dummy, yes =1)	0.174	0.158	-0.016
	(0.379)	(0.365)	(0.602)
Pruning (dummy, yes =1)	0.041	0.042	0.001
	(0.199)	(0.200)	(0.972)
Trellising (dummy, yes =1)	0.028	0.040	0.012
	(0.165)	(0.195)	(0.327)
Record keeping (dummy, yes =1)	0.052	0.040	-0.013
	(0.223)	(0.195)	(0.340)
Homemade pesticides (dummy, yes =1)	0.110	0.164	0.054**
	(0.313)	(0.371)	(0.042)
Mulching (dummy, yes =1)	0.127	0.181	0.054**
	(0.333)	(0.385)	(0.043)
Transplanting (dummy, yes =1)	0.444	0.418	-0.026
	(0.497)	(0.493)	(0.529)
Shade house (dummy, yes =1)	0.050	0.067	0.016
	(0.219)	(0.249)	(0.287)
Other agricultural inputs			

Used chemical fertilizer	0.920	0.892	-0.028
	(0.272)	(0.311)	(0.268)
Chemical fertilizer value of amount bought (Naira)	1.913	1.606	-0.307*
	(2.057)	(1.959)	(0.085)
Used organic fertilizer (dummy, yes =1)	0.873	0.846	-0.027
	(0.333)	(0.361)	(0.358)
Used chemical pesticides (dummy, yes =1)	0.487	0.514	0.027
	(0.500)	(0.500)	(0.478)
Used herbicides (dummy, yes =1)	0.632	0.606	-0.026
	(0.483)	(0.489)	(0.623)
Crop income			
Total value of top 3 commonly grown vegetables (Naira)	0.679	0.577	-0.102
	(1.277)	(1.183)	(0.312)
Total value of all vegetables produced (Naira)	0.698	0.596	-0.102
	(1.286)	(1.190)	(0.312)
Revenue for all vegetables produced (Naira)	0.452	0.324	-0.128*
	(0.867)	(0.735)	(0.067)
Total crop income (Naira)	4.446	4.573	0.127
	(5.741)	(5.114)	(0.796)
Food security			
Food secure (HFIAP, dummy, yes =1)	0.595	0.634	0.039
	(0.491)	(0.482)	(0.351)
Food Consumption Score (FCS score, 0-112)	44.418	44.050	-0.368
	(18.702)	(18.780)	(0.824)
Observations	536	962	1,498

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG1+TG2 mean – CG mean (Col.2 – Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01. Monetary values are scaled (divided by 100,000).

Appendix 4.5: Covariate variables balance tests between the two treatment arms (TG1 and TG2) using the baseline data.

	(1)	(2)	(3)
Variable	**All farmers (AES only)**	**All farmers (AES + Certification)**	**Diff/ (p-value)**
Socioeconomic characteristics			
Farmer gender (dummy)	0.905	0.985	0.080**
	(0.294)	(0.122)	(0.049)
Age of the respondent (years)	37.731	37.282	-0.449
	(11.110)	(11.437)	(0.673)
Education level respondent (dummy, finished secondary or higher = 1)	0.472	0.481	0.009
	(0.500)	(0.500)	(0.870)
Total land owned (acres)	2.865	2.727	-0.138
	(2.843)	(2.379)	(0.571)
Household size (count)	9.731	9.968	0.237
	(5.754)	(5.828)	(0.631)
Household dependency ratio (scale 0-1)	0.439	0.421	-0.018
	(0.205)	(0.220)	(0.332)
≥1 household member part of farming group (dummy)	0.587	0.466	-0.121***
	(0.493)	(0.499)	(0.009)
Vegetable production			
Vegetable production (dummy, yes = 1)	0.340	0.359	0.019
	(0.474)	(0.480)	(0.709)
Vegetable production in a home garden (dummy, yes =1)	0.164	0.150	-0.015
	(0.371)	(0.357)	(0.630)
Quality seed			
Used improved vegetable seed (dummy, yes =1)	0.051	0.046	-0.006
	(0.200)	(0.192)	(0.739)
Share vegetables grown with imp. seed (dummy, yes = 1)	0.071	0.062	-0.009
	(0.257)	(0.241)	(0.686)
Used government certified vegetable seed (dummy, yes =1)	0.045	0.051	0.007
	(0.206)	(0.221)	(0.696)
Good agricultural practices (GAP)			
Total number of GAP applied (count)	1.599	1.620	0.020
	(1.610)	(1.474)	(0.892)
Applied 5 or more GAP (dummy, yes =1)	0.040	0.036	-0.004
	(0.197)	(0.187)	(0.773)
Staking (dummy, yes =1)	0.085	0.053	-0.032
	(0.279)	(0.225)	(0.192)
Crop rotation (dummy, yes =1)	0.443	0.419	-0.025
	(0.497)	(0.494)	(0.604)
Thinning (dummy, yes =1)	0.166	0.150	-0.016
	(0.372)	(0.357)	(0.605)
Pruning (dummy, yes =1)	0.045	0.038	-0.006
	(0.206)	(0.193)	(0.729)
Trellising (dummy, yes =1)	0.036	0.043	0.006

	(0.188)	(0.202)	(0.687)
Record keeping (dummy, yes =1)	0.047	0.032	-0.015
	(0.211)	(0.176)	(0.306)
Homemade pesticides (dummy, yes =1)	0.154	0.175	0.021
	(0.361)	(0.381)	(0.548)
Mulching (dummy, yes =1)	0.162	0.201	0.039
	(0.369)	(0.401)	(0.223)
Transplanting (dummy, yes =1)	0.391	0.447	0.056
	(0.488)	(0.498)	(0.235)
Shade house (dummy, yes =1)	0.071	0.062	-0.009
	(0.257)	(0.241)	(0.687)
Other agricultural inputs			
Used chemical fertilizer	0.901	0.882	-0.018
	(0.299)	(0.322)	(0.564)
Chemical fertilizer value of amount bought (Naira)	1.646	1.564	-0.082
	(2.097)	(1.804)	(0.668)
Used organic fertilizer (dummy, yes =1)	0.868	0.823	-0.046
	(0.338)	(0.382)	(0.286)
Used chemical pesticides (dummy, yes =1)	0.526	0.500	-0.026
	(0.500)	(0.501)	(0.511)
Used herbicides (dummy, yes =1)	0.605	0.607	0.002
	(0.489)	(0.489)	(0.978)
Crop income			
Total value of top 3 commonly produced vegetables (Naira)	0.540	0.616	0.077
	(1.168)	(1.198)	(0.490)
Total value of all vegetables produced (Naira)	0.553	0.641	0.089
	(1.174)	(1.206)	(0.435)
Revenue for all vegetables produced (Naira)	0.336	0.311	-0.026
	(0.774)	(0.692)	(0.713)
Total crop income (Naira)	4.729	4.409	-0.320
	(5.390)	(4.806)	(0.507)
Food security			
Food secure (HFIAP, dummy, yes =1)	0.623	0.645	0.022
	(0.485)	(0.479)	(0.637)
Food Consumption Score (FCS score, 0-112)	43.729	44.389	0.660
	(18.695)	(18.885)	(0.727)
Observations	494	468	962

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG2 mean – TG1 mean (Col.2 – Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01. Monetary values are scaled (divided by 100,000).

Appendix 4.6: Covariate balance tests for the treatment non-host trained farmers and control non-host untrained farmers using the baseline data (exception of land size)

Variable	(1) Invited farmers (treatment)	(2) Neigh. farmers (control)	(3) Diff/ (p-value)
Socioeconomic characteristics			
Farmer gender (dummy, 1 = male)	0.909	0.942	0.033
	(0.288)	(0.234)	(0.341)
Age of the respondent (years)	38.012	37.165	-0.847
	(11.232)	(11.371)	(0.345)
Education level respondent (dummy,	0.442	0.471	0.029
finished secondary or higher = 1)	(0.497)	(0.499)	(0.531)
Total land owned (acres)	2.717	2.641	-0.076
	(2.487)	(2.499)	(0.732)
Household size (count)	9.851	9.655	-0.195
	(5.527)	(5.727)	(0.653)
Household dependency ratio (scale 0-1)	0.452	0.428	-0.024
	(0.207)	(0.213)	(0.149)
>1 household member part of farming	0.454	0.506	0.053
group (dummy, yes = 1)	(0.498)	(0.500)	(0.246)
Vegetable production			
Vegetable production (dummy, yes = 1)	0.351	0.348	-0.003
	(0.478)	(0.477)	(0.947)
Vegetable production in a home garden (dummy, yes =1)	0.139	0.150	0.011
	(0.346)	(0.358)	(0.685)
Quality seed			
Used improved vegetable variety (dummy, yes =1)	0.038	0.062	0.024
	(0.192)	(0.242)	(0.107)
Used government certified vegetable seed (dummy, yes =1)	0.042	0.040	-0.002
	(0.202)	(0.197)	(0.889)
Good agricultural practices			
Total number of GAP applied (count)	1.500	1.613	0.113
	(1.606)	(1.562)	(0.422)
Applied 5 or more GAP (dummy, yes	0.032	0.040	0.008
=1)	(0.177)	(0.197)	(0.562)
Staking (dummy, yes =1)	0.056	0.074	0.018
	(0.231)	(0.262)	(0.412)
Crop rotation (dummy, yes =1)	0.431	0.428	-0.004
	(0.496)	(0.495)	(0.926)
Thinning (dummy, yes =1)	0.173	0.163	-0.010
	(0.379)	(0.370)	(0.739)
Pruning (dummy, yes =1)	0.044	0.042	-0.003
	(0.206)	(0.200)	(0.867)
Trellising (dummy, yes =1)	0.022	0.034	0.011
	(0.147)	(0.180)	(0.309)
Record keeping (dummy, yes =1)	0.044	0.040	-0.004
	(0.206)	(0.197)	(0.760)
Homemade pesticides (dummy, yes =1)	0.113	0.163	0.050*
	(0.317)	(0.370)	(0.067)
Mulching (dummy, yes =1)	0.125	0.186	0.061**
	(0.331)	(0.389)	(0.028)
Transplanting (dummy, yes =1)	0.442	0.416	-0.025
	(0.497)	(0.493)	(0.554)
Shade house (dummy, yes =1)	0.048	0.067	0.019
	(0.215)	(0.250)	(0.234)
Other agricultural inputs			
Used chemical fertilizer	0.917	0.887	-0.031
	(0.276)	(0.317)	(0.232)

Chemical fertilizer value of amount	1.915	1.565	-0.350*
bought (Naira)	(2.071)	(1.886)	(0.054)
Used organic fertilizer (dummy, yes =1)	0.877	0.851	-0.026
	(0.329)	(0.356)	(0.369)
Used chemical pesticides (dummy, yes =1)	0.486	0.514	0.029
	(0.500)	(0.500)	(0.457)
Herbicides (dummy, yes	0.637	0.603	-0.034
=1)	(0.481)	(0.489)	(0.540)
Crop income			
Total value of top 3 commonly produced vegetables (Naira)	0.670	0.569	-0.101
	(1.253)	(1.165)	(0.326)
Total value of all vegetables produced (Naira)	0.684	0.590	-0.094
	(1.260)	(1.173)	(0.361)
Revenue for all vegetables produced (Naira)	0.449	0.317	-0.132*
	(0.852)	(0.723)	(0.062)
Total crop income (Naira)	4.466	4.548	0.083
	(5.691)	(5.090)	(0.867)
Food security			
Food secure (HFIAP, dummy, yes =1)	0.591	0.623	0.032
	(0.492)	(0.485)	(0.442)
Food Consumption Score (FCS score, 0-112)	44.545	43.615	-0.930
	(18.562)	(18.462)	(0.585)
Observations	496	865	1,361

Note: Table only shows comparability of both treatments and control groups and does not distinguish between the two treatment arms. *** p<0.01, ** p<0.05, * p<0.1. Monetary values are scaled (divided by 100,000).

Appendix 4.7: Adjusted p-values of treatment coefficients with MHT corrections.

Outcome variables	**Bonferroni (p-value)**	**Romano–Wolf (p-value)**
Vegetable cultivation (dummy, yes =1)	.000	.001
Home garden vegetable cultivation (dummy, yes =1)	0.896	.680
Used improved vegetable variety (dummy, yes =1)	.008	.013
Used government certified vegetable seed (dummy, yes =1)	.007	.010
Total GAP practices adopted (count)	.000	.001
≥5 GAP practices adopted (dummy, yes =1)	.000	.001
Total value of top 3 commonly produced vegetables (Naira)	.135	.156
Total value of all vegetables produced (Naira)	.135	.156
Total revenue for all vegetables (Naira)	.082	.095
Total crop income (total value minus total cost) (Naira)	1.000	.892
Food secure (HFIAP, dummy, yes =1)	.487	.477
Food Consumption Score (FCS score, 0-112)	1.000	.892

Appendix 4.8: Adjusted p-values of training and certification coefficients with MHT corrections.

	Training		Certification	
Outcome variables	**Bonferroni (p-value)**	**Romano–Wolf (p-value)**	**Bonferroni (p-value)**	**Romano–Wolf (p-value)**
Vegetable cultivation (dummy, yes =1)	.001	.002	1.000	.968
Home garden vegetable cultivation (dummy, yes =1)	.915	.915	1.000	.855
Used improved vegetable variety (dummy, yes =1)	.013	.020	1.000	.855
Used gov. certified vegetable seed (dummy, yes =1)	.013	.021	1.000	.968
Total GAP practices adopted (count)	.000	.001	1.000	.969
≥5 GAP practices adopted (dummy, yes =1)	.000	.001	1.000	.855
Total value of top 3 commonly produced vegetables (Naira)	.832	.563	1.000	.725
Total value of all vegetables produced (Naira)	.832	.563	1.000	.725
Total revenue for all vegetables (Naira)	.645	.452	1.000	.855
Total crop income (total value minus total cost) (Naira)	1.000	.944	1.000	.855
Food secure (HFIAP, dummy, yes =1)	.569	.423	.500	.968
Food Consumption Score (FCS score, 0-112)	.832	.563	1.000	.317

Appendix 4.9: Adjusted p-values of treatment coefficients for individual GAPs with MHT corrections.

Outcome variables	**Bonferroni (p-value)**	**Romano–Wolf (p-value)**
Shade house (dummy, yes =1)	.000	.001
Transplanting (dummy, yes =1)	.000	.001
Mulching (dummy, yes =1)	.000	.001
Crop rotation (dummy, yes =1)	.844	.641
Homemade biopesticide (dummy, yes =1)	.000	.001
Record keeping (dummy, yes =1)	1.000	.890
Staking (dummy, yes =1)	1.000	.890
Trellising (dummy, yes =1)	.039	.067
Pruning (dummy, yes =1)	.072	.106
Thinning (dummy, yes =1)	1.000	.890

Appendix 4.10: Adjusted p-values of treatment coefficients for other agricultural inputs with MHT corrections.

Outcome variables	**Bonferroni (p-value)**	**Romano–Wolf (p-value)**
Chemical fertilizer quantity applied (kg)	.093	.117
Chemical fertilizer value of amount bought (Naira)	.020	.019
Used organic fertilizer (dummy, yes =1)	.045	.057
Used chemical pesticides (dummy, yes =1)	.093	.109
Used herbicides (dummy, yes =1)	.582	.605



5

Can public certification enhance the impact of agricultural extension through spillovers? Evidence from Nigeria's vegetable sector

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Abstract

Agricultural Extension Services (AES) are widely promoted as a critical instrument to accelerate smallholder adoption of improved practices. Evidence has shown that combining AES with social network mechanisms can scale impacts beyond direct trainees by capitalizing on local interactions. However, much of this evidence relies on integrating a supply-driven social network approach that explicitly selects, trains, and often incentivizes 'model' or 'lead' farmers to disseminate information to peer farmers. Critics argue that because such approaches can be costly and not easily scalable, demand-driven approaches, which shift the diffusion burden to peer farmers seeking information, would be preferable. Yet there is limited evidence that such approaches are sufficient to disseminate agricultural technologies. We evaluated whether a demand-driven extension approach could generate measurable spillover effects using a randomized controlled trial (RCT) across 150 communities in Kano and Kaduna states, northern Nigeria. Communities were assigned to one of three arms: training only, training plus public certification of trained farmers, and a pure control group. We focused exclusively on spillover effects among non-targeted farmers. Although the intervention successfully stimulated vegetable production and technology adoption among direct participants, we found only very limited evidence of spillover effects. Specifically, the only spillover effect seemed to be an increase in the use of government-certified seeds among non-targeted farmers in the public certification arm. Our findings suggest that the diffusion of knowledge in trained communities is not automatic and public certification of trained farmers to signal expertise does not enhance peer-to-peer technology diffusion in a meaningful manner. Complementary supply-side conditions may be required to enable sustained knowledge transfer and adoption.

[*] Ethical clearance for this study was obtained via the Wageningen University & Research (WUR) Research Ethics Committee (Approval Number: 2024-083), the state governments (Kano state: NHREC/17/03//2018 and Kaduna state: NHREC/17/03/2018), and IFPRI (MTI-23-0521). The study's pre-analysis plan was registered in the American Economic Association's RCT Registry (AEARCTR) prior to endline data collection in June 2024 (ID: AEARCTR-0013489). Deviations are listed in Appendix 5.1.

5.1 Introduction

Agricultural Extension Services (AES) remain an essential institutional channel crucial in accelerating the adoption of agricultural technologies among farmers in sub-Saharan Africa (SSA) (Ruzzante et al., 2021; Yokamo, 2020; Wossen et al., 2017; Abdoulaye et al., 2014; Tambo & Abdoulaye, 2012). AES can provide farmers with skills and technologies that allow them to optimally participate in agricultural activities. Farming is particularly information intensive. Farmers need the right knowledge to select seeds, control pests and diseases, irrigate, and even harvest. Yet AES provision often faces persistent constraints, such as limited infrastructure, unskilled personnel, and weak logistics, reducing the effective dissemination of AES, particularly among smallholders (Tafida et al., 2024; Agwu et al., 2023; Kazeem et al., 2017; Adejo et al., 2012).

The challenges facing AES are particularly pronounced in vegetable production. Although public extension programmes targeting the horticultural sector in sub-Saharan Africa (SSA) have expanded in recent decades, they remain highly limited compared to those focused on staple crops (Mwangi et al., 2021; Dinssa et al., 2015). Similarly, private and donor-led initiatives often do not prioritize vegetables, instead concentrating on staple crops. As a result, the vegetable sector remains underserved, despite its significant contributions to food and nutrition security and income generation (Harris et al., 2022; Schreinemachers et al., 2017).

Beyond the availability of knowledge, the impact of AES ultimately depends on whether information reaches a large number of farmers in a form and at a time that changes their behaviour (Balew et al., 2023). Due to budgetary constraints, AES is often accessible only to a limited group of farmers, which restricts overall gains unless knowledge diffuses more broadly. For AES to generate sector-wide productivity improvements, its impact must therefore extend beyond direct beneficiaries and influence the practices of farmers who did not receive training (Norton & Alwang, 2020). From a policy perspective, this places information dissemination at the centre of extension design. If training effects remain confined to direct participants, scaling requires repeated trainings and entails high delivery costs (Takahashi et al., 2020). In contrast, if knowledge spreads through peer learning, the same investment can yield substantially broader returns (Lasdun et al., 2025; Norton & Alwang, 2020; Takahashi et al., 2020).

This study evaluates whether the impact of AES for commercial vegetable production extends beyond targeted farmers and whether the integration of a demand-driven social network component enhances the dissemination of knowledge. We focused on the agricultural extension programme of East-West Seed Knowledge Transfer (EWS-KT) in northern Nigeria. A clustered randomized controlled trial (RCT) with two treatment arms and a control group was implemented across 150 communities in Kano and Kaduna states. In the first treatment arm (training-only), EWS-KT delivered its standard agronomy training on demonstration plots (hereafter, demo plots) to targeted farmers. In the second treatment arm (certification), the same agronomy training was provided and complemented by the public certification of trained farmers. Data were collected in two waves (baseline and endline surveys) and covered household characteristics, agricultural practices, food security, and technology adoption. Rather than focusing on directly targeted farmers, our analysis focused exclusively on non-targeted farmers.

First, we tested whether spillovers occurred from trained farmers to non-targeted farmers within treatment communities. If the AES approach alone was sufficient to disseminate knowledge beyond direct trainees, we would observe higher adoption among non-targeted farmers in treatment communities relative to those in control communities. Second, we examined whether signalling the proficiency of trained farmers to their peers would amplify these spillover effects. To this end, trained farmers who passed a test received a certificate during a public ceremony in their community. This design allowed us to compare two pathways through which adoption may spread within social networks: one without deliberate support for diffusion, and one that explicitly positions trained farmers as credible sources of knowledge (e.g., Shaijumon, 2018; Wossen et al., 2017; Krishnan & Patnam, 2014; Conley & Udry, 2010). The latter can be interpreted as a demand-driven approach, as it encourages non-targeted farmers to seek information from trained peers based on their own interests.

Our findings were twofold. First, we found that, while the AES programme of EWS-KT successfully induced technology adoption amongst targeted farmers (see Chapter 4), this had no significant effect on the adoption behaviour of non-targeted farmers. Second, the public certification of trained farmers only slightly enhanced spillovers effects as shown by a positive effect on the increased use of government-certified seeds by non-targeted farmers. These results were robust to different specifications, including household controls, geographic fixed effects, and baseline outcomes.

This paper mainly contributes to two literature strands. First, it contributes to the literature on technology diffusion and social learning in agriculture, which emphasizes that adoption decisions are shaped by information acquired through peers and local networks (Krishnan & Patnam, 2014; Conley & Udry, 2010). While the diffusion of innovation theory predicts that information spreads from early to late adopters through social interaction and observing the results of early adopters (Rogers, 1995), a growing experimental literature shows that spillover effects are often not automatic and depend on how information is communicated, who communicates it, and what effort or incentives communicators face (Beaman et al., 2021; BenYishay & Mobarak, 2019; Kondylis et al., 2017; Feder et al., 2004). Social networks could be leveraged to strengthen AES by enabling farmers to learn from one another in a way that lowers dissemination costs and expands information reach (Chowdhury et al., 2022; Chaudhuri et al., 2021; Buskens, 2020; Takahashi et al., 2020; BenYishay & Mobarak, 2019; Dar et al., 2019; Shaijumon, 2018; Krishnan & Patnam, 2014). Given that social networks arise through repeated interactions and reciprocal exchange, these structures may easily facilitate information flow and observational learning, although they have also been criticized for being prone to information loss along transmission chains (Hörner et al., 2022; Buskens, 2020; Beaman & Dillon, 2018; Niu & Ragasa, 2018; Hayami, 2009).

In principle, social networks can be incorporated into AES in three ways: through supply-driven, demand-driven, or hybrid approaches combining the two. For the purposes of this study, we differentiate approaches as either 'supply-driven' or 'demand-driven' based on who bears the primary responsibility of transmitting extension knowledge: appointed farmer disseminators versus other farmers who engage with extension knowledge based on their own motivation. Supply-driven social network approaches explicitly recruit (and incentivize) selected farmers to promote adoption. Farmers considered ‘influencers’ or ‘models’ in their communities are recruited

as lead or contact farmers and tasked with the responsibility to promote technology to their fellow farmers, sometimes with compensation that comes as commissions or inputs (Balew et al., 2023; Cecchi et al., 2021; BenYishay & Mobarak, 2019; Shikuku et al., 2019; Kondylis et al., 2017). Despite being promising, supply-driven approaches are often critiqued. They are costly to sustain when regular supervision and incentives are required for information diffusion and can produce reverse effects when selected 'model' farmers are perceived as privileged (Ochieng et al., 2022; Ragasa, 2020; de Janvry et al., 2016; Kondylis et al., 2017; Feder et al., 2004). These concerns motivate the need to employ demand-driven approaches that shift the burden of diffusion away from actively facilitated disseminators and instead induce other farmers to seek information from trained farmers or early adopters through social interactions (Emerick & Dar, 2021; Dar et al., 2019). Though demand-driven approaches still, to some extent, rely on social interactions, they expand learning opportunities beyond farmers who are socially connected to 'model' farmers, giving a broader set of farmers direct access to information, and making them even more attractive when network-based diffusion is limited. If demand-driven diffusion works, and the costs of stimulating and maintaining demand are small relative to the resulting adoption gains, it offers an efficient pathway for sustained learning at the end of formal extension interventions in communities.

However, demand-driven approaches are not without challenges. Even when they can facilitate the cost-effective spread of innovations, peer learning may be constrained by weak incentives to share knowledge, competing time demands, and limited access to credit and inputs (Beaman et al., 2021; Buskens, 2020; BenYishay & Mobarak, 2019; Dar et al., 2019), thereby preventing information from translating into adoption. These constraints suggest that demand-driven approaches may fail to generate measurable spillover effects, even when knowledge diffusion occurs. This matters because, like many AES designs, demand-driven approaches may implicitly assume that information is the primary adoption constraint and that, once relaxed, impacts will diffuse beyond direct participants. Yet evidence that informs whether applying demand-driven approaches alone is enough to stimulate knowledge demand and trigger diffusion remains limited (e.g., Dar et al. (2019)), and to our knowledge, has not been documented in Nigeria's vegetable sector. Our results add to this literature by showing that the demand-driven approach used in our study did not lead to detectable spillover effects among non-targeted farmers within the study period, despite leveraging social networks.

Second, our results speak to the literature on signalling and credibility in low-information environments, where farmers may be uncertain about who holds relevant expertise, weakening incentives to search for information and learn. In such settings, diffusion may depend on the (social) conditions that make information credible and easy to access; for instance, trust, perceived reliability of sources, and how information spreads within the networks (Buskens, 2020; Dar et al., 2019). This raises the design question: how can AES incorporate signalling to strengthen the capacity of social networks to facilitate diffusion? Demand-driven approaches can make expertise more visible by positioning certain individuals as credible knowledge sources. In extension contexts, some interventions incorporate public recognition mechanisms (e.g., certificates) to motivate diffusion effort (Balew et al., 2023). We applied this signalling logic to EWS-KT's extension design as a standalone demand-driven approach and tested whether a publicly announced certification that identifies trained farmers as 'experts' was sufficient to motivate non-

targeted farmers to consult them and produce spillover effects. As such, our study contributes evidence on whether credibility cues alone can relax information-search frictions in extension settings. Our results showed that credibility cues alone had a limited impact, suggesting that a standalone signal to stimulate demand is unlikely to disseminate extension knowledge beyond direct participants. This suggests that the AES would be improved by an extension design with complementary supply- and demand-side inducements to motivate engagement and produce desired spillover effects.

The remainder of the paper is organized as follows. Section 2 describes the study context, experimental design, and sampling strategy. Section 3 presents the empirical strategy. Section 4 describes the sample and reports the main results including robustness checks. Section 5 discusses the results and Section 6 concludes.

5.2 Context, design, and sample description

5.2.1 Context and case study

This research was conducted in the Kano and Kaduna states of northern Nigeria, where, as in most parts of Nigeria, agriculture remains the primary economic activity, and most of the rural population is engaged in smallholder farming. These states are densely populated, hosting an estimated population of 20 million (National Bureau of Statistics, 2016), and support a range of agrarian activities such as crop farming, livestock production, agro-processing, and other agribusinesses. There are two distinct seasons for crop cultivation: the wet season, which usually lasts from May to October, and the dry season, which lasts from November to April. The climate supports the cultivation of different crops, including cereals like maize and sorghum, legumes like groundnuts and cowpeas, as well as vegetables like tomatoes, peppers, and onions.

This study evaluates the spillover effects of an AES implemented by EWS-KT, the corporate foundation linked to the company East-West Seed (EWS). EWS-KT offers AES to smallholder farmers to build their capacity in vegetable farming so that they can successfully contribute to and meaningfully benefit from vegetable production. By equipping farmers with updated farming skills and introducing them to improved varieties of EWS, the foundation aims to improve SHFs' livelihoods and increase the supply of high-quality and safe vegetables in the market (ter Steeg & Louwaars, 2024). While the EWS-KT model does not involve the sales of improved varieties to trained farmers, the programme does involve the training of agrodealers and a seed selection component teaching farmers to recognize quality seed. Moreover, the company EWS ensures seed becomes available via distribution channels. EWS-KT has a significant presence across Africa and Asia, with Nigeria being one of its focus countries for delivering AES.

The EWS-KT AES programme involves three main groups of actors: qualified extension officers, demo hosts, targeted farmers and non-targeted farmers. The extension officers are responsible for identifying demo hosts[2] and organizing five training sessions during each of the two cropping

[2] The EWS-KT AES selection criteria encompass a broad range of personal skills, social standing, and economic status. Specifically, demo hosts must own a suitable plot of land (with proof of ownership) that meets the following conditions: a flat area of at least 500 sqm, access to a reliable water source, and a

cycles within the farming year. Demo hosts manage the demonstration plot and help organize the group of targeted farmers. In our case, the demo hosts had to compile a list of at least 25 farmers within their communities. Subsequently, these farmers were invited to participate in the training of EWS-KT. It should be noted that not all invited farmers end up entering or completing the training programme and thus, not all targeted farmers are trained farmers. In addition to these three groups, there are also 'non-targeted' farmers: farmers who live in the communities who are not invited to the trainings. These farmers are indirectly exposed to the training of EWS-KT by witnessing potential adoption by their peers.

In Chapter 4, we have already shown that the EWS-KT programme on targeted farmers had meaningful impacts across all vegetable production and technology adoption outcomes. The pooled treatment increased the share of farmers cultivating vegetables by 15.8 percentage points (pp), the use of improved varieties and government-certified seeds by 7 pp, the probability of adopting at least five GAPs by 11.5 pp, and farmers' total GAPs adopted by 0.6 (all at $p<0.01$). However, it is important to assess whether and to what extent, these impacts diffuse to non-targeted farmers in the same communities. After implementation of the AES during two crop cycles, EWS-KT stops facilitating activities and moves on to the next community. This exit strategy assumes that information dissemination follows a top-down approach, where extension knowledge flows from qualified extension officers to trained farmers and subsequently to other farmers in the community. The adoption decisions of trained farmers are expected to inspire their untrained peers to also take on new practices. In this chapter, therefore, we zoom in on the potential spillover effects from the targeted and trained farmers to non-targeted farmers.

5.2.2 Research design

This study implemented the following interventions between March 2023 and June 2024:

- Training (AES) in line with the EWS-KT standard approach as described above.
- Certification: Training certificates were given to farmers who successfully completed a practical test. Farmers who attended at least 3 out of the 5 training sessions per season, so at least 6 in total, could opt to take a test about the sessions in which they participated. The certificates were awarded during a public ceremony, formally recognizing recipients' newly acquired skills in the presence of their community members.

EWS-KT selected 150 communities in Kano (80) and Kaduna (70) as the target communities for the study. More specifically, these communities were selected across eight local government areas (LGAs): Kubau, Kudan, Makarfi, and Soba in Kaduna state; and Dawakin Kudu, Dawakin Tofa,

strategic location for irrigation, free from waterlogging, with proper drainage and accessibility. Additionally, they must hold a position of influence within the community, such as a village or sub-village leader, chieftain, religious leader, or an active member of a farmer group specialising in vegetable cultivation. Strong communication skills, both in speech and writing, are also essential. Furthermore, demo hosts should exhibit personal attributes such as a commitment to learning and implementing new knowledge, a willingness to take risks and build relationships, and openness to innovation and adoption of introduced GAPs. Demo hosts receive free supply of farm inputs (seeds and other materials) as incentives during the training period.

Minjibir and Rimin Gado in Kano state (see Figure 5.1 for study location visual). These communities were randomly assigned to three groups:

- Treatment arm 1 'Training-only': farmers only receive standardized AES training.
- Treatment arm 2 'Certification': farmers receive AES training and are certified during a public ceremony in their community.
- Control: farmers receive neither training nor certification.

Treatment was randomized at the community level as we aimed to measure within community spillover effects.

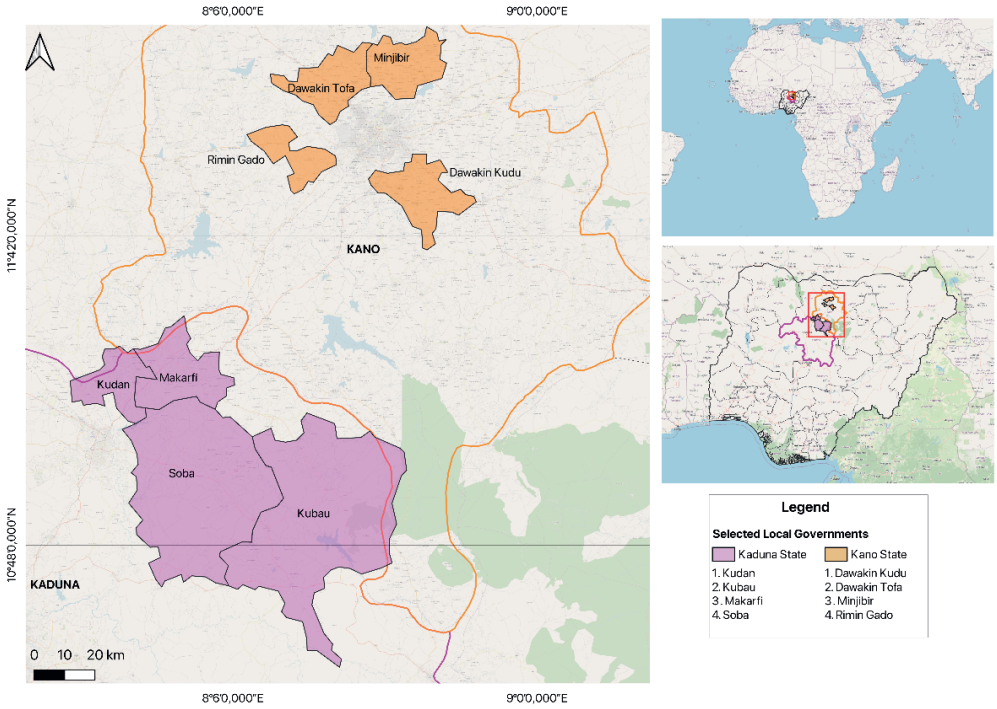


Figure 5.1: Geographical location of study LGAs, states, and country

5.2.3 Data collection, sample description, and attrition analysis

A total of 1,494 farmers who were not directly targeted by the programme (non-targeted farmers) were sampled for this study. In all treated communities (102), we randomly selected nine non-targeted farmers. In control communities (48), we randomly selected 12 non-targeted farmers. Survey data was collected in two rounds: a baseline (August–October 2023) and an endline (November–December 2024). The endline survey was conducted after the agricultural season following project completion allowing time for farmers to make adoption decisions. During the baseline, we surveyed 1,549 non-targeted farmers at baseline, distributed across three study groups: 495 farmers in the training-only group, 459 farmers in the certification group, and 595 farmers in the control group. At endline, we retained 1,290 non-targeted farmers (83% of baseline sample), with 400 farmers in the training-only group, 394 farmers in the certification group, and 496 farmers

in the control group. Both baseline and endline surveys used the same structured household questionnaire to collect data on household composition, farming activities, food security, and empowerment outcomes. To minimize misinterpretation and translation errors, the questionnaire was translated into the local language (Hausa), ensuring clarity and ease of administration by enumerators. Data collection was conducted using online platforms: KoboCollect for the baseline and ODKCollect for the endline survey. Baseline questions and format were maintained. Finally, data cleaning and analysis were performed using Stata statistical software.

5.2.4 Definition of outcome variables

We examined the programme effects using outcome indicators grouped into three main categories: vegetable production, adoption of quality seed, and adoption of good agricultural practices (GAPs). Vegetable production was captured as an indicator equal to one if the respondent cultivated any vegetables during the last farming year. Next, we captured adoption of quality seed using two binary outcomes: whether the farmer used vegetable seed of improved varieties, and whether the farmer used government-certified vegetable seed. Lastly, adoption of GAPs was measured along two margins. First, we considered a minimum threshold of the GAPs which we expected farmers to adopt through an indicator measuring whether farmers adopted at least five of the ten GAPs promoted. Second, we considered the intensity of adoption through the total number of GAPs adopted out of the ten. The promoted practices were transplanting, crop rotation, shade houses, staking, trellising, mulching, thinning, pruning, the production and application of biopesticides (e.g., neem oil), and record keeping. In Table 5.1, these indicators are defined per category.

Table 5.1: Outcome variables

Outcome category	Variables	Definition
Vegetable production	Share of farmers that cultivated vegetables	Dummy (1=if cultivated vegetables)
Adoption of quality seed	Share of farmers that bought improved vegetable seed varieties	Dummy (1=if used improved varieties for cultivated vegetables)
	Share of farmers that bought government-certified vegetable seeds	Dummy (1=if used government-certified seeds for cultivated vegetables)
Adoption of GAPs	Share of farmers that adopted at least 5 GAPs	Dummy (1=if used 5 or more GAPs for cultivated vegetables)
	Total number of GAPs adopted	Number of GAPs used (Max = 10)

5.2.5 Attrition analysis

Attrition between baseline and endline was 17% of the baseline sample. The main reason for attrition was migration. Due to insecurity issues, farmers were constantly moving with their families across states in northern Nigeria in search of stability. Unfortunately, long-term residence in the community was not a sampling criterion, so these 'travelling farmers' were included in the baseline. In addition, some respondents found temporary residence outside the village due to urban employment or travelled and did not return during the survey period. We attempted scheduling phone-based interviews, but that was futile due to unreachable numbers and poor

connectivity. A few respondents dropped from the sample because they died between baseline and endline. Finally, a number of targeted farmers were wrongly classified at baseline as non-targeted farmers, so we dropped them and corrected for this in our panel dataset.

We examined attrition through balance tests using eight baseline characteristics and five baseline outcomes and found only a few variables significantly different. A simple t-test was used to evaluate if farmers' socioeconomic characteristics and key agricultural production variables were similar across treatment and control arms. Comparing the combined treatment group and the control group, households in the two treatment groups who attrited appeared more likely to have a household member in a farmer group ($p<0.05$) and to be married ($p<0.10$). Attrited households in the training-only group were more likely to have a household member in a farmer group ($p<0.05$) compared to households in the control group. There were also more males in attrited households in the certification group compared to those in the control group ($p<0.10$). Comparing the two treatment groups, attrited farmers in the certification group were more likely to cultivate vegetables ($p<0.05$) compared to attrited farmers in training-only group. These findings suggest minimal bias due to attrition (see Appendix 5.2-5.5 for details).

5.2.6 Balance test

The baseline balance test gives information on the balance among the baseline characteristics and outcomes in our sample, given the random assignment of communities into treatment and control groups. Like the attrition analysis, simple t-tests were performed to check for any differences. Appendix 6 presents the balance test between the farmers in two treatment communities (AES-only and certification) and the control communities. Overall, only a few imbalances were observed across the 13 socioeconomic characteristics and outcomes tested, suggesting a good balance in treatment assignment. Households in control communities were more likely to be married ($p<0.01$); have a higher household dependency ratio and own more acreage of parcels ($p<0.05$); and had older respondents ($p<0.10$). Appendix 5.7 compares the farmers in the two treatment groups (training-only, and training-plus-certification). Again, no statistical differences were observed among the main outcome indicators and only a few socioeconomic characteristics were statistically significant. Results showed that households in the certification group were more likely to have male farmers than those in training-only groups ($p<0.05$), while households in training-only groups were more likely to have a member in a farmer group ($p<0.01$). Similarly, no significant difference across main outcomes and only a few imbalances among socioeconomic characteristics were obtained when comparing the training-only with the control group (Appendix 5.8) and the certification with the control group (Appendix 5.9). In conclusion, we found imbalances only among a couple of socioeconomic characteristics, which we then controlled for in our regression analyses. Overall, therefore, the random assignment of farmers to the treatment and control groups resulted in a good balance.

5.3 Empirical specification

Given the randomized controlled trial (RCT) design of the intervention, we estimate the intent-to-treat (ITT) effects of residing in a community assigned to treatment using ordinary least squares (OLS). Standard errors arere clustered at the community level to account for intra-community

correlation. Regressions follow an Analysis of Covariance (ANCOVA) specification, controlling for baseline value of the outcome. This approach typically improves statistical power and is a common practice in field experiments (McKenzie, 2012).

First, we examine the extent of technology dissemination by comparing adoption levels among non-targeted farmers in treatment communities (both training-only and certification) with those in control communities. If spillover effects are present, non-targeted farmers in treatment communities should exhibit higher levels of technology adoption and vegetable production than those in control communities. We capture this comparison using the general treatment dummy TT.

$$Y_{lci} = \beta_0 + \beta_1 \mathrm{TT}_{lc} + \beta_2 X_{lci} + \beta_3 Y^0_{lci} + \theta_l + \varepsilon_{lci} \quad \ldots\ldots\ldots\ldots\ldots\ldots 1$$

Here, Y_{ci} is the vector of outcomes for household *i* in community *c*, *TT* is a dummy variable that takes the value of 1 to indicate that the household lived in a community that received either training-only or certification treatment, and 0 otherwise. *X* is a vector of controls (age of respondents, total household size, household dependency ratio, education level of respondents, sex of respondent, marital status, having a household member in a farmer group, and total size of land owned in acres), θ_l are LGA fixed effects, and Y^0 is the baseline outcome. Standard errors ε are clustered at the community level. Here, β_1 is the parameter of interest, reflecting additional technology adoption by non-targeted farmers in treatment communities.

Second, we assess the potential enhancement of spillover effects in communities where trained farmers were certified during a public ceremony in comparison to the training-only and control communities. We capture this effect by adding the certification treatment dummy TC.

$$Y_{lci} = \beta'_0 + \beta'_1 \mathrm{TT}_{lc} + \beta'_2 \mathrm{TC}_{lc} + \beta'_3 X_{lci} + \beta'_4 Y^0_{lci} + \theta_l + \varepsilon_{lci} \quad \ldots\ldots\ldots\ldots\ldots\ldots 2$$

Here, β'_2 reflects the additional effect of public certification on technology adoption spillovers, while β'_1 captures the training-only effect.

5.4 Results

5.4.1 Summary statistics

Table 5.2 describes the baseline data for the full sample, organized by socioeconomic characteristics, outcome categories, and the use of other agricultural inputs.

Table 5.2: Descriptive statistics for the full sample using baseline data and grouped into socioeconomic characteristics and outcome categories (N=1290)

Variable	Mean	Std. Dev.	Min	Max
Socioeconomic characteristics				
Respondent's sex (1=male)	.921	.270	0	1
Respondent's age (years)	37.019	11.414	18	70
Respondent's education (1= > primary)	.471	.499	0	1
Household size	9.703	5.601	1	30
Household dependency ratio	.430	.211	0	1
Household member in farm group (1= ≥ 1)	.440	.497	0	1
Married (1=yes)	.498	.500	0	1
Total acreage of parcels owned (acres)	2.436	2.19	0	22.23
Vegetable production				
Farmer cultivated vegs (1=yes)	.340	.474	0	1
Adoption of quality seed				
Farmer used improved veg. variety (1=yes)	.043	.204	0	1
Farmer used govt-cert veg. seeds (1=yes)	.042	.200	0	1
Adoption of GAPs				
Applied 5 or more GAP (1=yes)	.036	.186	0	1
Total GAPs applied (count)	1.582	1.573	0	10

The sample consisted of 1,290 non-targeted farmers who were predominantly male (92%). On average, farmers were in their late thirties, indicating an active farming age. Farmers showed similar low education levels, with only approximately 47% having completed education beyond the primary level. Household sizes were relatively large (10 persons per household), while the household dependency ratio was 43%, meaning dependents were close to the working-age population in number. On average, only 44% of the sample reported having at least one member in a farming group and only half of the sample were married (50%). As for landholding, farmers owned small but non-negligible farms with an average of 2.4 and a maximum of 22 acres. Approximately 34% of farmers reported cultivating vegetables, with only about 4% using vegetable seed of improved varieties, as well as using government-certified vegetable seeds. These values suggest that there was a low use of quality vegetable seeds by vegetable farmers at baseline. Lastly, in terms of technology adoption, baseline use of the introduced technologies was low. Only 4% of farmers applied five or more GAPs, with an average of two GAPs applied per farmer for general farming (out of the 10 taught).

5.4.2 Main results

Pooled treatment effects

Table 5.3 reports the pooled treatment effect on vegetable cultivation, the use of quality seeds, and GAP adoption outcomes.

Table 5.3: Pooled treatment effects on vegetable cultivation, the use of quality seeds, and GAPs adoption

Variables	(1) Farmer cultivated vegetables	(2) Farmer used improved veg. seed variety	(3) Farmer used govt-cert. veg. seeds	(4) Applied 5 or more GAPs	(5) Total GAPs applied
Panel A: Without controls					
Treatment	0.012	0.002	0.011	0.006	-0.046
	(0.035)	(0.018)	(0.018)	(0.015)	(0.093)
Constant	0.377***	0.030	0.033*	0.068*	2.531***
	(0.090)	(0.019)	(0.020)	(0.037)	(0.185)
R^2	0.075	0.034	0.033	0.006	0.055
Panel B: With controls					
Treatment	0.027	0.016	0.026	0.012	-0.009
	(0.035)	(0.016)	(0.016)	(0.015)	(0.085)
Constant	0.284***	-0.006	0.008	0.043	1.704***
	(0.104)	(0.042)	(0.043)	(0.051)	(0.283)
R^2	0.098	0.056	0.055	0.020	0.111
Control mean	**.292**	**.073**	**.073**	**.071**	**2.379**
Control SD	**.455**	**.260**	**.260**	**.256**	**1.356**
Observations	**1,290**	**1,290**	**1,290**	**1,290**	**1,290**

All regressions include control for the baseline value of the outcome and LGA fixed effect. Control mean and SD are calculated using the control group for each endline outcome. Robust standard errors in parentheses, clustered at the community level. *** p<0.01, ** p<0.05, * p<0.1.

Relative to the control group averages, the point estimates for treatment communities appear positive and sizeable for four of the five outcomes estimated. However, across all five outcomes assessed, the pooled treatment effects are imprecisely estimated and none of the effects is statistically significant. Focusing on the specifications with household-level controls (Panel B), Table 5.3 suggests a potential increase of 2.7 percentage points (pp) in the share of farmers cultivating vegetables, which is equivalent to 9% of the control mean. In addition, living in a treatment community is associated with a 1.6 pp increase in the share of farmers using improved vegetables and a 2.6 pp increase in the share of farmers using government-certified seeds. Though modest in absolute terms, these potential effects are substantial compared to the control means, amounting to increases of 22% and 36%. Similarly, the point estimate for treatment community effects on the adoption of five or more GAPs corresponds to a 1.2 pp increase, equivalent to a potential 17% rise relative to the control mean, although the point estimate for the total number of GAPs adopted is close to zero. Hence, the direction and magnitude of the estimates indicate potentially meaningful spillover effects, but the statistical uncertainty is high.

Disaggregated treatment effects: Training and certification

In Table 5.4, we examine the additional effect of the certification treatment. The regressions test whether public certification influenced technology adoption among non-targeted farmers relative to training-only communities, as hypothesised. They provide no robust statistical evidence that either training or certification generated spillover effects on vegetable cultivation, use of quality seed, or the adoption of GAPs.

Table 5.4: Disaggregated treatment effects on vegetable cultivation, use of quality seeds, and GAPs adoption

Variables	(1) Farmer cultivated vegetables	(2) Farmer used improved veg. seed varieties	(3) Farmer used govt-cert. veg. seeds	(4) Applied 5 or more GAPs	(5) Total GAPs applied
Panel A: Without controls					
Training	-0.028	-0.003	0.003	-0.000	-0.103
	(0.043)	(0.024)	(0.023)	(0.019)	(0.122)
Certification	0.080*	0.010	0.017	0.013	0.114
	(0.046)	(0.024)	(0.024)	(0.021)	(0.137)
Constant	0.380***	0.030	0.034*	0.068*	2.535***
	(0.094)	(0.019)	(0.020)	(0.037)	(0.190)
R^2	0.080	0.034	0.034	0.006	0.056
Wald test p-value: TT+TC=0	0.215	0.708	0.326	0.470	0.921
Panel B: With controls					
Training	0.000	0.013	0.019	0.008	0.001
	(0.041)	(0.023)	(0.022)	(0.020)	(0.101)
Certification	0.054	0.008	0.013	0.008	-0.020
	(0.046)	(0.025)	(0.025)	(0.022)	(0.117)
Constant	0.289***	-0.005	0.009	0.043	1.702***
	(0.104)	(0.043)	(0.044)	(0.050)	(0.282)
R^2	0.100	0.056	0.056	0.020	0.111
Wald test p-value: TT+TC=0	0.197	0.259	0.085	0.373	0.857
Control mean	**.292**	**.073**	**.073**	**.071**	**2.379**
Control SD	**.455**	**.260**	**.260**	**.256**	**1.356**
Observations	**1,290**	**1,290**	**1,290**	**1,290**	**1,290**

TT=Training-only vs control and certification arms and TC=Certification vs control and training-only arms. All regressions include control for the baseline value of the outcome and LGA fixed effect. Control mean and SD are calculated using the control group for each endline outcome. Robust standard errors in parentheses, clustered at the community level. *** p<0.01, ** p<0.05, * p<0.1.

That said, the point estimates suggest non-negligible differences between the training-only and the certification group, signalling the potential of the certification treatment. The training treatment is not associated with a change in the share of farmers cultivating vegetables (0.000), while the certification treatment is associated with a 5.4 pp increase (18% increase from the control mean). In fact, in the specification without controls, certification corresponds to an increase in the share of farmers cultivating vegetables by 8 percentage points ($p<0.1$). Regarding the adoption of quality seed, the point estimates for the use of improved varieties suggest a potential increase of 1.3 pp in training communities and an additional 0.8 pp in certification communities (18% and 11% increases, respectively, relative to a control mean of 0.073), while the use of government-certified seed corresponds to an increase of 1.9 pp and 1.3 pp, respectively (26% and 18% increases relative to the control mean). The point estimates for the adoption of at least five GAPs suggest a potential rise of 0.8 pp in training communities (11% increase relative to control) and an additional 0.8 pp in certification communities. The point estimates on the total number of GAPs adopted are practically zero for both treatments. Yet all these coefficients are imprecisely estimated and not statistically significant.

As the point estimates of the effects of training and certification were mostly both positive, we did an explorative analysis to check whether their combined effect was statistically significant. The p-values corresponding to the associated Wald tests are reported in Table 5.4. While most tests suggested null effects, we reject the null hypothesis that the combined effect of training and certification on the use of government certified seed is equal to zero ($p < 0.1$). This provides suggestive evidence that there are positive treatment effects of both interventions that are strong enough to be detected when assessed jointly.

5.5 Discussion

Our findings are relevant to diffusion and social learning theories that often assume peer interactions will transmit information and technologies from early to later adopters (Rogers, 1995), especially within social networks. Relative to control means, point estimates from the pooled treatment (Table 5.3) suggested potential increases of approximately 9% in vegetable cultivation, 22% in the use of improved varieties, 36% in the use of government-certified seeds, and 17% in the likelihood of adopting at least five GAPs. Yet, the effects are quite small in absolute terms and statistically insignificant. These results suggest that information diffusion from targeted to non-targeted farmers within communities is neither automatic nor guaranteed. This aligns with evidence that extension can benefit trained or lead farmers without diffusing to others. In Rwanda, Duflo et al. (2023) show that extension interventions relying on diffusion of agronomic practices through social networks may produce limited diffusion and can even generate negative spillover effects for untrained farmers. Similarly, Ragasa (2020) find that farmers' exposure to trained lead farmers had no average significant effect on technology awareness or adoption.

In addition, the results relate to works on signalling credibility and information frictions. The certification intervention was intended to signal 'expertise' in the community, thereby lowering information search friction. As theorised, if public certification operated as a demand-driven mechanism that signalled knowledge sources to strengthen information access, spillover effects should be stronger in certification communities in comparison to training-only communities. Our disaggregated estimates provided limited support for this hypothesis (Table 5.4). The point estimates for the additional effects of certification were all positive and in one case (vegetable cultivation) larger than the coefficients for the training effect (18% against 0% in training-only communities). However, these estimates were statistically insignificant with one exception. The Wald test indicated that there was a combined effect of the training and certification treatments on the use of government certified seed. This provides weak evidence that certification could strengthen the otherwise limited spillover effects of AES and that the bundling of training with other public recognition methods could produce more spillover effects than training alone. Moreover, it may reflect that the barrier to switch to seed with an external and verifiable quality marker is relatively low in comparison to adopting other, more complex, agricultural technologies.

There are at least four alternative explanations for the limited spillover effects reported here, beyond the possibility that non-targeted farmers were unaware of or uninterested in the promoted technologies. First, our design may have lacked sufficient statistical power to detect small spillover effects. As a result, modest diffusion effects below the minimum detectable threshold cannot be

ruled out. Second, even when non-targeted farmers observe peers adopting new practices, they may update their beliefs only gradually and delay experimentation. In such cases, a single production cycle may be insufficient to capture meaningful behavioural change. Second, while certification may have increased the visibility of trained farmers, this may have been too weak to overcome supply-side constraints to knowledge diffusion. Trained farmers may lack the incentives, time, or capacity to actively share information with others. If so, effective dissemination may require more than signalling competence and instead depend on complementary interventions, such as explicit information-sharing responsibilities or performance-based incentives (Balew et al., 2023; Emerick & Dar, 2021; BenYishay & Mobarak, 2019). Moreover, Shikuku et al. (2019) show that increased efforts on the supply side does not necessarily translate into increased adoption amongst peers. Third, certification may have had ambiguous or even adverse effects on demand for information. If public recognition functions as a status marker and introduces social distance, non-targeted farmers may become more reluctant to seek advice. Given that information exchange tends to occur more readily among socially similar individuals, such dynamics could impede diffusion rather than facilitate it (Conley & Udry, 2010; Takahashi et al., 2020).

Future research should examine spillover dynamics over longer time horizons to account for gradual learning and delayed adoption. In addition, experimental designs that explicitly address both supply- and demand-side constraints to information diffusion would help to disentangle the underlying mechanisms. On the supply side, this could involve strengthening incentives or formalizing the responsibilities of trained farmers as information providers. On the demand side, alternative signalling strategies that enhance credibility could be explored, assessing whether more formal and informal approaches have differential effects due to their potential to remove or reinforce social distance. Such approaches would offer a more nuanced test of whether, and under what conditions, AES can generate meaningful spillover effects beyond direct beneficiaries.

5.6 Conclusion

This study assesses whether a demand-driven social network diffusion approach, which was implemented as publicly certifying farmers to signal expertise, extended the reach of AES beyond directly targeted farmers. Using a RCT across 150 communities in Kano and Kaduna states in northern Nigeria, we compared a training-only arm, a training-plus-certification arm, and a control group, focusing on spillover outcomes among non-targeted farmers. Our study findings caution against relying on designs that focus on passive, network-based diffusion or a simple approach of expert recognition to encourage information dissemination. This does not imply that social learning or farmer certification are ineffective, but rather that diffusion may require complementary design elements. On the supply side, interventions may require stronger incentives for communication and designs that create more opportunities for interaction. On the demand side, diffusion may depend on mechanisms that better inform farmers and relax other constraints that hinder technology adoption.

Three limitations are important. First, spillover effects may require more time to materialize than the 1.5-year research period. Second, additional supply-side interventions may be needed to overcome broader learning barriers. Third, certification may have had an ambiguous effect on dissemination, encouraging certain farmers from seeking knowledge while discouraging others.

Future work could test stronger and clearer signals or integrated designs combining signalling with supply- and demand-side mechanisms to generate sustained diffusion beyond direct trainees. Third, our design may have been underpowered to detect small spillover effects. We therefore cannot rule out modest diffusion effects below the minimum detectable effect of our design, nor their potential economic relevance, particularly relative to the effects observed among direct trainees.

Appendix

Appendix 5.1: Deviations

Type of change	Adjustment
Outcome indicator	As the share of farmers growing vegetables in our sample is limited and the average number of vegetables cultivated per vegetable farmer is small, we decided to remove the percentage of vegetables grown with improved varieties as an outcome indicator.
Explorative analysis	We conduct Wald tests of linear combinations of the treatment coefficients (TT + TC = 0) to assess whether the combined effect of the two treatments is statistically different from zero. This allows us to account for the possibility that two individually small or imprecisely estimated effects may jointly amount to a meaningful and statistically significant effect.

Appendix 5.2: Baseline balance table – Comparing socioeconomic characteristics and outcomes between the training-only (TG1) and certification groups (TG2) versus control group (CG) for the attritted sample

Variable	(1) Control	(2) Pooled treatment	(3) Diff.(p-value)
Socioeconomic characteristics			
Respondent's sex (1=male)	0.869	0.931	0.063
	(0.339)	(0.254)	(0.118)
Respondent's age (years)	37.222	35.987	-1.235
	(11.601)	(10.072)	(0.417)
Respondent's education (1= > primary)	0.384	0.475	0.091
	(0.489)	(0.501)	(0.217)
Household size (count)	9.899	8.894	-1.005
	(5.471)	(5.447)	(0.188)
Household dependency ratio	0.428	0.447	0.020
	(0.204)	(0.217)	(0.434)
Household member in farm group (1= $\geq$ 1)	0.323	0.494	0.171**
	(0.470)	(0.502)	(0.015)
Married (1=yes)	0.697	0.550	-0.147*
	(0.462)	(0.499)	(0.079)
Total acreage of parcels owned (acres)	7.353	6.597	-0.756
	(7.590)	(8.065)	(0.554)
Vegetable production			
Share of farmers: cultivated vegs (1=yes)	0.303	0.262	-0.041
	(0.462)	(0.441)	(0.553)
Adoption of quality seeds			
Share farmers: used improved seed variety for vegs (1=yes)	0.051	0.044	-0.007
	(0.220)	(0.205)	(0.803)
Share farmers: used govt-cert veg seed (1=yes)	0.030	0.031	0.001
	(0.172)	(0.175)	(0.965)
Adoption of GAPs			
Applied 5 or more GAP (1=yes)	0.030	0.056	0.026
	(0.172)	(0.231)	(0.292)
Total GAPs applied (count)	1.465	1.550	0.085
	(1.335)	(1.624)	(0.674)
Observations	99	160	259

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG1+TG2 mean - CG mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 5.3: Baseline balance table – Comparing socioeconomic characteristic between the training-only group (TG1) and the certification group (TG2) for the attritted sample

Variable	(1) Training-only	(2) Certification	(3) Diff.(p-value)
Socioeconomic characteristics			
Respondent's sex (1=male)	0.916	0.954	0.038
	(0.279)	(0.211)	(0.416)
Respondent's age (years)	36.484	35.262	-1.223
	(10.265)	(9.816)	(0.457)
Respondent's education (1= > primary)	0.484	0.462	-0.023
	(0.502)	(0.502)	(0.802)
Household size (count)	8.916	8.862	-0.054
	(4.876)	(6.227)	(0.953)
Household dependency ratio	0.445	0.451	0.006
	(0.224)	(0.209)	(0.863)
Household member in farm group (1= $\geq$ 1)	0.537	0.431	-0.106
	(0.501)	(0.499)	(0.289)
Married (1=yes)	0.558	0.538	-0.019
	(0.499)	(0.502)	(0.865)
Total acreage of parcels owned (acres)	6.569	6.638	0.069
	(8.685)	(7.127)	(0.966)
Vegetable production			
Share of farmers: cultivated vegs (1=yes)	0.200	0.354	0.154**
	(0.402)	(0.482)	(0.029)
Adoption of quality seeds			
Share farmers: used improved seed variety for vegs (1=yes)	0.053	0.031	-0.022
	(0.224)	(0.174)	(0.485)
Share farmers: used govt-cert veg seed (1=yes)	0.032	0.031	-0.001
	(0.176)	(0.174)	(0.977)
Adoption of GAPs			
Applied 5 or more GAP (1=yes)	0.053	0.062	0.009
	(0.224)	(0.242)	(0.799)
Total GAPs applied (count)	1.411	1.754	0.343
	(1.512)	(1.768)	(0.154)
Observations	95	65	160

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG2 mean – TG1 mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 5.4: Baseline balance table – Comparing socioeconomic characteristics between the training-only group (TG1) and control group (CG) for the attritted sample

Variable	(1) Control	(2) Training-only	(3) Diff.(p-value)
Socioeconomic characteristics			
Respondent's sex (1=male)	0.869	0.916	0.047
	(0.339)	(0.279)	(0.302)
Respondent's age (years)	37.222	36.484	-0.738
	(11.601)	(10.265)	(0.667)
Respondent's education (1= > primary)	0.384	0.484	0.100
	(0.489)	(0.502)	(0.210)
Household size (count)	9.899	8.916	-0.983
	(5.471)	(4.876)	(0.220)
Household dependency ratio	0.428	0.445	0.017
	(0.204)	(0.224)	(0.553)
Household member in farm group (1= $\geq$ 1)	0.323	0.537	0.214**
	(0.470)	(0.501)	(0.011)
Married (1=yes)	0.697	0.558	-0.139
	(0.462)	(0.499)	(0.180)
Total acreage of parcels owned (acres)	7.353	6.569	-0.784
	(7.590)	(8.685)	(0.634)
Vegetable production			
Share of farmers: cultivated vegs (1=yes)	0.303	0.200	-0.103
	(0.462)	(0.402)	(0.173)
Adoption of quality seeds			
Share farmers: used improved seed variety for vegs (1=yes)	0.051	0.053	0.002
	(0.220)	(0.224)	(0.947)
Share farmers: used govt-cert veg seed (1=yes)	0.030	0.032	0.001
	(0.172)	(0.176)	(0.959)
Adoption of GAPs			
Applied 5 or more GAP (1=yes)	0.030	0.053	0.022
	(0.172)	(0.224)	(0.431)
Total GAPs applied (count)	1.465	1.411	-0.054
	(1.335)	(1.512)	(0.806)
Observations	99	65	194

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG1 mean – CG mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 5.5: Baseline balance table – Comparing socioeconomic characteristics between the certification group (TG2) and control group (CG) for the attritted sample

Variable	(1) Control	(2) Certification	(3) Diff.(p-value)
Socioeconomic characteristics			
Respondent's sex (1=male)	0.869	0.954	0.085*
	(0.339)	(0.211)	(0.072)
Respondent's age (years)	37.222	35.262	-1.961
	(11.601)	(9.816)	(0.260)
Respondent's education (1= > primary)	0.384	0.462	0.078
	(0.489)	(0.502)	(0.414)
Household size (count)	9.899	8.862	-1.037
	(5.471)	(6.227)	(0.301)
Household dependency ratio	0.428	0.451	0.023
	(0.204)	(0.209)	(0.472)
Household member in farm group (1= ≥ 1)	0.323	0.431	0.108
	(0.470)	(0.499)	(0.224)
Married (1=yes)	0.697	0.538	-0.159
	(0.462)	(0.502)	(0.104)
Total acreage of parcels owned (acres)	7.353	6.638	-0.714
	(7.590)	(7.127)	(0.583)
Vegetable production			
Share of farmers: cultivated vegs (1=yes)	0.303	0.354	0.051
	(0.462)	(0.482)	(0.502)
Adoption of quality seeds			
Share farmers: used improved seed variety for vegs (1=yes)	0.051	0.031	-0.020
	(0.220)	(0.174)	(0.519)
Share farmers: used govt-cert veg seed (1=yes)	0.030	0.031	0.000
	(0.172)	(0.174)	(0.986)
Adoption of GAPs			
Applied 5 or more GAP (1=yes)	0.030	0.062	0.031
	(0.172)	(0.242)	(0.336)
Total GAPs applied (count)	1.465	1.754	0.289
	(1.335)	(1.768)	(0.246)
Observations	99	65	164

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG2 mean – CG mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 5.6: Baseline balance table - Comparing between the training-only (TG1) and certification (TG2) groups versus control group (CG)

Variable	(1) Control	(2) Pooled treatment	(3) Diff.(p-value)
Socioeconomic characteristics			
Respondent's sex (1=male)	0.909	0.928	0.019
	(0.288)	(0.258)	(0.594)
Respondent's age (years)	38.012	36.399	-1.613*
	(11.232)	(11.490)	(0.071)
Respondent's education (1= > primary)	0.442	0.489	0.047
	(0.497)	(0.500)	(0.290)
Household size	9.851	9.611	-0.240
	(5.527)	(5.648)	(0.577)
Household dependency ratio	0.452	0.416	-0.036**
	(0.207)	(0.213)	(0.025)
Household member in farm group (1= > 1)	0.454	0.432	-0.022
	(0.498)	(0.496)	(0.652)
Married (1=yes)	0.623	0.419	-0.204***
	(0.485)	(0.494)	(0.005)
Total acreage of parcels owned (acres)	2.717	2.260	-0.457**
	(2.487)	(1.964)	(0.030)
Vegetable production			
Share of farmers: cultivated vegs (1=yes)	0.351	0.332	-0.018
	(0.478)	(0.471)	(0.668)
Adoption of quality seed			
Share farmers: used improved seed variety for vegs (1=yes)	0.038	0.047	0.008
	(0.192)	(0.211)	(0.565)
Share farmers: used govt-cert veg seed (1=yes)	0.042	0.042	-0.001
	(0.202)	(0.200)	(0.954)
Adoption of GAPs			
Total GAPs applied (count)	1.500	1.634	0.134
	(1.606)	(1.550)	(0.355)
Applied 5 or more GAP (1=yes)	0.032	0.038	0.006
	(0.177)	(0.191)	(0.705)
Observations	496	794	1,290

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG1+TG2 mean – CG mean (Col.2 – Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 5.7: Baseline balance table - Comparing between training-only group (TG1) with the certification group (TG2)

Variable	(1) Training-only	(2) Certification	(3) Diff.(p-value)
Socioeconomic characteristics			
Respondent's sex (1=male)	0.873	0.985	0.112**
	(0.334)	(0.123)	(0.011)
Respondent's age (years)	37.167	35.619	-1.548
	(11.672)	(11.262)	(0.147)
Respondent's education (1= > primary)	0.500	0.477	-0.023
	(0.501)	(0.500)	(0.651)
Household size	9.693	9.528	-0.165
	(5.432)	(5.865)	(0.728)
Household dependency ratio	0.413	0.420	0.007
	(0.212)	(0.213)	(0.699)
Household member in farm group (1= > 1)	0.517	0.345	-0.172***
	(0.500)	(0.476)	(0.002)
Married (1=yes)	0.417	0.421	0.004
	(0.494)	(0.494)	(0.963)
Total acreage of parcels owned (acres)	2.134	2.389	0.255
	(1.841)	(2.076)	(0.163)
Vegetable production			
Share of farmers: cultivated vegs (1=yes)	0.343	0.322	-0.020
	(0.475)	(0.468)	(0.698)
Adoption of quality seed			
Share of farmers: used improved seed variety for vegs (1=yes)	0.055	0.038	-0.017
	(0.228)	(0.192)	(0.398)
Share of farmers: used govt-cert veg seed (1=yes)	0.038	0.046	0.008
	(0.190)	(0.209)	(0.636)
Adoption of GAPs			
Total GAPs applied (count)	1.607	1.660	0.052
	(1.609)	(1.490)	(0.759)
Applied 5 or more GAP (1=yes)	0.038	0.038	0.001
	(0.190)	(0.192)	(0.973)
Observations	400	394	794

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG2 mean – TG1 mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 5.8: Baseline balance table - Comparing between the training-only group (TG1) versus control group (CG)

Variable	(1) Control	(2) Training-only	(3) Diff.(p-value)
Socioeconomic characteristics			
Respondent's sex (1=male)	0.909	0.873	-0.037
	(0.288)	(0.334)	(0.468)
Respondent's age (years)	38.012	37.167	-0.845
	(11.232)	(11.672)	(0.424)
Respondent's education (1= > primary)	0.442	0.500	0.058
	(0.497)	(0.501)	(0.236)
Household size	9.851	9.693	-0.158
	(5.527)	(5.432)	(0.745)
Household dependency ratio	0.452	0.413	-0.039**
	(0.207)	(0.212)	(0.027)
Household member in farm group (1= > 1)	0.454	0.517	0.064
	(0.498)	(0.500)	(0.228)
Married (1=yes)	0.623	0.417	-0.205**
	(0.485)	(0.494)	(0.015)
Total acreage of parcels owned (acres)	2.717	2.134	-0.583**
	(2.487)	(1.841)	(0.014)
Vegetable production			
Share of farmers: cultivated vegs (1=yes)	0.351	0.343	-0.008
	(0.478)	(0.475)	(0.871)
Adoption of quality seed			
Share of farmers: used improved seed variety for vegs (1=yes)	0.038	0.055	0.017
	(0.192)	(0.228)	(0.395)
Share of farmers: used govt-cert veg seed (1=yes)	0.042	0.038	-0.005
	(0.202)	(0.190)	(0.766)
Adoption of GAPs			
Total GAPs applied (count)	1.500	1.607	0.108
	(1.606)	(1.609)	(0.524)
Applied 5 or more GAP (1=yes)	0.032	0.038	0.005
	(0.177)	(0.190)	(0.740)
Observations	496	400	896

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG1 mean - CG mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.

Appendix 5.9: Baseline balance table - Comparing between the certification group (TG2) versus control group (CG)

Variable	(1) Control	(2) Certification	(3) Diff.(p-value)
Socioeconomic characteristics			
Respondent's sex (1=male)	0.909	0.985	0.075***
	(0.288)	(0.123)	(0.010)
Respondent's age (years)	38.012	35.619	-2.393**
	(11.232)	(11.262)	(0.020)
Respondent's education (1= > primary)	0.442	0.477	0.036
	(0.497)	(0.500)	(0.504)
Household size	9.851	9.528	-0.323
	(5.527)	(5.865)	(0.517)
Household dependency ratio	0.452	0.420	-0.032*
	(0.207)	(0.213)	(0.092)
Household member in farm group (1= > 1)	0.454	0.345	-0.108*
	(0.498)	(0.476)	(0.058)
Married (1=yes)	0.623	0.421	-0.202**
	(0.485)	(0.494)	(0.016)
Total acreage of parcels owned (acres)	2.717	2.389	-0.328
	(2.487)	(2.076)	(0.142)
Vegetable production			
Share of farmers: cultivated vegs (1=yes)	0.351	0.322	-0.028
	(0.478)	(0.468)	(0.562)
Adoption of quality seed			
Share of farmers: used improved seed variety for vegs (1=yes)	0.038	0.038	-0.000
	(0.192)	(0.192)	(0.988)
Share of farmers: used govt-cert veg seed (1=yes)	0.042	0.046	0.003
	(0.202)	(0.209)	(0.833)
Adoption of GAPs			
Total GAPs applied (count)	1.500	1.660	0.160
	(1.606)	(1.490)	(0.339)
Applied 5 or more GAP (1=yes)	0.032	0.038	0.006
	(0.177)	(0.192)	(0.745)
Observations	496	394	890

Notes: Robust standard errors clustered at the community level in parentheses. The difference in means is measured as TG2 mean - CG mean (Col.2 - Col.1). The significant indicators are * p<0.1, ** p<0.05, *** p<0.01.



6

Last-mile distribution of vegetable seed in northern Nigeria: perspectives of agrodealers and farmers on trust and seed quality

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Abstract

The circulation of low-quality agricultural inputs remains a persistent concern in sub-Saharan Africa, with important implications for farmer investment and market development. In vegetable seed systems, where private actors play a central role, information asymmetries and weak enforcement mechanisms create uncertainty about product quality at the point of sale. This article examines how trust operates at the last mile of vegetable seed distribution in northern Nigeria, focusing on how signals of seed quality shape farmers' sourcing decisions. It centres primarily on tomato, which is the dominant commercial vegetable crop. A qualitative research design was employed using framework analysis, drawing on focus group discussions with vegetable farmers and interviews with agrodealers. The findings showed that farmers relied on a combination of product signals (such as packaging, branding, and labelling) and agrodealer characteristics (including social capital, knowledge, shop outlook and accountability) when making purchasing decisions. Trust developed gradually through repeated interactions, and agrodealers played a broader role beyond input provision by offering credit, information, and tailored services. Overall, the results suggest that vegetable seed markets are not purely transactional but are shaped by social relationships and learning processes. Strengthening seed system performance therefore requires attention to the last mile of distribution, including supporting agrodealers in maintaining quality and reliability, as well as enhancing farmers' ability to interpret product signals.

6.1 Introduction

Agricultural development in sub-Saharan Africa (SSA) continues to lag, with the adoption of modern inputs remaining low and yield gaps high. These outcomes are shaped by a complex set of structural constraints, including limited access to information and credit, exposure to risk, and poorly functioning input and output markets (Suri and Udry, 2022). Within this context the circulation of low-quality agricultural inputs, including counterfeit products, represents a critical concern. Existing estimates have suggested that 15-50% of agricultural inputs available in SSA may be substandard or counterfeit (de Boef et al., 2019). Such products do not only generate direct income losses for farmers but also undermine trust in input markets, thereby discouraging investment in inputs.

Seed is an essential input in all crop production. Almekinders and Louwaars (1999) have distinguished four dimensions of seed quality: genetic, physiological, sanitary, and analytical. The genetic traits embodied in a seed largely determine the yield potential, stress tolerance, and the market qualities of a crop. Furthermore, attributes of the seed, such as germination capacity, seedling vigour, and the absence of seed-borne diseases, are critical for the development of healthy crops. Often the word "improved seed" is used for modern varieties (and hybrids) and "quality seed" for seed with high or controlled physiological, physical and sanitary quality. However, this distinction is not always made explicitly. Various types of poor-quality seed are present in agricultural input markets. De Boef et al. (2019) have made a distinction between diluted, expired, and counterfeit seed. These terms cover actions that wilfully or unknowingly affect the quality of the seed. Diluted seed refers to authentic seed that has been mixed with substandard material or other seed, while expired seed involves the sale of authentic seed beyond its recommended shelf life resulting in reduced germination and vigour. Counterfeit seed is misrepresented as a specific variety or brand despite not originating from the claimed source.

A key challenge is that farmers are unable to reliably distinguish between high- and low-quality seed at the point of sale (Bulte et al., 2025). There is information asymmetry as agrodealers possess more knowledge about the quality of their products than the farmers who purchase them (Kapoor and Kumar, 2021). As a result, markets for quality seed are imperfect, creating challenges for both farmers and agrodealers (Wiggins and Cromwell, 1995). On this market, farmers face the risk of buying low-quality seed, a problem that is only apparent after germination, when an entire growing season may be lost. Therefore, they must navigate the challenge of identifying quality seed and buying it at an affordable price. Agrodealers, in turn, face the challenge of anticipating farmer demand while managing costs related to inventory, storage, and potential wastage if seed remains unsold after the planting season (Wiggins and Cromwell, 1995; Willwerth et al., 2026). Moreover, agrodealers must credibly signal product quality to farmers in order to overcome uncertainty. These dynamics are likely the reason why Gharib et al. (2021) found that farmers are willing to pay a 15% premium for maize seed purchased directly from a seed company rather than an agrodealer.

Vegetable seed represents an interesting case when it comes to seed quality assurance. Vegetables have received less attention at the policy level as food security has been prioritized over nutrition security and accordingly, public investments in support of agricultural development have prioritized major food crops like maize (Nabuuma et al., 2022). The management of vegetable seed

supply has therefore been largely left to a combination of private sector actors. Private sector interest in the vegetable seed market is spurred by the high value of seed based on the high value of fresh vegetables and limited competition of farm-saved seed (Schreinemachers et al., 2021). This incentivizes vegetable seed companies to invest in market development and quality assurance (Ter Steeg and Louwaars, 2024). Meanwhile, these margins also fuel malpractice and fraudulent operations, which remain profitable as long as farmers are unable to distinguish between 'good' and 'bad' seed and the enforcement of regulations remains ineffective (de Boef et al., 2019; Keller and Csörgo, 2024).

The literature, largely focusing on staple crop seed, includes contesting views on seed quality assurance. Bold et al. (2017) have argued that farm input quality concerns are largely accurate. Others, however, have suggested that farmers tend to overestimate the severity of the issue (Hoel et al., 2024; Michelson et al., 2021). When the quality of inputs is indeed low, it remains unclear where the problems arise and whether there is malintent. Several authors have pointed to (unregistered) agrodealers or traders as suspects using practices such as mixing of quality seed with substandard seed, dressing grain with an artificial colour, and reusing packaging of seed companies (Bold et al., 2017; de Boef et al., 2019; Poku et al., 2018; Sisay et al., 2025). However, Michelson et al. (2023) have highlighted that there is little evidence regarding the cause of quality issues. Seed quality can also be affected by poor storage conditions or handling; for instance, seed viability goes down when seed bags are stored on the floor or touch fertilizer bags.

Either way, research indicates that trust plays an important role in purchasing decisions, especially for products like seed with an uncertain quality. In general terms, "trust is seen as an expression of security between partners when making an exchange" (Garbarino and Johnson, 1999). In retail marketing specifically, trust refers to "the consumer's confidence in a retailer's reliability and integrity" (Doney and Cannon, 1997). In marketing, sellers with quality products will attempt to send signals to convince buyers and these signals can take many forms including branding, labelling, pricing and warranties (Kirmani and Rao, 2000). Besides the product, the seller and retail environment also send signals, which influence consumer trust. Signals can help consumers form a perception of a product, but often they require prior knowledge (regarding the brand or label) to be deciphered (Javeed et al., 2022). Therefore, research indicates that trust is an important concept: trust, both in the product on offer, and in the seller.

The question arises; therefore, which strategies can effectively reduce uncertainty for farmers when purchasing vegetable seed. The most conventional approach involves quality assurance systems at the product level, but the results are inconclusive. In terms of packaging type, pouches and cans (or tins) are used for vegetables. The type of packaging as well as the sealing of the package are important as this impacts the longevity of the seed. However, there is little information about the perception of farmers of different packaging types. Gharib et al. (2021) found that trained farmers recognize compromised maize seed packaging with broken seals, while untrained farmers do not. They also found that quality labelling of maize seed increases farmer willingness to pay only when combined with an information treatment. However, Mastenbroek et al. (2021) did not find such effects on farmer demand for maize seed. Furthermore, farmers seem to recognize company brands, as Sperling and Boettiger (2013) have explained how seed companies try to enter markets early on with small packets, which is a long-term investment to build brand equity. Accordingly,

Rutsaert et al. (2024) found that farmers tend to choose an alternative maize variety of the same brand in case of an out-of-stock situation.

In addition to product-level guarantees, agrodealers can play an important role in building trust. Registered agrodealers are valued as reducing perceived risk, especially where counterfeit seed is common in the market (Poku et al., 2018). Kilwinger et al. (2020) have found that an improved banana variety offered is easier to sell when sold by a trusted vendor instead of an unknown channel. Rutsaert and Donovan (2020) have highlighted the added value of the information that the vendor can provide about new maize hybrids influencing the farmer's varietal choice. Dar et al. (2024) have shown that an information treatment targeting agrodealers can be more effective in raising farmer adoption of new rice varieties compared to a government extension approach. More innovative approaches are also emerging, such as platforms with farmer reviews of agrodealers, which improve the ability of agrodealers to signal leading to increased revenues as well as increased use of quality seed by farmers (Miehe et al., 2023).

This chapter focuses on last-mile distribution and quality assurance in vegetable seed markets in northern Nigeria with a particular focus on the perspectives of farmers and agrodealers. The focus is on tomato seed as this is one of the few crops for which a "large, stable markets exist" with farmers buying seed on a frequent basis (Ter Steeg and Louwaars, 2024). This paper contributes to the literature on vegetable seed systems by using qualitative methods to zoom in on last-mile distribution and more specifically the theme of seed quality seeking to identify signals that contribute to trust sent by the seller or product. We used qualitative methods to address the research question: how do product and agrodealer signals of seed quality shape farmer seed sourcing practices? Based on focus group discussions (FGDs) with farmers and interviews with agrodealers, we first describe the sourcing practices of farmers and agrodealers. Secondly, we identify different types of 'bad' seed and quality issues. Thirdly, we identify product and agrodealer signals that reduce uncertainty in farmer seed purchasing decisions. Shedding light on the last mile of seed distribution networks may help strengthen seed system performance by supporting agrodealers in maintaining quality and reliability, as well as enhancing farmers' ability to interpret quality signals.

6.2 Conceptual framework

This study builds on the literature on seed systems and information asymmetry. The FAO (2016) uses four indicators to evaluate the functioning of seed systems: availability, access, varietal suitability and quality. Seed availability is defined as whether or not seed is present in a geographical area. Seed access refers to the ability of farmers to access seed via financial or social resources. Varietal suitability refers to the extent to which there is a match with farmers' conditions and preferences. Finally, seed quality encompasses the dimensions mentioned in the previous section: genetic, physiological, sanitary, and analytical quality. Vegetable seed market systems in northern Nigeria face challenges related to all four dimensions. Firstly, vegetable seed availability is often unreliable in Nigeria due to weak distribution systems and poor coordination across the value chain. Moreover, large gaps exist between demand and supply of quality seed. Secondly, scarcity also reduces access as prices remain high and the affordability of quality (vegetable) seed for smallholders has been stressed as an issue (NASC and Seedan, 2020). Thirdly, suitability to local

conditions and consumer preferences is often still limited in the absence of locally bred and adapted vegetable varieties (Schreinemachers et al., 2021). Fourthly, seed quality issues have been widely documented in Nigeria, which suggests that diluting and counterfeiting remain persistent (NASC and Seedan, 2020). However, progress has been made introducing an electronic verification system and the private sector is content with the government's efforts (Mabaya et al., 2023). Therefore, besides trust factors, farmer seed sourcing decisions are also shaped by availability, access, suitability and quality. In this context, farmer seed sourcing decisions represent risk management strategies.

The literature on information asymmetry has identified signalling as a key strategy to reduce uncertainty in markets (Kirmani and Rao, 2000). 'Signals' act as proxies in the absence of direct information about product quality. Consumer 'knowledge' may be required to decipher certain signals, especially complex ones (Javeed et al., 2022). Moreover, the goal for a seller of quality products is to persuade the buyer to make at least one purchase so the buyer learns about the quality level leading to 'experience' (Kirmani and Rao, 2000). In the case of seed markets, farmers are unable to observe product quality at the point of purchase and hence, they must rely on signals, knowledge or experience. Trust can be understood as a positive expectation about an outcome despite the presence of uncertainty with signals providing a basis for assessing trustworthiness. Farmers may then express their (dis)trust through their purchasing behaviour.

We conceptualize farmer seed sourcing decisions as shaped by two distinct but interacting domains of trust: product-level trust and agrodealer-level trust. This distinction is based on the work of Kilwinger et al. (2020) focusing on the attributes of seed sources as opposed to the attributes of the seed itself. At the product level, farmers infer seed quality based on signals linked to product attributes, including packaging (e.g. cans or pouches, seal integrity) (Gharib et al., 2021), branding (Rutsaert et al., 2024) and labelling (expiry date, certification) (Bagamba et al., 2023; Atieno et al., 2023). At the agrodealer level, farmers rely on signals linked to the characteristics of the seller including shop characteristics, social capital, location, expertise and potential warranty arrangements (Dillon et al., 2025; Goeb et al., 2026). Importantly, there might be interaction effects meaning when product-level signals are strong, reliance on the agrodealer may decrease, and vice versa. We propose that farmers use knowledge and experience to interpret signals sent by seed products and agrodealers. Certain formal signals like 'labelling' may require more prior knowledge to decipher and other informal signals like 'friendliness' may require little deciphering but are less reliable. Together, product-level and agrodealer-level trust shape farmer purchasing decisions under uncertainty. Both forms of trust are embedded in a broader context of seed systems, which in the context of northern Nigeria are shaped by fluctuating availability, limited access, limited varietal suitability and uncertain quality.

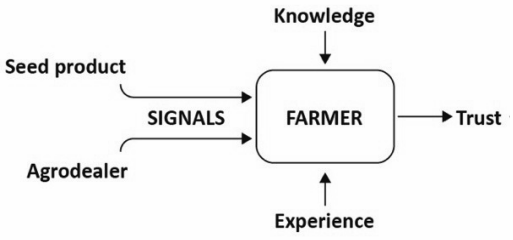


Figure 6.1: Conceptual framework in which farmer trust is shaped by signals sent by the seed product and agrodealer, knowledge and experiences

Guided by this conceptual framework (Figure 6.1), we examine how farmers navigate uncertainty when sourcing vegetable seed in northern Nigeria. From the farmer perspective, we investigate how farmers source vegetable seeds, which quality issues they encounter, how they interpret product-level signals of seed quality, and how they determine which agrodealers are reliable sellers. In doing so, we pay particular attention to how farmers use knowledge and experience to assess signals related to packaging, branding, pricing, and labelling, as well as seller characteristics such as shop attributes, social relations, and perceived expertise. From the agrodealer perspective, we examine how agrodealers source their seed, the challenges they face in running their businesses, and how they build and maintain relationships of trust with their customers. We consider the purchasing of seed to be an expression of trust in the product and/or the seller, and so with these questions we aim to shed light on how product-level and agrodealer-level trust interact in shaping farmer trust and seed sourcing decisions within a broader context of seed system constraints.

6.3 Methodology

Our study focused on the last-mile distribution of vegetable seed, studying the perspectives of farmers and agrodealers. It centred primarily on tomato, which is the dominant vegetable crop for which a stable seed market exists. Focus groups with farmers and structured interviews with agrodealers were used to collect qualitative data regarding these themes. All data were collected between June and July 2024.

6.3.1 Context

Vegetable production in Nigeria is promoted for its impact on nutrition, household income and employment (Adeoye, 2021). Kano and Kaduna states in northern Nigeria are vegetable production hubs supplying the Southern states (Plaisier, Sibomana et al., 2019). More than two-thirds of the population of Kano and Kaduna are involved in farming with the majority being smallholders cultivating around one to three hectares (Chiaka et al., 2022). The main vegetable crops are tomato, pepper and onion, which are primarily produced for commercial sale (Adeoye, 2021). Evidence on gender roles in vegetable production in northern Nigeria remains limited. One available study by Tafida and Ayuba (2020) suggests that commercial tomato production is predominantly undertaken by men reporting an 80:20 male-to-female distribution. This pattern is consistent with evidence from the region, where commercial vegetable production is often reported to be male dominated, while women commonly manage home gardens (Kramer and Trachtman, 2024).

Kaduna is the country's leading producer of tomatoes and onions, while Kano ranks closely behind (Plaisier, Dijkxhoorn et al., 2019). Average yields for crops such as tomatoes (around 6-10 t/ha) are similar to, or slightly below, regional benchmarks (Adeoye, 2021; Plaisier, Dijkxhoorn et al., 2019). Most farmers still use farm-saved seed or source their seed via informal channels without quality guarantees and so far, only about 2% of the farmers use hybrid seed (Plaisier, Dijkxhoorn et al., 2019). Vegetable seed sold through formal channels is imported from abroad (NASC and Seedan, 2020). The National Seed Road Map concludes that local vegetable seed companies still lack professionalism in "their practices in identifying varieties, (re-) packaging, promotion and marketing" (NASC and Seedan, 2020). A key constraint for the development of the agricultural sector is the circulation of substandard inputs and the lack of an effective system for monitoring

and quality assurance (IFPRI et al., 2024; Plaisier, Dijkxhoorn et al., 2019). It remains a challenge to monitor the quality of inputs as the distribution system is highly scattered and informal; it is estimated that there are about one to three million agrodealers in Nigeria (Steemers et al., 2022).

6.3.2 Sample structure

We employed purposive sampling to recruit participants. For our focus group discussions (FGDs) we selected smallholder farmers engaged in vegetable cultivation. All communities were deliberately selected at a sufficient distance from the city centres to ensure a broadly comparable rural context, while still allowing for variation in the degree of remoteness. We conducted FGDs in communities exposed to a seed sector development programme and similar communities without such training. The study was designed to explore differences in perceptions between these communities, rather than to estimate causal effects of the intervention. Both programmes combined farmer training on good agricultural practices with exposure to improved vegetable varieties, but differed in their duration, implementing partnerships and broader focus.

The HortiNigeria programme (2021–2025), funded by the Embassy of the Kingdom of the Netherlands, was led by IFDC in partnership with East-West Seed Knowledge Transfer Foundation (EWS-KT), KIT Royal Tropical Institute and Wageningen University & Research (WUR) (IFDC, 2026). Transforming Nigeria's Vegetable Markets (2019–2024), funded through the Netherlands Enterprise Agency (RVO), was implemented by a partnership including EWS-KT, Ahmadu Bello University, Solidaridad, WUR and the Kaduna State Ministry of Agriculture and Forestry (EWS-KT, 2026). In both programmes, EWS-KT was the organisation primarily responsible for the direct farmer training using a standardized module, which also covers seed selection. In Kano, FGDs were organized in Bunkure, Garko and Makoda. In Kaduna, the FGDs were organized in Anguwan Rafi, Kankanki and Zabi. HortNigeria was implemented in Anguwan Rafi, Garko and Zabi, 'Transforming Nigeria's Vegetable Markets' was implemented in Bunkure and no interventions were implemented in Kankanki and Makoda. Not all farmers part of the sample were necessarily trained as part of the program and potential differences may be partially explained by direct or indirect exposure.

The number of participants varied between 16-20 participants including both males and females. Taking into account the relatively high number of participants, experienced enumerators were recruited locally to facilitate the discussions. The team of enumerators and interpreters also provided feedback on the discussion guides to avoid any misunderstandings or controversy. All participants were encouraged to contribute to answering all discussion questions while not requiring anyone to answer. The number of females varied from 5-8 per group. For the FGDs, enumerators and extension officers jointly sensitised the community about the study. Community leaders then prepared a list of farmers, from which enumerators randomly selected potential participants. If a selected farmer was unavailable or unwilling to participate, another farmer from the list was invited as a replacement. In the treated communities, recruitment did not specifically target project beneficiaries; instead, farmers were drawn from the wider community.

For the individual interviews, we recruited agrodealers selling vegetable seed in both urban and more remote locations, aiming for diversity in terms of shop age and characteristics. Enumerators visited locations across 15 LGAs where they sought to interview as many agrodealers as feasible.

This resulted in variation in the number of agrodealers sampled per LGA ranging from 1 to 12. As female agrodealers were rare in the study area, gender balance was not a feasible sampling criterion. Some agrodealers may have served FGD participants, but this was not a sampling criterion. Additional information regarding the agrodealer sample can be found in Appendix 6.1. The structure of the two samples is outlined below in Table 6.1. All participants received a token of appreciation: farmers received refreshments and a family-sized detergent, while agrodealers received customised caps and T-shirts.

Table 6.1: Sample structure

Sample	Sample size	Method
Farmer sample	116 farmers Kaduna: 20, 16, 20 Kano: 20, 20, 20	6 focus group discussions
Agrodealer sample	78 agrodealers Kaduna: 32 Kano: 46	Structured interviews

6.3.3 Data collection

The farmer data were collected through six FGDs involving a total of 116 participants. Each discussion was facilitated by an experienced moderator who was supported by two interpreters. Discussions lasted approximately one hour, excluding the briefing, to help maintain participants' engagement. The FGDs were conducted in Hausa, recorded, and subsequently transcribed and translated into English by the interpreters. The FGDs began with questions on seed sourcing practices, including both individual preferences and common practices within the community. The discussion then progressed to farmers' perceptions of seed products and agrodealers, with questions about observed differences used to identify signals. Subsequently, the questions focused more specifically on how these perceptions shape decision-making processes, with the aim of identifying outcomes associated with trust. Questions about negative experiences were introduced after the more general discussion to avoid steering responses. The concept of trust itself was discussed only at the end to clarify how farmers understood and interpreted trust.

Agrodealer data were collected through structured interviews conducted by enumerators working in pairs. Interview questions were administered in a standardized manner, using the same wording and order across respondents. These interviews were also conducted in Hausa, recorded, and later transcribed and translated into English by the enumerator team. The agrodealer interviews began with questions about the respondent, the seed shop, its customer base, and the competitive environment. The questions then focused on factors agrodealers believed influenced farmers' choice of shop, allowing us to identify signals associated with the agrodealer. After a more general discussion, we also asked about the role of trust in customer relationships explicitly. Finally, the interviews shifted to product portfolios, sourcing practices, and agrodealers' observations of farmer product preferences to identify and verify signals associated with seed products.

The two authors were not present during fieldwork in Nigeria. The presence of foreign researchers was expected to influence the atmosphere during FGDs and interviews, potentially leading to more formal or constrained interactions. Instead, the study relied on close collaboration with two local team leaders in Kano and Kaduna. Enumerator training and briefings were conducted through online meetings during which a member of the research team was present. To ensure data quality, FGDs were independently transcribed and translated by two interpreters, allowing for comparison. Unclear or inconsistent passages were discussed with the interpreters, who revisited the original Hausa recordings and provided revised translations where necessary. Given the large number of agrodealer interviews, only one interpreter translated these interviews. All respondents provided informed consent prior to participation; the consent was oral. Ethical clearance for the study was obtained from the Wageningen University & Research (WUR) Research Ethics Committee on June 24, 2024 (Approval Number: 2024-097).

6.3.4 Data analysis

We applied framework analysis following its seven core stages of transcription, familiarisation, coding, developing a 'working' framework, applying the framework, charting the data into the framework matrix, and interpretation (Klingberg et al., 2024; Ritchie and Spencer, 2002). Framework analysis was preferred as it is valued for its descriptive and practical qualities analysing structured qualitative data (Klingberg et al., 2024). The first step was to transcribe the recordings of the FGDs and interviews. As explained, the transcribing of the FGDs and agrodealer interviews were handled by the enumerators as these were conducted in Hausa and then translated to English. After familiarization, the transcripts were coded all transcripts were coded by the first author and analysed using Atlas.ti. Having a single researcher conduct the coding ensured a consistent coding approach across the dataset, although we acknowledge the potential influence of researcher interpretation. An initial set of deductive codes was defined based on the research questions, while additional codes and themes were generated inductively when relevant issues emerged from the data. Related codes were subsequently consolidated into broader themes and subthemes and refined as the analysis progressed. Using these codes, two partially overlapping but distinct frameworks were developed for the two different types of data, which have been included in Appendix 6.2 and 6.3. The themes were organized into a matrix allowing for the systematic comparison of data extracts and notes in a spreadsheet structure. Some of the qualitative data could be quantified, but this was not possible for more nuanced and complex questions. The completed matrix was then used during the interpretation phase to identify the patterns and relationships that structured the results section. Given the challenge of conducting fieldwork in the study region, the sample size was determined in advance and was therefore not guided by data saturation or information power.

6.4 Results

6.4.1 Seed sourcing strategies

Agrodealers

Agrodealers relied on multiple sourcing channels, most commonly procuring seed directly from seed companies (reported by 61 agrodealers), but also (partly) sourcing through other agrodealers (27), wholesalers (19) or a combination of these. In northern Nigeria, Royal Blue Company

emerged as a key regional wholesaler, mentioned by 10 respondents. Across interviews, agrodealers consistently expressed a preference for sourcing directly from seed companies or from trusted wholesalers in order to ensure product genuineness. However, this preference was not always feasible, particularly in out-of-stock situations. Three agrodealers indicated that direct sourcing from seed companies was expensive. Further inquiry suggests that this was partly linked to the two-tiered registration system governing agrodealers in Nigeria. First, agrodealers are required to formally register their business with the government to obtain a certificate of incorporation, a process that can involve substantial upfront costs for smaller operators. Second, agrodealers may register with specific seed companies to become formal agents, which enables direct procurement but requires the submission of official documentation, including the government registration certificate. While most agrodealers emphasized sourcing certified seed, isolated cases of informal practices were also reported. One respondent indicated that he sold seed produced by farmers, and three others referred to cases in which other agrodealers sold extracted seed. Such practices have implications for seed quality and trust and are discussed further in Section 4.2.

Ensuring consistent seed availability remains a widespread challenge: 46 out of 78 agrodealers reported experiencing stock shortages. These situations were sometimes described as stressful, with farmers aiming to plant within narrow time windows and becoming frustrated when seed is unavailable. Agrodealers who did not report such challenges typically attributed this to timely ordering and forward planning. Among those facing shortages, 16 agrodealers noted that restocking could take time (usually between one and five days), and a common strategy to mitigate delays was trading with neighbouring agrodealers. In addition, six agrodealers reported instances of broader seed scarcity, where certain products were unavailable for a longer period. Several factors contributed to stock shortages. Seven agrodealers reported purchasing small quantities of seed to reduce the risk of unsold stock before expiry, often buying based on demand or pre-orders. Financial constraints further shaped stocking decisions: three agrodealers stated that they lack sufficient funds to maintain larger inventories, placing them at a disadvantage compared to better-capitalized competitors. Agrodealers with greater financial resources could stock larger quantities and a wider range of products, thereby gaining a competitive edge. In some cases, agrodealers could access credit from wholesalers or seed companies, but this typically depended on personal relationships and their financial standing.

Farmers

Farmers employed a range of seed sourcing strategies, including purchasing seed, saving seed, and combining both approaches. Across groups, purchasing seed each season emerged as the most commonly reported strategy, which might also be because of social desirability. Another frequently reported approach involved a combination of purchasing and saving seed using open-pollinated varieties. In this case, farmers purchase seed, extract and save seed from the harvested tomato if they are satisfied with the variety, and reuse it for one or more subsequent seasons. When farmers save seed from hybrids, they lose uniformity and yield advances, while the impact is very limited in case of open pollinated varieties. Exclusive reliance on seed saving was mentioned least often with few farmers reporting this as their primary sourcing strategy, which may reflect underreporting if farmers perceived saving as a less desirable response. In Makoda, there were two farmers who explained that they were disappointed in seed they bought and prefer to save their own seeds. A couple of farmers obtained seed from a trusted community member who saved seed.

A frequently mentioned reason why farmers kept to their current seed sourcing strategy was familiarity or experience, captured by statements like: "if we see that the seed is a good one then we continue using it" (Garko) or "we have tested it and know its performance" (Kankanki) or seed is simply "reliable" (Anguwan Rafi and Zabi). Another frequently mentioned reason was yield, which was sometimes linked to hybrid varieties. Agrodealers similarly identified familiarity as the most commonly reported reason for a variety's popularity followed by high yields.

The farmers who bought seed generally sourced their seed from agrodealers, while few mentioned buying seed from other farmers in their community. Across groups, farmers expressed mixed preferences regarding agrodealers: some preferred to purchase seed from agrodealers they knew, while others were willing to buy from any agrodealer. When buying seed from unknown agrodealers, farmers seemed to prefer to buy seed from agrodealers with permanent and registered shops, but for some, these shops were out of reach. The number of agrodealers varied greatly per community: there were communities without any agrodealer, but also communities with as many as 10. In remote communities, the absence of agrodealers forced farmers to travel long distances. Intermediaries seemed to play an important role in farmer seed sourcing strategies here. It seemed common for farmers to ask others to buy seed for them, especially for those in remote communities where there was no agrodealer. This practice was consistently reported in Zabi and Kankanki and was also commonly reported in Bunkure and Garko. This was reported as a convenient way to save money and time. In other communities where trust was placed in a specific agent, farmers gave their money to this person: "he knows where to get quality seeds more than we do" (Zabi). Also, there was a gender dimension as women sometimes relied on their husbands or others to purchase seeds due to distance and cultural constraints; this pattern was particularly pronounced in Garko. Consequently, female participants had fewer insights to share on agrodealer shops, as they visited them less frequently.

6.4.2 Seed quality issues

Seed quality was a concern for farmers and agrodealers. 20 agrodealers used words like 'genuine' (or authentic) to describe their products, and as explained, agrodealers stressed that they bought products directly from companies or wholesalers to ensure product quality. During the FGDs and interviews, the term 'repacked' seed sparked a wide variety of responses related to seed quality, which guided us towards defining different types of potentially poor-quality seed based on the provided answers. All these types of seed were sold by agrodealers on the vegetable seed market.

Repacked seed

14 agrodealers explained that some farmers cannot afford to buy a full pack of seed and hence, they helped their customers by repacking the seed themselves. One agrodealer explained that he refused to repack seed, but instead encouraged customers to share a pack of seed with their neighbours. This was confirmed by farmers who explained that within their community they might agree to purchase and share a package together. Based on these answers, repacked seed can be defined as quality seed (authentic product), which is repackaged into smaller packages and may lose quality aspects such as viability when not sold and used quickly. Repacked seed is thus not by definition poor quality seed, but it carries a risk for the farmer. One agrodealer explained: "Farmers need smaller portions, and I can ensure quality." From the answers, it seems like the practice is more common for staple crops (cow pea and maize), but it also occurs for vegetables.

Expired seed

73 agrodealers reported that they did not sell expired seed, defined as seed that had passed the expiration date stated on the package. For example, because their experience was that "it hardly germinates." One agrodealer explained that he burned expired seed. As a coping strategy, some agrodealers mentioned buying smaller quantities of seed to avoid situations in which their seed stock expired: "I purchase a small quantity, so it does not expire." Few agrodealers reported selling expired seed, but explained they inform farmers that the seed had expired offering it at a discounted price. The practice may have been underreported, as respondents may have been aware that selling expired seed is often prohibited. Some farmers explained that they checked the label of the seed package and expiry date before buying, especially when dealing with unknown agrodealers.

Counterfeit or 'fake' seed

No agrodealer in our sample explicitly reported selling counterfeit seed. However, this cannot be interpreted as evidence that the practice did not occur, because respondents may be reluctant to disclose illegal or reputation-damaging behaviour. For this reason, we only collected hearsay and anecdotal evidence about these practices. In terms of hearsay or anecdotal accounts, one story was shared about a tomato processing factory selling the extracted seed from fruits at a larger scale in pouches.

In terms of personal experience, one agrodealer explained that he sources and sells farm-saved seed: "The process is that I will go and buy saved seeds from farmers which they believe is good, then buy an empty package from the market, wash it, dress the seed with dressing chemicals, measure it and then put it in a see-through plastic bag before putting it into package, gum/seal it then finally, I sell it to the farmers." In this case, it was not entirely clear whether the agrodealer was completely transparent vis-à-vis his customers and took responsibility for possible quality issues of his product. It was also unclear what kind of empty package the agrodealer used: a reused branded or unbranded package. This could be regarded as 'fake' seed.

While some farmers willingly and knowingly bought repacked or farm-saved seed, they were concerned about buying counterfeit or 'fake' seed: "if you don't have good seed that means you will just lose the whole season" (Garko). Experiences with purchasing poor-quality inputs, including seed, fertilizer, and insecticides, were reported across all FGDs. Such experiences may be underreported if farmers feel embarrassed about having purchased poor-quality inputs. The accounts indicate that poor-quality inputs are a salient concern, but the study design does not permit estimation of their prevalence.

The experiences were described in different ways but what is similar is that the farmers only realized that they made a bad investment after planting and waiting (in vain) for the seed to germinate. The outcome was often a total loss of the season. "There was a year that someone came to us with a seed in a sack named Mai Damma, we bought the seed and planted it, but we end up getting nothing. Other farmers started making fun of the farmers that bought the seed" (Kankanki). In Garko, a farmer shared: "There was a time I bought tomato seed from Kano. I thought it was produced by a company. It produced small fruits, and I didn't enjoy tomato that year at all." Another farmer bought tomato seed, which after sowing turned out to be pepper seed:

"It was pepper and not the tomato I saw on the label and so that made me lose trust in agrodealers that I don't know" (Bunkure). In other cases, farmers reported bad experiences with other inputs like fertilizer mixed with sand, expired insecticides and ineffective pesticides.

Farmers reported that these instances fuelled distrust. Some said that they would never again buy a product from an agrodealer that once sold them bad products: "If he cheats me, he cheats himself" (Anguwan Rafi) or "If you buy fake, trust me, you will never go back to his place" (Garko). Some ended up either using their own seed instead of buying seed, or only buying agricultural inputs from known agrodealers with whom they have a personal relationship: "There was a time I went to town and bought a seed packet. After planting it, I encountered a huge loss that year because the seed was not a good one. And since then I promised myself never to buy from someone I don't know again" (Garko). Another farmer shared a similar story: "I bought seed once and I had a bad experience. I thought I bought the UTC variety, but after planting, I got a different result. So since then, I started saving seeds myself" (Makoda).

Origin of seed products

Based on the FGDs and interviews, we suggest the following value chains illustrating verified, reported and hypothesised distribution pathways for different types of products in different types of packaging originating from different sources (Figure 6.2). The value chains show a complex situation as authentic product can turn into expired product when sold after its expiration date, and an authentic product can be repacked in a compromised package. Moreover, an authentic (and repacked) product can be turned into a diluted product when adding sub-standard seed. Farm-saved seed can be a product in itself when it is openly sold by agrodealers in unbranded packages. However, it can also end up in different types of 'bad' products: a diluted product in a compromised package or a fake product when sold in a reused branded package. Agrodealers (black) and farmers (black or grey) primarily participate in the value chains illustrated by the thick lines. However, the findings suggested that agrodealers may sell seed originating from both formal and informal sources. While agrodealers in our sample did not report selling seed of unknown origin, farmer testimonies indicated that such practices occur among other agrodealers.

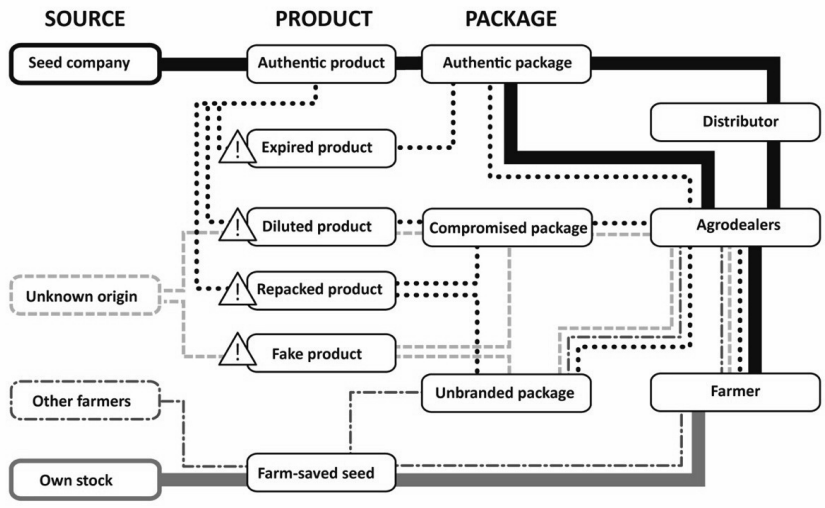


Figure 6.2: Representation of reported, perceived or hypothesised pathways of different seed types of varying quality sold by agrodealers showing the source, product, and packaging type. Value chains marked with exclamation marks indicate a risk to the farmer. Thick lines indicate transparency and managed quality expectation: these are verified pathways. The dotted lines indicate lower transparency or non-transparency and represent reported and hypothesised pathways. Amongst the dotted lines, the pathways for expired, repacked and farm-saved seed have been directly reported. The pathways for diluted and fake products are hypothesised and based on hearsay or second-hand accounts.

6.4.3 Indicators of trustworthiness: the product and the supplier

The data also provided insights regarding the ways in which farmers seek to estimate the quality of a product and trustworthiness of an agrodealer, and how agrodealers try to win the trust of farmers. A distinction can be made here between indicators of trustworthiness at the product level versus the agrodealer level. Below, we describe our findings regarding the signals sent by the product and by the agrodealer, which were associated with trust. At the product level, three features are central in supporting quality perception of the seeds: packaging type, branding and labelling. At the agrodealer level, social capital, product quality, expertise, pricing, credit, shop outlook, certification and accountability are central features. Figure 6.3 depicts the reported factors during the FGDs and interviews for both levels.

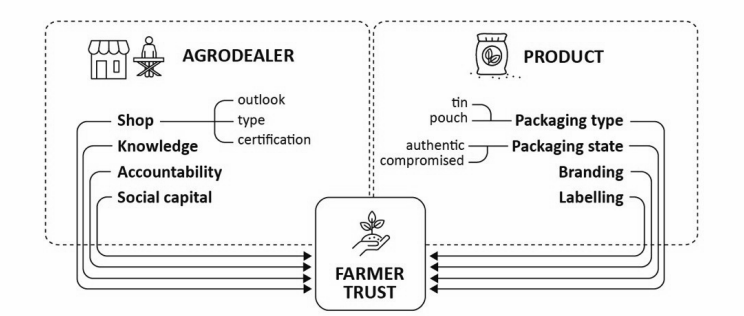


Figure 6.3: Agrodealer and product-level factors contributing to farmer trust.

6.4.3.1 Trust in the product

Packaging

On the Nigerian market for vegetable seed, we found two types of 'authentic' packaging: pouches (also called packets) and cans (or tins). Additionally, there were unbranded (see-through) pouches and 'fake' branded pouches, which are not from an actual existing brand. Vegetable seed sold in cans was generally trusted by farmers because this packaging type was perceived as the most secure. Both agrodealers and farmers mentioned either in a positive way that cans or tins were "genuine" or in a negative way that they could not be adulterated or "tampered with". Farmers also preferred cans because they offered a larger quantity for a lower price. 57 out of 78 agrodealers stated that the can was the most popular package type as farmers were familiar with it, the quantity was larger, and that storability of cans was considered more robust as the seed could not be eaten by rats or other animals. The importance of 'familiarity' indicates that farmer experience played an important role here.

There was a conflicting perception of pouches. Some farmers preferred the pouch because they associated this packaging type with hybrid (F1) seeds. Hybrids were deemed of a higher quality leading to higher yields. These farmers also expected the pouch to be more expensive than the can, which was in line with market prices. However, other farmers believed the pouch to be cheaper as they were focused on the quantity of seed inside. These farmers did not link the pouch with quality and could not distinguish between branded and unbranded pouches circulating in the market. One agrodealer even said: "Honestly, they should stop producing seeds in pouches or sachets because some people copy and adulterate it."

Branding

Branding also appeared to play an important role in building trust amongst farmers. Brand may relate to the company name or the variety: when a variety was common in the market and farmers had grown it for many years, they considered it a trusted brand. Some farmers explained that they only bought specific brands or varieties and in certain cases, they even remarked that the supplier did not matter: "I will buy as far as it is the same brand I know. The person selling is not my problem" (Bunkure). It may also create trust if an agrodealer sells a specific brand, as one farmer says: "What gives us confidence is […] the brands he sells" (Kankanki) or "I look at the shop if he has the logo of the company that I use" (Anguwan Rafi). Farmers explained that they trusted their own ability to check the product: "I can buy any EWS product because I know their products quite well now" (Zabi). Some agrodealers also referred to brands: "People trust the quality of their products" referring here to Jubaili specifically.

Labelling

Some farmers explained that they paid close attention to the labels of seed products. One farmer explained: "I have to check the product label to confirm the quality of the product. That's looking at the seed scratch code, expiring date, brand name and so on" (Kankanki). One reason farmers might check the label was to make sure that the product had not expired: "I will check the expiry date before buying" (Makoda). Farmers also looked for a contact address, which allowed them to reach out in case of issues: "When you check the product, you'll see the manufacturer's contact address. So, if there's any issue with the product, farmers can reach out to them directly" (Kankanki).

With packaging, branding, and labelling, it appears that knowledge and experience were both relevant as farmers used their knowledge to 'read' the product packaging and their experience with a brand to make a decision. If farmers felt sufficiently confident, the agrodealer might not matter much as their clients only focused on the products on offer. This was expressed in the previous statement, and by "The person selling is not my problem" (Bunkure). Other farmers shared similar views: "I am an experienced farmer, I know what to buy" (Anguwan Rafi) and "If I see the product I want, I will buy (it) even if I don't know the agrodealer" (Makoda).

6.4.3.2 Trust in the agrodealer

The data gave two main findings. Firstly, the agrodealers played a central role in fostering the trust that farmers required to make seed purchasing decisions. Building and maintaining trust is therefore a key objective for agrodealers operating in input markets. Secondly, there were

similarities and differences between the trust factors listed by farmers and agrodealers when explaining how trust is built.

Social capital

71 out of 78 agrodealers reported having repeat customers amongst whom some came back very often, and some of whom also sent other customers. This meant that farmers built up experience with a certain agrodealer allowing them to learn about product quality. Accordingly, farmers commonly reported purchasing products only from agrodealers they already knew. Moreover, 19 agrodealers also explained having personal relationships with some of their customers. One agrodealer explained: "I think the reason why they come to my shop is because we have been doing business for very long time. So, we have personal relationship with them." A couple of agrodealers even said customers had become "like family" to them. Similarly, some farmers seemed to feel a sense of loyalty towards agrodealers, one farmer stated that: "if you have a good relationship with an agrodealer, you see you cannot leave him and go to another person" (Garko) and "The agrodealer I get my inputs from has been there for me for more eight years now and he has never failed me. So, nothing will affect my decision as far as I am concerned" (Anguwan Rafi). Other farmers mostly seemed to feel a sense of security: "I can't play with my farming because what you sow is what you will reap, so I always go to the person I trust" (Anguwan Rafi) and "If I have a good relationship with him, I know he cannot cheat me" (Makoda). In addition to their own experiences, farmers also relied on recommendations from their peers, and 12 agrodealers reported receiving a substantial number of referrals.

Product quality

A primary factor underlying repeat purchases was the perceived quality of products offered by agrodealers. Product quality was the most frequently cited reason by agrodealers when explaining repeat purchasing by farmers, mentioned by 67 out of 78 respondents, and was also commonly emphasized in farmer FGDs. However, the notion of "product quality" reflected two distinct, yet related, dimensions. First, product quality referred to the attributes of specific seed types or brands, which generates trust at the product level. In this case, the type of products sold by an agrodealer made a farmer trust the seller. Second, product quality reflected trust in the agrodealer as a reliable supplier of quality inputs. Here, trust is built through repeated interactions and positive experiences over time. As one agrodealer noted, "They have tried us many times and we didn't fail them." Similarly, a farmer remarked: "I don't know the quality of the product unlike if it is someone I know" (Bunkure).

Expertise

Another key factor influencing farmers' choice of agrodealer was perceived expertise. This was highlighted by 52 out of 78 agrodealers, who emphasized their ability to provide advice and viewed these consultations as an important driver of repeat purchasing: "If they benefit from the advice, they come back." Many agrodealers were farmers themselves, and some operated demonstration plots that customers could visit. Several even described their role as comparable to that of extension agents. As one agrodealer explained: "An agrodealer now is just like an extension agent. Some farmers see agrodealers for advice 10 times without seeing an extension agent once. So, if an agrodealer does not have the knowledge of farming, there will be a problem for the farmer." Some farmers, in turn, actively assessed agrodealer expertise. They reported testing agrodealers'

knowledge directly; as one respondent noted, "I ask him a few questions that I think all agrodealers should know the answer to. If he answers correctly, then I know whether to patronize him or not" (Anguwan Rafi). Others relied on observable cues: "I first look at how the agrodealer is, does he look like sensible person that can solve a farmer's problem when presented with one? Because most times you meet the salesperson in the shop instead of the agrodealer" (Zabi). In some cases, farmers also associated age or maturity with experience and knowledge.

Pricing

Prices or discounts were mentioned by a majority of the agrodealers (46), while they were mentioned by relatively few farmers. Agrodealers explained that they might offer "fair" (also "friendly", "cheap" or "low") prices or discounts, especially to their loyal customers. Farmers seemed to consider pricing a more ambiguous signal when it came to trust; prices should definitely not be too high, but they should also not be too low. These dynamics were mostly clear during the FGD in Kankanki. During this discussion, the farmers explained that they had to travel a longer distance to obtain a discount: "We prefer going to Jos because of the discount. Sometimes we get a discount of 2000 Naira or more per can." However, later, another farmer said: "Unless a farmer is negligent or acting out of selfish interest, they shouldn't fall victim. After all, how can someone expect to buy a product worth 6,000 Naira for just 3,000 Naira."

Credit

Credit was mentioned by 33 agrodealers as a reason why their customers returned. Agrodealers stressed that credit was only provided to trusted customers, hence it seems beneficial for farmers to have a more longstanding relationship with an agrodealer. One agrodealer also said he provides credit "without mocking." Only a few farmers reported credit as a reason to buy from an agrodealer: "The reason why I buy from one person is because if it is time to sow my seed and I don't have money, this agrodealer used to give me seeds on credit" (Garko).

Shop outlook

The physical appearance and characteristics of the shop were also perceived as important indicators of an agrodealer's reliability and financial stability. A well-stocked, orderly shop offering a diverse range of products tended to increase farmers' confidence. While only few agrodealers mentioned product variety or stock availability as a reason for repeat purchasing, farmers in Anguwan Rafi, Kankanki, and Zabi explicitly identified these features as contributing to trust. For example, one farmer from Zabi noted: "What I first observe is the content of his shop whether it is well stocked or looks scanty," while a farmer from Kankanki stated: "What we look at is the diversity and quantity of products in the shop. It shows us that he has invested in the business." Some farmers further associated well-stocked shops with a larger customer base, reinforcing perceptions of reliability. Some agrodealers argued that larger businesses have a competitive advantage due to greater access to capital which enables them to purchase inputs in bulk and pay for seed upfront, thereby avoiding credit-related costs. However, farmers themselves did not mention such price differences during the discussions.

Certification

While agrodealers themselves did not explicitly refer to certification as a source of trust, farmers did. In Anguwan Rafi, Bunkure, and Zabi, several farmers reported a preference for purchasing

from registered or certified agrodealers. As noted earlier, agrodealers can formally register their businesses with the government and may obtain certificates through participation in training programmes. Farmers appeared to interpret such certification as a signal of accountability or as an indication of the agrodealer's knowledge and training. As one farmer from Zabi explained: "Agrodealers that underwent some trainings tend to hang or showcase their certificate in their shops. Whenever I see that, I feel confident that the agrodealer is a good one." Although agrodealers did not mention certification when discussing trust, they did display their certificates in their shops.

Accountability

Accountability was mentioned during four of the FGDs as an important factor, which contributed to trust. There are several ways through which accountability could be established. Firstly, farmers in Bunkure, Kankanki and Makoda stressed the ability to be able to return to a shop if something was wrong. This ability depended on geographic distance, which meant closer is better: "Distance is what I consider because if there is problem after using it, I can be able to go back to the agrodealer" (Makoda). Also, this depended on the shop being permanent or stationary. One agrodealer explained: "We are stationary, so they can come if there is a problem" and a farmer said: "He has to have a permanent shop so that whenever something comes up, I can reach out to him" (Kankanki). Secondly, accountability signals included the dealer offering a refund or compensation, or agreeing beforehand that the product could be returned if issues arose. For instance, one farmer explained he remained loyal to a dealer after the dealer compensated him for an ineffective product by giving a replacement and adjusting the price. One agrodealer explained that he saved the empty seed containers when a complaint was filed, so that he could report this to the seed company.

6.4.4 Exploratory differences by intervention exposure

Exploratory differences in farmers' seed purchasing decisions were observed primarily at the product level rather than at the supplier level in intervention-exposed communities. Purchasing seed was commonly reported in three of the four targeted communities: Anguwan Rafi, Bunkure, and Zabi. In these communities, farmers placed strong emphasis on branding and collectively praised the varieties of a specific seed company. Packaged seed (pouches or packets) was frequently associated with hybrid varieties and higher yields, as reflected in statements such as: "I mostly buy the packet ones because I believe they are hybrid varieties and grow better" (Bunkure). Garko constituted an exception: although it was also targeted by an intervention, farmers' seed sourcing practices remained mixed, with continued reliance on both purchased and farm-saved seed. In contrast, farmers in the two non-targeted communities (Kankanki and Makoda) predominantly relied on farm-saved seed. In these communities, preferences were oriented toward farm-saved seed and seed sold in cans, justified by familiarity, quantity and yields: "We prefer the can because we are familiar with it, there is much inside, and it gives us a good yield" (Makoda). By contrast, farmers in intervention-exposed communities did not report different perceptions of agrodealers than farmers in other communities. Across targeted and non-targeted communities, farmers differed in their preference for purchasing from known versus unknown agrodealers. The only notable distinction was that references to agrodealer certification or registration were made exclusively by farmers in targeted communities. Overall, these findings suggest that differences

were more apparent in farmers' choices related to product attributes, while their evaluations of agrodealer characteristics showed less variation across intervention exposure.

6.6 Discussion

The findings outlined in the results section are context-specific with primary relevance to tomato seed markets in northern Nigeria. Still, these findings regarding farmer and agrodealer perspectives can help shed light on the last mile of vegetable seed distribution in other situations. In this section we will reflect on important findings regarding seed sourcing practices, perceived seed-quality issues, and trust linking these to the four indicators of seed system functioning: availability, access, varietal suitability and quality (FAO, 2016). Also, we will draw lessons learned from these findings which may help improve farmer access to quality seed as well as trust in the quality of seed.

Availability and access emerged as connected in farmers' and agrodealers' accounts with periods of scarcity. Periods of seed scarcity appeared to increase the likelihood that farmers and agrodealers deviated from their preferred value chains either because of availability or based on price. In these moments, farmers are especially vulnerable: they are impatient because they need seed to plant their crops and need to make a considerable upfront investment at the start of the growing season. Out-of-stock situations seemed to result amongst other factors from the credit limitations of agrodealers as well as their risk-aversion to end up with expired seed. Several authors have pointed at the inverse relationship: agrodealers in Nigeria often provide credit to farmers, while it is highly unlikely that they receive credit from their supplier (Steemers at al., 2022; Dillon et al., 2025). Improved credit provision for agrodealers by their suppliers or agricultural banks, may contribute to removing this constraint.

Varietal suitability was reflected in farmers' preferences for farm-saved seed or particular commercial varieties or brands. In this case, suitability was often associated with expected yield. One characteristic that was not frequently mentioned by respondents but may have fuelled demand for hybrid tomato varieties in the treatment communities is their extended shelf life. This trait is highly relevant in the Nigerian context, where tomatoes are transported from the north to the south (Plaisier, Sibomana et al., 2019). Furthermore, it is important to distinguish varietal suitability from familiarity: familiarity does not necessarily imply that a variety is the most suitable option available. Limited varietal turnover has been discussed extensively for crops such as maize (Rutsaert and Donovan, 2020), and similar dynamics may also influence varietal choice in tomato.

Quality was a recurring concern. Ideally, agrodealers are trustworthy and knowledgeable, both about the correct way to handle the products in their shop, and the best way to use these products at the farm. However, the farmers' responses in our research show that not all agrodealers rated positively on these criteria. For obvious reasons, none of the agrodealers in our sample reported selling poor quality seed, but farmers did report bad experiences with agrodealers. Several agrodealers did share that they sold repacked seed, which was considered a service provided to farmers who cannot afford a whole package. Repacking can affact seed quality when not handled properly or could lead to (un)intentional mixture with other seeds or matter. One solution could be to promote collective buying by groups of farmers, which was mentioned by both farmers and agrodealers, which allows agrodealers to reduce seed quality risks for farmers up to the point of

sale. Another solution would be for seed companies to offer smaller packages. However, these may come at a higher cost per unit and therefore do not necessarily improve affordability.

Importantly, the findings also give insight how trust interacts with these four dimensions. Our results indicate that trust between agrodealers and farmers is earned over time. Agrodealers earn the trust of farmers by selling quality products again and again. It seems beneficial for farmers to have a longstanding relationship with an agrodealer because of advice, security, discounts or credit. Also, these findings show that informal dynamics play a role in formal seed systems, which are shaped by social relationships. Strengthened partnerships with agrodealers may be an effective strategy for seed companies to expand their markets. For farmers, agrodealers are not only input suppliers but also serve as extension agents and financiers. This resonates with the observation made by Dillon et al. (2025) that agrodealers have an increasingly important role in rural development, particularly as support for public extension systems has declined.

The data further suggest that product-level trust may, for some farmers, reduce the importance of agrodealer-level trust. Farmers with a strong focus on brand and variety appeared less concerned about the agrodealer selling the product. There seemed to be different levels of seed product 'literacy' referring to the focus of farmers on signals send by the packaging, branding, and labelling of products. This raises the possibility that confidence in a recognised brand or product may partly substitute for trust in the agrodealer for some farmers. However, farmers may use different combinations of product- and agrodealer-level signals depending on experience, literacy and previous interactions. Overall, the findings suggest that seed companies may themselves can play an important role in generating trust in their products, which is consistent with the importance of labelling, packaging and branding highlighted by Gharib et al. (2021), Sperling and Boettiger (2013) and Bagamba et al. (2023).

This study has several limitations. First, the purposive and geographically limited sampling method limits the generalisability of the findings. Moreover, the study relied on self-reported experiences and may therefore be subject to recall and social-desirability bias. As seed quality was not independently tested, the findings reflect perceived quality issues rather than allowing us to estimate their prevalence. The FGDs were conducted in Hausa without the authors present and subsequently transcribed and translated into English, which may have resulted in a loss of nuance. Comparisons across intervention groups are exploratory and should not be interpreted causally. Finally, the study design did not support systematic gender-disaggregated analysis, and observed differences should therefore also be regarded as exploratory. Taking these limitations into account, the study still highlights several avenues for future research on seed quality, trust and sourcing practices.

6.7 Conclusions

Our study confirms, firstly, that agrodealers constitute a critical link in vegetable seed value chains. Seed quality cannot be reliably assessed prior to planting and hence, farmer purchasing decisions are shaped not only by product price and availability but also by trust; both in the quality of the seed itself and in the agrodealer supplying it. Secondly, our study documents reported experiences of seed-quality problems in vegetable seed markets, while also demonstrating that defining 'bad-

quality seed' is certainly not straightforward. Thirdly, our study shows that trust is built gradually through repeated interactions and can erode rapidly. It operates at multiple levels, including trust in a specific product or brand and trust in the agrodealer as a supplier. These forms of trust may interact in different ways across farmers. While seed system interventions seem to increase farmers' willingness to buy seed and enhance brand awareness, they do not diminish farmers' reliance on agrodealer-related trust. Together, these findings suggest that vegetable seed companies and development practitioners seeking to strengthen seed markets may benefit from greater downstream engagement, either by supporting agrodealers in maintaining seed quality and providing services or by investing in brand equity, packaging, and the 'seed literacy' of farmers.

Appendix

Appendix 6.1: Summary Statistics Agrodealer Sample

Agrodealer sample					
Variable	Obs	Mean	Std. Dev.	Min	Max
State (Kano = 1, Kaduna = 0)	78	0.59	0.50	0.00	1.00
LGA Tofa (yes = 1)	78	0.04	0.19	0.00	1.00
LGA Dawakin Tofa (yes = 1)	78	0.05	0.22	0.00	1.00
LGA Makarfi (yes = 1)	78	0.06	0.25	0.00	1.00
LGA Ikara (yes = 1)	78	0.05	0.22	0.00	1.00
LGA Kumbotso (yes = 1)	78	0.04	0.19	0.00	1.00
LGA Dambatta (yes = 1)	78	0.03	0.16	0.00	1.00
LGA Wudil (yes = 1)	78	0.01	0.11	0.00	1.00
LGA Garko (yes = 1)	78	0.03	0.16	0.00	1.00
LGA Sabon Gari (yes = 1)	78	0.14	0.35	0.00	1.00
LGA Garun Malam (yes = 1)	78	0.09	0.29	0.00	1.00
LGA Dawakin Kudu (yes = 1)	78	0.03	0.16	0.00	1.00
LGA Zaria (yes = 1)	78	0.15	0.36	0.00	1.00
LGA Rano (yes = 1)	78	0.09	0.29	0.00	1.00
LGA Bunkure (yes = 1)	78	0.06	0.25	0.00	1.00
LGA Kura (yes = 1)	78	0.13	0.34	0.00	1.00
Gender (male = 1)	78	0.04	0.19	0.00	1.00
Age	78	36.68	12.01	15.00	70.00
Role of agrodealer: Shop owner (yes = 1)	78	0.62	0.49	0.00	1.00
Role of agrodealer: Manager (yes = 1)	78	0.15	0.36	0.00	1.00
Role of agrodealer: Salesperson (yes = 1)	78	0.23	0.42	0.00	1.00
Number of years of shop existence	78	13.03	10.95	0.50	45.00

Appendix 6.2: Thematic Framework Farmers

Theme	Sub-themes	Key concepts
Seed sourcing and access	Seed sourcing strategies	The practice of buying seed, saving seed or alternating between buying seed and saving seed.
	Role of intermediaries	Reliance on agents, extension workers, husbands, or fellow farmers to purchase seeds, especially among women.
	Accessibility	Number of local agrodealers in a community determines access and low-density forces farmers to travel longer distances.
	Collective buying	A popular solution for communities with no or few agrodealers is to buy collectively to save on transport costs.
Market risks and bad quality seed	Input adulteration	Experiences with counterfeit seeds and other 'fake' inputs.
	Repacked seed	Experiences with repacked seed and the advantages and disadvantages of repacked seeds.
	Expired products	Experiences with expired inputs.
	Risk aversion	Strategies to avoid buying bad inputs – mostly the avoidance of unknown agrodealers.
Products	Packaging	Three types of packaging: can, branded pouch, and see-through bag.
	Branded can	The can is preferred for familiarity, quantity, and difficulty of adulteration.
	Branded pouch	The pouch is preferred as it is associated with hybrid seeds (F1) and high yield. Also, farmers recognize the brand.
	Pricing	Diverse perceptions of price: some cite the pouch as the most expensive because of quality, others the can because of quantity.
Farmer-Agrodealer Dynamics and Trustworthiness	Relationship characterization	Relationships are characterized by loyalty built on reliability and services like offering advice and credit.
	Personal-level indicators of trust	Signals used to assess trustworthiness: behaviour (good interaction), appearance, religiousness and knowledge.
	Shop-level indicators of trust	Signals to assess trustworthiness are permanent shop or location, the shop size, stock and certification.
	Unknown dealers	Farmers refuse to buy from unknown dealers due to the high risk or accept the risk after checking the product/dealer signals.
	Guarantees	Farmers require or agrodealers offer an agreement that the product can be returned or refunded if problems arise.

Appendix 6.3: Thematic Framework Agrodealers

Theme	Sub-themes	Key concepts
Seed sourcing and access	Upstream sourcing practices	Agrodealers ensure genuineness by sourcing directly from seed companies or by using trusted wholesalers.
	Managing stock	Out-of-Stock (OOS) is a common challenge. Dealers mitigate OOS by referring customers to or purchasing from other agrodealers.
Market risks and bad quality seed	Condemning repacking	Most agrodealers refuse to sell repacked seed, viewing it as a practice that will break customer trust. Mostly, they cannot guarantee the quality of repacked products.
	Justifying repacking	A minority of agrodealers admit to repacking, mostly justifying the practice because farmers cannot afford the full original package.
	Expired products	Dealers actively manage expiry dates, confirming they usually sell before the product expires.
Product-level trust signals	Brand loyalty	The most popular brands cited are Griffaton and Jubailee. EWS varieties are also popular, cited for yield, quality, and profitability.
	Security	The can is the most preferred packaging type as farmers believe it is sealed, secured, and cannot be adulterated.
	Familiarity	Farmers also prefer the can because they are used to this type of packaging. It has been around for a long time.
	Affordability	The can is often preferred for larger quantity and sometimes referred to as cheaper than the pouch. Conversely, the Pouch is preferred by a minority because it is smaller, more affordable.
Farmer-Agrodealer Dynamics and Trustworthiness	Customer loyalty	Customer loyalty is primarily built on two factors: selling genuine/quality products and providing advice and knowledge to customers. Dealers may also use discounts and offer credit to trusted, long-term customers.
	Dealer trust signals	Dealers establish trustworthiness by being truthful in their interactions and advice. They ensure product quality by only buying from companies and by testing new products on their own farm.
	Competition	Most dealers describe the environment as highly competitive based on price, quality, and the ability to stock variety. Dealers strive to win competition by offering the cheapest price or better service.
	Guarantees	Some dealers offer a refund or warranty if problems arise.



7

Signalling trustworthiness in agricultural input markets: experimental evidence from Nigeria

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Abstract

Agricultural input markets in low-income countries suffer from information asymmetries, causing "market-for-lemons" situations with poor-quality dominating the market. To reduce information asymmetries, agrodealers may wish to signal their trustworthiness. We studied signalling in input markets in Nigeria and found that farmers used agrodealer observables to distinguish between trustworthy and not-so trustworthy sellers, and that perceived trustworthiness correlated with actual agrodealer trustworthiness as measured in a mystery shopper experiment. Overall, the study suggests that farmer perception of the trustworthiness of agrodealers does not affect farmer willingness-to-pay for seed, which is consistent with the outcomes of germination and vigour tests showing that seed is of high quality across agrodealer types.

* Ethical clearance for this study was obtained via the Wageningen University & Research (WUR) Research Ethics Committee (Approval Number: 2024-097). All respondents provided informed consent prior to their participation. The study's pre-analysis plan was registered in the American Economic Association's RCT Registry prior to finalizing data collection in October 2024 (ID: AEARCTR-0014532). Stellamaris Aju and Emily ter Steeg share first authorship.

7.1 Introduction

The share of African agriculture in GDP is much smaller than its share in employment, so farmers are less productive than workers in other sectors (e.g., Gollin et al. 2014). African smallholders are also less productive than farmers elsewhere in the world, and productivity growth rates remain lagging (Suri and Udry 2022). One important explanation is the low adoption rate of modern inputs (e.g., Thiele et al., 2021), caused by a variety of reasons. These include failure of financial markets such as lack of access to credit or insurance (e.g. Karlan et al., 2014; Belissa et al., 2019), behavioural factors (e.g. Kremer et al., 2019), the absence of competitive and transparent output markets that reward quality (e.g. Anissa et al., 2021; Bold et al., 2022), inefficient tenancy arrangements and the lack of land titles (e.g. Goldstein and Udry, 2008; Burchardi et al., 2019) and various informational inefficiencies (e.g., Jack, 2013, Oliva et al. 2020, Fishman et al. 2022, Bonan et al. 2025). Many farmers lack information about input markets, and don't know how to appropriately use modern inputs.

A related issue is the existence of informational asymmetries between sellers and buyers on the market for inputs, possibly resulting in *moral hazard* (counterfeiting and adulteration by agrodealers) and *adverse selection* (honest agrodealers leaving the sector).[3] Fuelled in part by extensive media coverage, many African farmers believe that agrodealers offer low-quality inputs (African Fertilizer and Agribusiness Partnership [AFAP], 2024). It is not clear whether quality issues reflect malfeasance by agrodealers (Bold et al. 2017) or "poor storage and handling" along the value chain (Barriga and Fiala, 2020; Michelson et al., 2021, 2023).[4] Regardless, farmers may struggle to distinguish between low and high-quality inputs, and between *bona fide* and cheating agrodealers. This reduces farmers' willingness-to-pay (WTP) for inputs and discourages sustained adoption (Bulte et al. 2025). Nevertheless, agrodealers remain mostly absent in analyses of agricultural development. The literature overwhelmingly focuses on smallholders and is relatively silent on input markets and the important but underappreciated role of agrodealers (Dillon et al. 2025).

The main objective of this paper is threefold. First, we examine whether formal and informal quality signals help to attenuate asymmetric information problems in agricultural input markets. Formal signals include the packaging and labelling of inputs. If farmers perceive these signals as unreliable, they may also look for informal signals sent consciously or unconsciously by agrodealers about their trustworthiness (and competence). We evaluate how formal signals interact with informal signals. We explore how perceived trustworthiness co-varies with agrodealer observables ('signals' like age, body type and type of clothing) and underlying characteristics that are more difficult to observe (e.g. wealth, religiosity) called 'traits' in what follows. We explore whether farmers distinguish between more and less trustworthy agrodealers, and how perceived

[3] For evidence of the role of asymmetric information on the market for farm outputs, refer to Mitra et al. (2018).

[4] For example, Tjernstrom et al. (2017) found that 25% of hybrid maize seed in Kenya does not germinate, and Kilic et al. (2017) found that 25% of hybrid seed in Uganda is not of the advertised type (see also CPRA 2016). Ashour et al. (2019) studied herbicides and found that the average bottle is missing 15% of the active ingredient and 31 per cent of samples contain less than 75% of the ingredient advertised.

trustworthiness, signals and traits affect farmer WTP for inputs supplied by agrodealers.[5] Second, we analyse the relationship between actual seed quality and quality as perceived by farmers, evaluating to which extent farmers can accurately predict seed quality. Third, we establish how perceived trustworthiness of sellers correlates with agrodealer behaviour in two honesty tasks, which again speaks to the accuracy of farmer beliefs.

This chapter reports on our study, which combined a field experiment, mystery shopper approach, and two honesty tasks, using multiple samples of agrodealers and farmers. We assessed the perceived and real quality of two types of maize seed, and two types of tomato seed. Seed types varied along multiple dimensions, including the susceptibility of quality to agrodealer behaviour. For example, we used branded and unbranded maize seed. Unbranded maize seed is often repackaged and prone to dilution and counterfeiting, as well as quality loss due to improper handling. This is not the case for branded maize seed, packaged and sealed by the seed company. We also used branded tomato seed packaged in pouches (bags) and tins (cans), where tin-packaged seed are considered tamper-proof whilst pouches are not. We examined how WTP for these four types of seed correlates with 'appearances' of the supplying agrodealer. We asked farmers to evaluate photos of real (but unknown) agrodealers in terms of signals, traits, and trustworthiness. Perceived trustworthiness strongly correlated with agrodealer signals (such as body type, age, and type of clothing) and perceived traits (such as wealth, experience, and religiosity). Next, we auctioned off seed supplied by different agrodealers in a BDM setting, using both full-body photographs of real agrodealers and AI-generated images with amplified signals. We explored whether farmer WTP varied with trustworthiness, signals and traits, and whether this relation was mediated by tamper-proofness of the seed type. Subsequently, we evaluated real seed quality by conducting germination and "vigour" tests on seeds obtained from a small sample of traders. Finally, we revisited the agrodealers for a generic die-rolling experiment and tailored mystery shopper activity (regarding the price charged for insecticides). These honesty tasks acted as independent measures of the honesty of the agrodealer.

Our main results were as follows. First, farmers distinguished between trustworthy and not-so trustworthy sellers, and signals and traits explained part of the variation in trustworthiness of agrodealers in intuitive ways. Second, WTP for seed did not vary with trustworthiness, signals or traits of agrodealers. As expected, trustworthiness did not matter for 'tamper-proof' seeds (branded maize, tomato seed in tins). Indeed, if formal and informal quality signals are substitutes, then informal signals are unimportant for tamper-proof seed. However, and more surprisingly, farmer WTP for seed that is not tamper-proof also did not vary with seller characteristics. This finding was consistent with our third result, based on the outcomes of germination and vigour tests; actual seed quality did not vary much across sellers. In contrast to common beliefs, seed quality was uniformly good. Contributing to the literature on farmer beliefs and input quality (e.g., Ashour et al. 2019; Michelson et al. 2021, Hoel et al., 2024), we found that farmers' assessment of seed quality was consistent with actual quality. However, agrodealer trustworthiness mattered for other spheres of seller-buyer interaction. Our fourth result was that farmers' perceptions of

[5] This complements work by Michelson et al (2021) that highlighted how "product observables" (like discoloration and dirt) affected perceived product quality and demand.

agrodealer trustworthiness correlated with the honesty of agrodealers in a mystery shopper experiment. Agrodealers with low trustworthiness were more likely to try to 'cheat' uninformed farmers by overcharging for a low-quality chemical input.

This paper aims to contribute to two strands of the literature. First, our results are relevant for the literature on signalling in low-information contexts. In the presence of imperfect formal quality verification systems for certain agricultural inputs, agrodealers may try to signal their trustworthiness to prospective buyers. A small literature is emerging on signalling in low-income countries, including saving behaviour (Breza and Chandrasekhar, 2019), child marriage (Buchmann et al., 2023), child immunization (Karing, 2024), and household investments (Buchmann et al. 2025). Our paper is closest to that of Macchi, who studied access to financial services in Uganda; loan officers considered financial information provided by potential customers unreliable (e.g. unverified or incomplete) and relied on stereotypes to reduce uncertainty about applicants' ability to repay loans. Since obesity is a credible signal of wealth in Uganda, obese applicants received a higher rating and were more likely to obtain a loan. 'Investing' in body weight had material pay-offs for borrowers (Macchi, 2023). We have applied this idea to agricultural input markets and examined which other informational shortcuts are relevant for the seed market in Nigeria.

Second, our results are relevant to the literature on agricultural input markets. While a large literature has evaluated the incentives and constraints to adoption by smallholders, few papers have focused on the interaction between suppliers and farmers in agricultural input markets (Dillon et al. 2025, Macours 2019, Dar et al. 2024). Typically, input markets are crippled by high transport costs and remoteness (e.g., Rutsaert et al. 2021, Kumar et al. 2023, Aggarwal et al. 2024, 2025); search frictions (Bergquist et al. 2024); timing, commitment, and credit constraints (Dillon and Tomaselli 2025); and demand uncertainty, liquidity constraints, and unsupportive government regulation (Asante et al. 2021, Dillon et al., 2025). In this study we focus on asymmetric information between sellers and buyers (Bold et al. 2017, Bohr et al. 2024, Bulte et al. 2025). Agricultural inputs are a "credence good", and productivity depends on the interplay between multiple factors. It is difficult for farmers to learn about input quality by observing how crops develop (Bold et al. 2017; Hoel et al. 2024), which erodes incentives of agrodealers to invest in developing a reputation for selling high-quality inputs.[6] Reducing information asymmetries could increase input trading. In this vein, Miehe et al. (2023) created a platform for farmers to share experiences, Hsu and Wambugu (2024) trained farmers to distinguish between low and high quality seed, and Michelson et al. (2023) informed farmers about the quality of fertilizer for sale on local markets.[7] We contribute to this literature by examining the quality of maize and tomato seed

[6] This statement needs a qualification. The agricultural input market is characterized by very high turnover or drop-out and entry rates of agrodealers. Naugler et al. (2025) has shown that farmer beliefs of input quality improve as agrodealers exit the market (suggesting they expect low-quality suppliers to exit first). Farmers also mistrust the quality of inputs supplied by entrants relative to the quality of agrodealers they regularly visit. This suggests that some reputation building is possible for agrodealers.

[7] The literature is divided on whether information treatments affect adverse selection and moral hazard in a market setting. For example, Annan (2025) and Hasanain et al. (2023) have analysed, respectively, mobile money transactions (in Ghana) and artificial insemination and other veterinary services (in Pakistan). These studies documented moral hazard, and found that market transparency improves seller performance,

supplied by agrodealers in Nigeria, how this quality correlates with sellers' signals and buyers' perceptions of seller trustworthiness, and how perceptions matter for WTP.

The chapter is organized as follows. In section 2, we sketch a simple model of signalling trustworthiness in a market with asymmetric information and show how the value of informal signals varies with the quality of formal quality assurance that is in place. In section 3, we introduce relevant characteristics of seed markets in northern Nigeria and outline the design of our field experiment. In section 4, we summarize and discuss our data. Section 5 contains our results, including correlations between perceived trustworthiness and observables; between trustworthiness, signals, traits and WTP; and finally, between WTP and actual seed quality. In section 6, we discuss results of an auxiliary analysis where we obtain independent measures of agrodealer honesty, and test whether these correlate with farmer beliefs. Section 7 concludes.

7.2 Theoretical considerations

We follow Spence (2002) and present a simple model capturing how agrodealers can signal their type to farmers in a context of imperfect formal quality verification. Assume there are two types of agrodealers; trustworthy ones who never cheat and carefully handle inputs, and not-so trustworthy ones who dilute high-quality inputs with lower-quality inputs, offer counterfeit products, or reduce input quality by not carefully handling them. Slightly abusing terminology, we refer to not-so trustworthy agrodealers as 'cheaters' in what follows. Assume that the value of an input sold by a cheater is v_1, and the value of an input sold by a trustworthy agrodealer is v_2 (with $v_2 > v_1$). The share of cheaters on the market for inputs is known and given by α. If product quality is observable, signalling is unimportant and farmers always pay the right price. The same is true if agrodealer trustworthiness would somehow be perfectly observable.

If product quality and trustworthiness are not observable, farmers do not know what they are buying and base their WTP on the average quality of inputs in the market (Akerlof, 1970). The average value of inputs on a competitive market is given by $v_2 - \alpha(v_2 - v_1)$, which may drive trustworthy agrodealers from the market. If so, average input quality and WTP go down over time and only cheaters remain in equilibrium. However, this dismal scenario does not need to play out if trustworthy sellers can credibly signal their type to prospective buyers.

Suppose that trustworthiness correlates with a 'bundle of traits' that can be unpacked, such as experience, wealth, and religiosity. For example, mature traders have learned how to resist the temptation to cheat, rich traders can afford to forego short-term gains from cheating, and religious people don't cheat because "God is watching". Traits are not directly observable, but agrodealers

increasing value-for-money for buyers and demand by buyers. See also Klein et al. (2016) who demonstratede that improving the transparency for buyers on an anonymous product market (eBay) reduced moral hazard but had no effect on sellers exiting the market. In contrast, Hsu and Wambugu (2024) helped smallholder farmers to identify high-quality seed on local markets (based on subtle observable "quality markers") and found that transparency causes low-quality sellers to exit the market.

can make an effort to 'signal' them to farmers. Experience can be signalled by age,[8] wealth can be signalled by obesity (see Macchi 2023) or expensive clothing and shoes, and religiosity can be signalled by traditional clothing or a prayer mark. The cost of signalling is negatively correlated with the underlying trait. Gaining body weight or buying expensive clothes is less costly for wealthy people, for whom the opportunity cost of expenditure is lower. Devout Muslims are most comfortable wearing traditional clothes and do not risk of being accused of hypocrisy when wearing them. Assume that investments in these signals can be aggregated to produce an index score, *I*. The unit cost for cheaters to produce one unit of *I* is β and the unit cost for trustworthy agrodealers is γ, with $\beta > \gamma$.

An equilibrium exists where (i) agrodealers make rational decisions about how much to invest in signalling trustworthiness (given costs and benefits of signalling) and (ii) farmers have accurate expectations about the relationship between the signal and the agrodealer's trustworthiness. Since farmer beliefs determine their WTP for inputs at different levels of perceived trustworthiness, agrodealer willingness to invest in signalling is endogenously determined. The result is a relationship between trustworthiness and signalling, where farmer beliefs are self-confirming (Spence 2002). What does the equilibrium look like?

Assume that cheaters set $I_C = 0$ and trustworthy agrodealers set $I_T = I^*$. Also assume that farmers believe to encounter a cheater when observing $I < I^*$ and a trustworthy agrodealer when observing $I \geq I^*$. Cheaters will choose $I = 0$ when $v_1 \geq v_2 - \beta I^*$ and trustworthy agrodealers will choose $I = I^*$ if $v_2 - \gamma I^* > v_1$. Investment choices are rational and farmer beliefs are confirmed if the following holds:

$$\frac{v_2 - v_1}{\beta} \leq I^* < \frac{v_2 - v_1}{\gamma}. \quad (1)$$

If investments are costly and serve no purpose but signalling trustworthiness, then the most efficient equilibrium occurs when investments are as low as possible while still enabling farmers to distinguish between cheaters and trustworthy agrodealers: $I^* = (v_2 - v_1)/\beta$.

The signalling equilibrium is illustrated in Figure 7.1. On the vertical axis are the (expected) returns for farmer *i* of purchasing a unit of input from agrodealer *j*. In a competitive market these are also the returns from selling that unit by the agrodealer. For agrodealers with high signalling cost β it is better to not invest in signalling and accept the lower price v_1 (as $v_1 > v_2 - \beta I$ for $I \geq I^*$). For traders with signalling cost γ the reverse is true, and they will select $I = I^*$.

[8] Spence (2002) refers to age not as a "signal" but an "index" because the trader has no control over his age; it is an unalterable attribute that conveys information. Agrodealers can make an effort to appear older, for example by applying make-up or growing a beard, but there are limits to what can be accomplished.

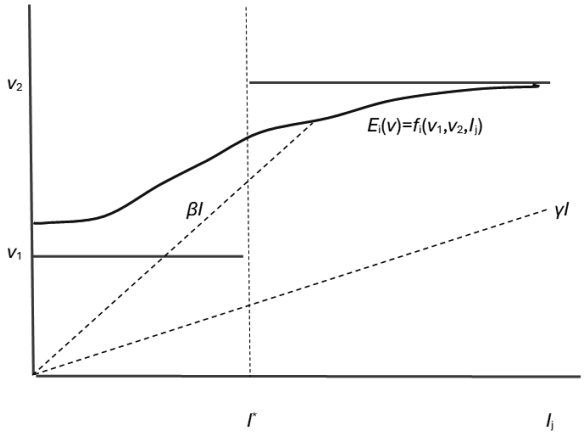


Figure 7.1: Signalling equilibrium

Does a separating equilibrium exist where farmers distinguish between cheaters and trustworthy agrodealers and pay different prices for inputs offered by these two types? The literature suggests this might not be the case on real input markets. There is no clear relationship between market prices and unobservable input quality, and farmers' beliefs about quality are often inaccurate (Ashour et al. 2019; Michelson et al. 2021, Hoel et al., 2024). In a pooling equilibrium, farmers pay an average price for inputs and are uncertain about the quality of the inputs that they buy.

A separating equilibrium may not exist for various reasons. First, and trivially, a separating signalling equilibrium will not exist when there is no asymmetric information problem to address. For example, if formal signals "work" traders do not need to send signals and inform farmers about the quality of inputs. Second, a separating equilibrium cannot exist if it is easy for cheaters to mimic trustworthy agrodealers, i.e. if $\beta \approx \gamma$. In this case, signals lose their informational value. Third, trustworthy agrodealers prefer to be in a pooling equilibrium if the share of cheaters in the population is "low". They receive a price based on the average value of inputs in the market and avoid the investment cost of signalling. Trustworthy agrodealers rationally signal only if $v_2 - \gamma I^* > v_2 - \alpha$, or if:

$$\alpha > \frac{\gamma(v_2 - v_1)}{\beta}. \qquad (2)$$

Fourth, if the relationship between signals or the underlying traits and trustworthiness is fuzzy, then farmers remain uncertain about the agrodealers' type even after observing the signal. For example, while obese people may on average be more wealthy than non-obese people, it is not evident how much wealthier they are. Moreover, mapping wealth on trustworthiness is far from straightforward. Different signals may also contradict each other; for example, a trader may be both young and obese. Farmers have to form subjective appraisals of agrodealer trustworthiness based on what they observe and likely make mistakes. Assume that farmer *i* expects that the value of an input offered by a trader who signals I_j is given by:

$$E_i(v) = f_i(v_1, v_2, \alpha, I_j) \qquad (3)$$

It seems plausible to assume that $f_i(\cdot)$ is increasing in v_1, v_2 and I_i and decreasing in a. An example of an expected value curve for a specific farmer is provided in Figure 7.1. Since beliefs vary across farmers there exists a distribution of expected value functions at the level of the market. Depending on the distribution of beliefs (and the nature of the matching process of buyers and sellers, see Antras and Costinot 2011, Bardhan et al. 2013) some low-quality sellers may decide to invest in signalling if they believe to be matched with 'optimistic farmers' (with high levels of $E(v)$ for low levels of I). Similarly, some high-quality sellers may decide not to invest in signalling if they expect to be matched with pessimistic farmers. The separating equilibrium disappears if signals convey only fuzzy information about the unobserved traits or trustworthiness of agrodealers.

We explore whether a separating signalling equilibrium exists on the seed market in northern Nigeria, which is ultimately an empirical question. We test whether signals are correlated with traits in the expected direction and whether both signals and traits are correlated with perceived trustworthiness. If farmers use signals to judge the quality of seed, then signals and perceived trustworthiness should be correlated with WTP—at least for seed for which no formal quality assurance is in place. Instead, if WTP does not vary across agrodealers, then either signalling is unimportant (e.g., all seed is of good quality) or signalling is not feasible, for example because it is cheap for cheaters to mimic trustworthy agrodealers.

7.3 Context and experimental approach

7.3.1 Context

We set up an experiment in Kano and Kaduna in northern Nigeria. Population size in these states is approximately 14.3 million and 8.3 million, respectively (Harry, 2020), and agriculture remains the dominant activity to support livelihoods. Smallholder farmers make up 80% of the population working in agriculture (Plaisier et al. 2019), and cultivate cereals (maize, sorghum), legumes (groundnuts, cowpeas) and vegetables (tomatoes, peppers, onions) during the wet (May–October) and dry season (November–April). Yields are comparable to, or slightly below, Western African averages. For example, average tomato yield in Kano and Kaduna is nearly seven tons per hectare (Plaisier et al. 2019) and maize yield between 2.5-3.0 tons per hectare (Japan International Cooperation Agency [JICA], 2024). There are concerns about the circulation of low-quality inputs and the absence of an effective quality monitoring system (Plaisier et al. 2019, IFPRI, 2024), and quality seems hardly enforced in markets other than those in the bigger cities. The Nigerian Government recently announced new measures to crack down on low-quality and fake seeds.[9] However, it is difficult to enforce such measures as the market is mostly scattered and informal; there are about one to three million agrodealers in Nigeria (Steemers et al., 2022).

7.3.2 Experimental approach

Our empirical strategy combined qualitative methods, photo-taking of agrodealers, Becker-DeGroot-Marchak (BDM) auctions with smallholders, seed quality testing, a mystery shopper approach, and a die-rolling task. A roadmap of the stages of the experiment is provided below. An overview of the various farmer and agrodealer samples is provided in Appendix 7.1.

[9] https://punchng.com/fg-to-curb-fake-seeds-improve-export-standards/.

Stage 1: Trustworthiness and identification of signals (FGD)

To understand the role of trust in seed trading and identify which signals and traits farmers associate with trustworthy agrodealers, we conducted focus group discussions (FGDs) with farmers (Farmer Sample 1) and semi-structured interviews with agrodealers (Dealer Sample 1). Traits associated with trust included trader wealth, experience, and religiosity. These traits can be proxied (or signalled) by, respectively, body size, age, and traditional clothing.

Stage 2: Ranking of trust signals

To quantify the strength of these signals we obtained photographs of a new sample of 45 agrodealers selling tomato and maize seed (Dealer Sample 2). We used these full-body portraits for a ranking exercise with a new group of farmers (Farmer Sample 2), Farmers were asked to rank pictures based on signals (body type, age, and clothing type) and traits (wealth, experience, trustworthiness). We constructed score cards provided in Figure 7.2 and asked farmers to evaluate each signal and trait on a scale from 1 to 5. We also asked farmers to evaluate the perceived trustworthiness of the agrodealers directly, based on the photo. After aggregating scores across farmers, we classified agrodealers into three categories of perceived trustworthiness: low, medium, and high. To safeguard the privacy of agrodealers and avoid prior interaction bias, farmers from Kano ranked agrodealers from Kaduna and *vice versa*. This was also how we implemented the WTP auction experiment discussed below.

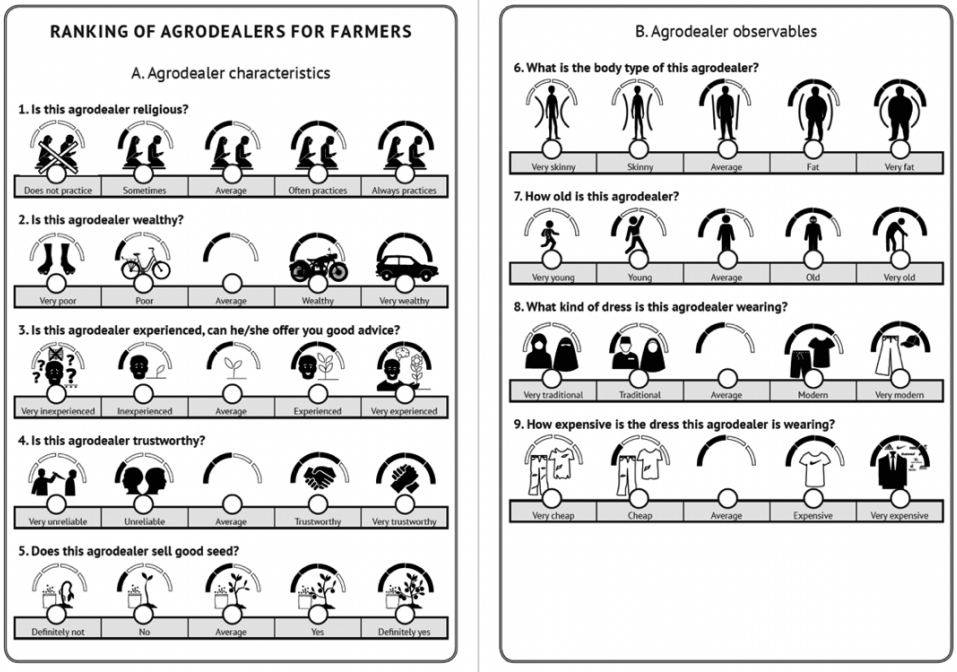


Figure 7.2: Scorecards to evaluate agrodealers' signals and traits

Stage 3: BDM auction I

For both Kano and Kaduna we selected the photo of one agrodealer per category of perceived

trustworthiness (low, medium, or high). For the low and high trustworthy categories, we selected agrodealers with extreme scores. For the medium category, we selected agrodealers with scores close to the mean trust score. These six agrodealers made up Dealer Sample 3, and from each we purchased the above-mentioned four types of maize and tomato seed. In procuring seeds for the BDM auction, we sourced seeds from these six pre-selected agrodealers. When a selected agrodealer was insufficiently stocked, we replaced it with a pre-identified backup agrodealer from the same category. This happened with two agrodealers and we resorted to using our third and fourth choice. We offered the seed to a third group of farmers (Farmer Sample 3) who participated in a BDM auction. Before placing their bid, respondents saw the package of seeds and a photo of the agrodealer selling it. Each farmer made twelve bids: four bids (one for each product type: branded and unbranded maize, tomato in tins and pouches) for each of the three categories of agrodealer (low, medium, and high trustworthiness). After bidding, one bid was randomly selected and compared to a randomly drawn strike price.[10] If the bid was equal to or greater than this strike price, the farmer purchased the seed at the strike price. Otherwise, no transaction occurred. BDM auctions are incentive compatible and easy to implement, even among sample populations with little formal education (Burchardi et al, 2021).

Stage 4: BDM auction II

To further explore how signals affect bidding behaviour, we also generated eight AI images with amplified agrodealer features (while maintaining the style of the original portraits). Each of the eight AI-generated agrodealers represented extreme values of one of the signals that matter for trust. We created "pairs" of otherwise similar images with variation in body type, wealth, age, or religiosity (Appendix 7.2). For our second BDM auction we used Farmer Sample 4, which was randomly divided into two groups. Participants expressed WTP for half of the pictures (one image from each pair) to avoid that participants would guess the purpose of the experiment and allow them sufficient time to focus on each image. In total, each farmer provided 16 bids in a session: one bid for each combination of the four product types, and four hypothetical agrodealers. We followed Macchi (2023) and informed farmers that, after bidding above the strike price, they could purchase the seed from a 'comparable' agrodealer (somebody who looked like the person on the picture selected by us).[11] One of the sixteen bids was randomly selected and effectuated.

In addition, we asked farmers to state sixteen bids based on their beliefs about how *other* farmers in their community would value the package. Farmers were informed that for each product category, the top 25 respondents whose beliefs were closest to the average bid of their peers would receive a prize. These so-called second-order beliefs are incentive compatible, even if the agrodealers displayed were hypothetical (i.e. generated by AI).

[10] All farmers' bids were recorded both digitally and physically with pen and paper. The paper bids were in turn folded shut in the form of a ball and put in a bid bowl. No ink was visible. After all bids were placed in the bid bowl, farmers were asked to randomly pick from the bowl. Equally, we had a similar bowl with different randomly generated strike price with no repeated value. Farmers were also required to pick one of the papers from the strike price bowl. Afterwards, the farmer opened both papers. The randomly drawn strike price was compared against the randomly drawn paper bid. This assured both clear understanding and transparency of the bidding process to the farmers.

[11] Macchi (2023) allowed loan officers to meet a "comparable candidate" for a loan after assessing a hypothetical one.

Data from the BDM auctions was used to evaluate whether farmer valuation of seed from different sellers is correlated with signals, traits, and "trustworthiness" of agrodealers. We also explored whether the impact of agrodealer type, if any, was mediated by the presence of formal quality signals associated with the packaging of the seed. Appendix 7.3 shows all variables from Stages 1-4 along with the expected impacts of signals and traits on WTP.

Stage 5: Seed quality assessment

We were interested in assessing whether there was variation in seed quality across the different seed types (branded and unbranded maize seed, tomato seed in tins and pouches). Moreover, we also wished to test whether there was a correlation between farmers' WTP for different seed-agrodealer combinations, and whether these valuations were related to actual seed quality, allowing us to assess whether farmers beliefs and expectations were correct. We conducted germination and vigour trials for samples of maize and tomato seed obtained from a sub-sample of 36 agrodealers including the six agrodealers who featured in BDM I (Dealer Sample 3). The sample was increased by agrodealers from popular seed markets in each state. In total we tested 130 seed samples (67 from Kaduna and 63 from Kano) in an independent research laboratory.[12] The objective was to determine the germination percentage and vigour index—indicators of seed quality and potential field performance.[13] Tests were conducted under controlled laboratory conditions following a standardized protocol.[14]

Stage 6: Independent measures of agrodealer trustworthiness

Finally, we used data from two honesty tasks collected during follow-up visits to the 45 agrodealers from Dealer Sample 2. We aimed to obtain two independent measures of agrodealer trustworthiness unrelated to selling seed. First, a mystery shopper visited the shop and made enquiries about the price of agrochemicals. Virtually all agrodealers sold both low-quality (locally produced) agrochemicals and high-quality (imported) agrochemicals. We focused on insecticides, which were used by most vegetable producers in the study region. There was a standard price for low-quality insecticides, but many agrodealers have some leeway to offer low-quality insecticides to (naïve) farmers at the prices of high-quality ones. To classify ago-dealers as trustworthy or untrustworthy we used mystery shoppers dressed as farmers. These shoppers were instructed to

[12] The Seed Technology Laboratory, Institute for Agricultural Research, Ahmadu Bello University, Samaru, Zaria.

[13] Vigour tests are commonly used to detect early deterioration from storage and handling, because vigour tends to decline before standard germination does, serving as a good indicator of storability and field performance.

[14] The growing medium used was sea sand, filled to half the depth of non-perforated plastic boxes. This medium was selected for its superior aeration and ability to hasten germination. Maize samples were planted in 5.6-litre boxes, while tomato samples were planted in 1.18-litre boxes. For each sample source, four replicate sand boxes were used, and each box contained five rows with five seeds per row, totaling 25 seeds per box and 100 seeds per sample. Sand was wetted to an optimal moisture content determined by visual observation and watered daily with a fixed amount of water. No fertilizer was applied, and room temperature was maintained at a constant 29°C throughout the testing period. Germination counts were recorded daily from day 4 until day 8, and a vigour index was calculated based on an average of the daily readings.

mention that they were "new to farming" and to ask for the price of the low-quality insecticide.[15] We collected information on the price offered first, as well as the 'final price' or lowest price that the agrodealer would accept after negotiations. To assess trustworthiness, we assessed the two prices (with higher prices as a sign of untrustworthiness).

We also used a die-rolling experiment to produce an additional measure of agrodealer trustworthiness. An enumerator visited the agrodealer in their shop, thanked him for his previous participation in our survey, which was instrumental in understanding how farmers interact with agrodealers, and proposed a die-rolling game as a thank-you parting gift. The agrodealer was invited to roll three dice in private, report the total number of pips, and receive 500 Naira per pip from the enumerator. If the agrodealer reported three pips he would receive 1,500 Naira, and if he reported 18 pips he would receive 9,000 Naira. While a die-rolling experiment does not enable us to say anything about the dishonesty of *individual* agrodealers, we can say something about dishonesty at the level of the group. Specifically, we can evaluate the correlation between the number of pips reported and the agrodealers' trustworthiness as perceived by farmers. If this correlation is negative, farmers are, on average, able to identify which agrodealers behave more honestly in this task.

7.3.3 Data collection and summary statistics

Trained local enumerators collected data in five stages. Exploratory focus group discussions and interviews were conducted between June and July 2024. The ranking exercise using agrodealer photographs was implemented in September and October 2024. The first round of BDM auctions took place in May 2025, followed by the second round in June 2025 during the period farmers typically purchase maize and tomato seed. Germination and vigour trials were carried out in September 2025. Finally, the independent measurements of agrodealer trustworthiness were completed in November 2025.

Agrodealer sample 2 consisted of 45 individuals, 25 of which were from Kano state and the remaining 20 from Kaduna state. Almost all agrodealers were men (98%). The average age of agrodealers was 31 years, with ages ranging between 16 and 50 years. On average, the shops had been in existence for twelve years (ages ranging between 1 and 30 years).

Our BDM samples almost exclusively consisted of males, which was intentional as it became apparent during the FGDs that very few female farmers ever visited agrodealer shops. More than half of the farmer respondents had completed primary education (57%), and the great majority of farmers in samples 3 and 4 reported cultivating maize (83% and 74%), while a much smaller group of farmers reported cultivating tomatoes (20% and 23%). Only 17% and 27% of farmers reported sometimes buying tomato seed and 12% and 20% reported growing improved varieties; for the sub-sample of tomato growers, this accounted for 61% and 62% who reported buying seeds, and 39% and 46% that cultivated seeds of improved varieties. Meanwhile, 31% of farmers reported buying maize seeds, with 16% and 19% cultivating maize seeds of improved varieties; considering the subsample of maize growers, this accounted for 33% of farmers who reported buying seeds,

[15] We selected a product called Best Cypermethrin, an insecticide frequently used for vegetable cultivation (the activity took place during the main vegetable cultivation season and traders were very likely to have it stocked; see Appendix 7.8 for product image). This product was of much lower quality than other cypermethrin insecticides in the market, and hence typically offered at a lower price. Best cypermethrin was typically sold for 6,500–6,800 Naira, but some traders offered it for up 9,500 Naira, which was the price commonly charged for the high-quality version.

and 17% to 19% who cultivated improved varieties. The percentage of the production sold on the market varies across crops, about 46% and 48% for maize growers and 86% and 87% for tomatoes growers. Detailed summary statistics for the three farmer samples and the variables used across the different stages of the analysis are shown in Appendix 7.4 and 7.5.

7.4 Empirical specification

We first regress the trait scores T_{ij}^{m} of agrodealer *j* (*m* = wealth, experience, religiosity) perceived by farmer *i* on the signal scores S_{nij} (*n* = body type, age, modernity of clothes, cost of clothes) controlling for farmer characteristics (age, gender, education, buying seeds), x_i, and agrodealer characteristics (shop background), z_j. This enables verifying whether signals are informative about unobservable traits:

$$T_{ij}^{m} = \alpha_0^m + \sum_{n=1}^{4} \alpha_{1n}^m S_{nij} + \alpha_2^m x_i + \alpha_3^m z_j + \varepsilon_{ij}^m \quad (4a)$$

Farmers use observables to infer something about underlying characteristics of agrodealers if $\alpha_{1n}^m \neq 0$. We also regress perceived trustworthiness scores W_{ij} on signal scores and trait scores.

$$W_{ij} = \alpha_0^{signal} + \sum_{n=1}^{4} \alpha_{1n}^{signal} S_{nij} + \alpha_2^{signal} x_i + \alpha_3^{signal} z_j + \varepsilon_{ij}^{signal} \quad (4b)$$

$$W_{ij} = \alpha_0^{trait} + \sum_{m=1}^{3} \alpha_{1m}^{trait} T_{mij} + \alpha_2^{trait} x_i + \alpha_3^{trait} z_j + \varepsilon_{ij}^{trait} \quad (4c)$$

Farmers believe that underlying characteristics are associated with trustworthiness if $\alpha_{1m}^{trait} \neq 0$, and the same is true for observable signals if $\alpha_{1n}^{signal} \neq 0$. The assumption that agrodealers aim to signal their type to farmers in input markets rests on the assumption that $\alpha_{1n}^{signal} \neq 0$. We also run alternative regressions using farmer *i*'s expectations regarding the quality of seed sold by agrodealer *j* as the dependent variable.

Next, we analyse how farmers' WTP for seed packages offered by different types of agrodealer is affected by their perceived trustworthiness, signals, and traits. We estimate the following three specifications for the four types of seed separately (*k* = tomato seed in tins and pouches, branded and unbranded maize seed):

$$WTP_{ijp}^{k} = \sum_{l=1}^{3} \beta_l^k dW_{lij} + \mu_i^{k\ level} + \vartheta_p^{k\ level} + \varphi_{ijp}^{k\ level} \quad (5a)$$

$$WTP_{ijp}^{k} = \sum_{n=1}^{4} \beta_n^k S_{nij} + \mu_i^{k\ signal} + \vartheta_p^{k\ signal} + \varphi_{ijp}^{k\ signal} \quad (5b)$$

$$WTP_{ijp}^{k} = \sum_{m=1}^{3} \beta_m^k T_{mij} + \mu_i^{k\ trait} + \vartheta_p^{k\ trait} + \varphi_{ijp}^{k\ trait} \quad (5c)$$

In specification (5a) dW_{lij} represents dummies for three trustworthiness levels (*l* = low, medium, and high alternatively) based on the trustworthiness scores. β_l^k captures the effects on WTP. Specifications (5b) and (5c) estimate the effects of signals, S_{nij}, and traits, T_{mij}, on WTP captured

by β_n^k and β_m^k. In each case we control for farmer fixed-effects, μ_i, and position fixed-effects, ϑ_p, i.e. the order in which bids were made (first, second, …). $\varphi_{ijp}^{k\ level}$, $\varphi_{ijp}^{k\ signal}$, and $\varphi_{ijp}^{k\ trait}$ are the corresponding error terms. We estimate the model using genuine agrodealer photographs and AI-generated images, as well as second-order belief data regarding other farmers' WTP for package *k*.

The last stage of our empirical analysis consists of testing the correlation of farmers' perceived trustworthiness of agrodealer and independent measures of agrodealer trustworthiness obtained through the mystery shopper approach and the die-rolling experiment. We estimate the following specifications:

$$Price_{jes}^{t} = \gamma_0^{t\ price} + \gamma_1^{t\ price} W_j + \gamma_2^{t\ price} z_j + \theta_s^{t\ price} + \nu_e^t + \psi_{jes}^{t\ price} \quad (6a)$$

where $Price_{jes}^{t}$ is alternatively the initial and final price offered by agrodealer *j* for the insecticide requested by our mystery shopper. W_j stands for the average trustworthiness score perceived by the farmers. In specification (6a), we condition on age of the agrodealer, z_j, state fixed-effects, $\theta_s^{t\ price}$, and enumerator (mystery shopper) fixed-effects, ν_e^t. $\psi_{jes}^{t\ price}$ stands for the error term. If $\gamma_1^{t\ price} < 0$ farmers' perceived trustworthiness correlates with actual trustworthiness as measured through the mystery shopper approach.

With the data from the die-rolling experiment we estimate the following specification:

$$Pips_j = \gamma_0^{die} + \gamma_1^{die} W_j + \gamma_2^{die} z_j + \theta_s^{die} + \psi_j^{die} \quad (6b)$$

where $Pips_j$ stands for the number of reported pips by farmer *j*. In specification (6b) we do not add enumerator fixed effects as we collected the data with just one enumerator per state. Again, if $\gamma_1^{die} < 0$, farmers' perceived trustworthiness correlates with actual trustworthiness as measured through the die-rolling experiment.

7.5 Results

7.5.1 Identification of signals

The FGDs revealed that most farmers switch between buying and saving their own seed.[16] Some farmers only buy seed from known agrodealers, and others alternate between sources. Many farmers were concerned about seed quality. In each FGD, at least one farmer had personally experienced buying 'bad seed' or another substandard input. The main traits associated with trustworthiness were religiousness ("*If he is God fearing...*") and family ties. A few farmers observed that religious clothing is not a very reliable signal of religiosity: "*Nowadays even when you go to market and see someone with big gown, cap, and prayer beads, if care is not taken that man will just cheat you, and sometimes you will see someone dressed in polo and jeans, but all his words are truth.*" Wealth sometimes came

[16] Farmers exposed to a training by an international seed company were better informed about seed quality and improved varieties, and more likely to purchase high-quality seed on the market.

up as a trait that is correlated with trustworthiness, and some farmers interpret wealthy agrodealers as not having the need to engage in cheating to support themselves. However, this was not uniformly true, and several farmers understood that the accumulation of wealth may involve cheating of unwitting clients (or untrustworthy behaviour). Some agrodealers suggested that wealthier agrodealers have capital to stock up and do not need credit, which reduces costs and, hence, prices for farmers.

Most agrodealers have a fixed customer base with repeat customers. Competition between sellers varies depending on remoteness. Agrodealers explained that trust is built primarily by selling high-quality products from reputable companies and providing good advice to customers. A clear distinction is made between repacked and "fake" seed. Repackaging seed is common because some customers cannot afford to purchase an entire package. Others refuse to repackage because, after repacking, seed quality cannot be guaranteed. This means repacked seed is not per se poor quality seed, but it does pose a risk for the farmer. According to agrodealers, fake seeds are sometimes sold 'on the market', but mostly by 'mobile' salesmen seeking to benefit from temporary episodes of seed scarcity when reputable shops went out of stock. Agrodealers recognize that seed quality is a concern amongst customers and emphasize that tomato tins are more popular than pouches because they 'cannot be tampered with.'

7.5.2 Correlates of trustworthiness

The first regression results are based on survey responses of 288 farmers (Farmer Sample 2). In Table 7.1, columns (1)-(3), we verify whether traits are correlated with signals using specification (4a). We find strong support for our initial hypotheses. Religiosity is negatively correlated with wearing modern clothing (trousers and shirt instead of a boubou). Wealth is positively correlated with being overweight (as in Macchi, 2024) and costly clothes. Experience is positively correlated with age. Somewhat unexpected, to us, many signals appear to come as a bundle of several desirable traits. Older dealers are rated as more religious, wealthier, and more experienced. The same is true for wearing expensive clothes, which is interpreted as a signal of religiosity, wealth, and experience. In contrast, wearing "modern clothes" signals undesirable traits, and is associated with low religiosity, poor wealth, and little experience. The exception to the rule that one signal maps on all traits is a heavy body type. While big agrodealers are associated with wealth and experience, they are not seen as more religious.

Table 7.1: Signals, Traits and Trustworthiness

	(1) Religiosity [1-5]	(2) Wealth [1-5]	(3) Experience [1-5]	(4) Trustworthy [1-5]	(5) Trustworthy [1-5]	(6) Quality [1-5]	(7) Quality [1-5]
Body type	-0.005	0.300***	0.207***	0.092**		0.148***	
	(0.046)	(0.031)	(0.040)	(0.041)		(0.038)	
Age	0.187***	0.103***	0.209***	0.243***		0.151***	
	(0.041)	(0.028)	(0.039)	(0.037)		(0.038)	
Modern Clothes	-0.267***	-0.117***	-0.119***	-0.165***		-0.111***	
	(0.034)	(0.020)	(0.026)	(0.027)		(0.027)	
Costly clothes	0.179***	0.389***	0.386***	0.243***		0.327***	
	(0.041)	(0.030)	(0.035)	(0.037)		(0.037)	
Religiosity					0.266***		0.168***
					(0.025)		(0.025)

Wealth					0.105***		0.202***
					(0.030)		(0.028)
Experience					0.405***		0.392***
					(0.030)		(0.030)
Controls	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Mean score	3.647	3.172	3.591	3.688	3.688	3.8125	3.8125
StD score	1.12	0.838	1.063	0.979	0.979	1.001	1.001
R2	0.132	0.351	0.211	0.197	0.469	0.182	0.399
Observations	1,440	1,440	1,440	1,440	1,440	1,440	1,440
Farmers	288	288	288	288	288	288	288

Notes: Robust standard errors, clustered at the farmer level in parentheses. All scores measured on a scale from 1-5. Signals and traits on the right-hand-side are also measured as scores (see Figure 2). Controls used: Shop background, farmer's gender, farmer's age, farmer's education, farmer buys seeds. *** p<0.01, ** p<0.05, * p<0.1

The results in columns (4)-(5) relate signals and traits to perceived trustworthiness using specifications (4b and 4c). In column (4) we regress trustworthiness on signals and find that all signals work as expected: agrodealers are seen as more trustworthy if they are heavier, older, and wear traditional yet expensive clothes. In column (5) we regress perceived trustworthiness on the (perceived) underlying traits of agrodealers. The coefficients consistently support the hypotheses that farmers rate agrodealers as more trustworthy if they believe them to be more religious, wealthy or experienced. We obtain similar results if we use the answer to the question whether the farmer "expects the agrodealer to sell good quality seed" instead of perceived trustworthiness (columns 6 and 7). Overall, the results in Table 7.1 tell a consistent story about signals, traits, and perceived trustworthiness that aligns well with the outcomes of the FGDs.

Result 1: Perceived trustworthiness of agrodealers is related to unobservable traits (religiosity, wealth, experience) which can be signalled to prospective customers by specific investments in body weight or wearing expensive and traditional clothes.

7.5.3 Willingness to pay and trustworthiness

We selected three agrodealers per state (six in total) for different levels of trustworthiness (low, medium, high). We purchased seed from these agrodealers and offered it to a sample of 560 farmers from the other state (Farmer Sample 3) in a BDM auction setting. Each farmer provided twelve bids (four seed types and three trustworthiness levels). In Table 7.2 we regress bids for different seed types on trustworthiness (low trustworthiness is the omitted category). It is not surprising that perceived trustworthiness does not explain variation in WTP for branded maize seed and tomato seed in tins. These are considered tamper-proof, so the formal quality signal is a substitute for informal trustworthiness signals. However, it is more surprising that trustworthiness does not affect WTP for unbranded maize seed and tomato seed in pouches. While highly trustworthy agrodealers can sell unbranded maize seed at a premium of 106 Naira per 100 grams, this premium is very small (mean WTP for unbranded seed by low trustworthiness agrodealers is nearly 3,000 Naira). Moreover, the remaining coefficients are not significant or consistently of the "right sign."

To probe this issue further we regress WTP on agrodealer traits and signals using specifications (5b) and (5c). Results are summarized in Table 7.3 (in Panel A for signals and in Panel B for traits). These regression results also do not provide robust support for the hypothesis that farmers are

willing to pay more for seed from agrodealers that have traits associated with trustworthiness (or send signals associated with these traits). In Panel A, signals of trustworthiness do not affect WTP for branded maize and tomato seed in tins, as expected, and no signal of trustworthiness is significantly correlated with WTP for unbranded maize seed. Several coefficients enter significantly in the model explaining variation in WTP for tomato seed in pouches, but now the signals Age and Expensive clothes have the "wrong" sign.

Table 7.2: Willingness-to-pay by trustworthiness (BDM I)

	(1) Unbranded Maize	(2) Branded Maize	(3) Tomato Pouch	(4) Tomato Tin
Trustworthiness (medium)	-66	41	53	-41
	(49)	(54)	(66)	(84)
Trustworthiness (high)	106**	68	20	67
	(49)	(54)	(66)	(84)
Respondent FE	Yes	Yes	Yes	Yes
Position FE	Yes	Yes	Yes	Yes
Mean WTP	2,278	2,653	2,808	6,789
StDev	2,129	2,276	3,186	5,929
Observations	1,680	1,680	1,680	1,680
Farmers	560	560	560	560

Notes: Robust standard errors, clustered at the farmer level in parentheses. Position FEs control for the position of each bid (1st, 2nd, …). WTP is measured in Naira (1,440 Naira ≈1 USD). *** p<0.01, ** p<0.05, * p<0.1. WTP winsorized.

Panel B reveals not a single significant correlation between traits and WTP for tomato seed in pouches. The traits *Religiosity* and *Experience* have a negative sign in the model explaining variation in WTP for unbranded maize seed—the opposite of what we expected. Also surprisingly, farmers bid less for maize seed offered by religious or experienced agrodealers.

We further examine the robustness of these results using AI-generated images with amplified agrodealer signals. These pictures were introduced to 585 farmers (Farmer Sample 4), and we explain variation in WTP for the same four types of seed. Results are summarized in Appendix 7.6. These results are consistent with those summarized in Table 7.3 – there is no robust correlation between agrodealer signals and farmers' WTP.

As another robustness check we explain variation in second-order beliefs by the amplified signals. This is based on results of the incentivized exercise where farmers provided their best estimate of the WTP of "other farmers" for seed "supplied" by AI-generated images. The results are summarized in Appendix 7.7. Again, there is no significant correlation between signals and WTP.

Result 2: WTP for tomato and maize seed sold in "tamper-proof" packages does not vary with perceived trustworthiness of the agrodealer, nor with perceived traits or observable signals. WTP for tomato and maize seed sold in "not-tamper-proof" packages also does not vary with perceived agrodealer trustworthiness, traits, or signals.

This leaves us with a bit of a conundrum. Reports in the media suggest that there is variation in seed quality due to adulteration and poor handling of seed by untrustworthy agrodealers. Our analysis reveals variation in perceived trustworthiness among agrodealers and suggests that farmers can pick up signals of trustworthiness. However, neither perceived trustworthiness nor signals and traits associated with trustworthiness can explain variation in WTP for seed offered by different agrodealers even if the seed is not offered in 'tamper-proof' packages. In the following, we explore possible explanations for this result.

Table 7.3: Willingness-to-pay, signals and traits (BDM I)

	(1) Unbranded Maize	(2) Branded Maize	(3) Tomato Pouch	(4) Tomato Tin
Panel A: Signals				
Body type	144	179	641*	283
	(268)	(296)	(357)	(455)
Age	-209	-169	-464*	-315
	(196)	(216)	(261)	(332)
Modern Clothes	-52	-102	-267**	-145
	(90)	(100)	(120)	(153)
Costly clothes	45	-76	-423**	-134
	(150)	(166)	(200)	(255)
Respondent FE	Yes	Yes	Yes	Yes
Position FE	Yes	Yes	Yes	Yes
Mean WTP	2,278	2,653	2,808	6,789
StDev	2,129	2,276	3,186	5,929
Panel B: Traits				
Religiosity	-17.510	23.558	38.881	-28.887
	(68.810)	(75.914)	(116.654)	(91.694)
Wealth	-334.949	-200.612	-431.812	-567.559
	(274.013)	(302.303)	(464.533)	(365.141)
Experience	357.013	203.306	368.699	621.136
	(343.789)	(379.282)	(582.823)	(458.121)
Respondent FE	Yes	Yes	Yes	Yes
Position FE	Yes	Yes	Yes	Yes
Mean WTP	2,278	2,653	2,808	6,789
StDev	2,129	2,276	3,186	5,929
Observations	1,680	1,680	1,680	1,680
Farmers	560	560	560	560

Notes: Robust standard errors, clustered at the farmer level in parentheses. Signals and traits on the right-hand-side are measured as scores from 1-5 (see Figure 2). Position FEs control for the position of each bid (1st, 2nd, …). WTP is measured in Naira (1,440 Naira ≈1 USD). *** p<0.01, ** p<0.05, * p<0.1. WTP winsorized.

7.5.4 Seed quality from trustworthy and not-so trustworthy agrodealers

A first step is to analyse whether seed quality varies with trustworthiness of agrodealers. Farmers should make similar bids in the absence of quality differentials. We used seed from the mystery farmer exercise (seeds procured during stage 5 of the experiment) and conducted germination and vigour tests in an independent laboratory. Results are summarized in Table 7.4. This analysis is based on a small number of seed samples; 130 seed samples from six agrodealers. Overall, seed quality is high and seeds from both Kaduna and Kano state met high-quality standards. Seed and vigour for different seed types appear similar across states (the germination rate of unbranded seed in Kaduna is lower than in Kano but still very high). More surprisingly, germination and vigour rates of tamper-proof and not-tamper-proof seed also are very similar. Tomato seed in tins does not outperform seed sold in pouches by a high margin, and the same is true for branded maize and unbranded maize seed. While some differences are detectable, the overall magnitude is modest. For tomato, this is expected as we use branded tins and pouches, which should both contain quality seed. For maize, this is unexpected as the quality of repacked seed is expected to be lower than seed in sealed packages.

Table 7.4: Seed quality and agrodealer trustworthiness

	Tomato				Maize			
	Tin		Pouch		Branded		Unbranded	
	Germ%	Vig%	Germ%	Vig%	Germ%	Vig%	Germ%	Vig%
Panel A: Kaduna								
Low-trust agrodealer	100	76	98	78	96	78	83	73
Medium-trust agrodealer	100	75	99	80	96	84	86	75
High-trust agrodealer	98	81	94	77	94	80	97	83
Panel B: Kano								
Low-trust agrodealer	100	77	98	75	94	73	100	79
Medium-trust agrodealer	100	83	99	73	95	79	98	77
High-trust agrodealer	98	77	94	77	93	70	99	75

Source: Seed Technology Laboratory, Institute for Agricultural Research, Ahmadu Bello University, Samaru, Zaria.

We obtain similar findings when we evaluate the germination - and vigour rate of seed samples from the sample of 36 agrodealers (including those for which we do not have assessments of trustworthiness).[17]

[17] Appendix 7.9 summarizes germination and vigour test results for seed packages collected from all 36 sampled agrodealers. Panel A shows that germination rates are generally high across all seed types, with mean germination exceeding 93% and a max value of 100% in every category. Tomato seeds in pouches have a higher average germination (98%) compared to tomatoes in tins (93%). For maize, branded packages (N=22 due to limited stocks) show slightly higher average germination (95%) than unbranded maize (94%). Panel B reports vigour results. Vigour shows more variation, with mean scores ranging between 76%–80%. Nevertheless, the mean score across categories suggests an excellent vigour rate. Tomato seeds in pouches also have higher vigour than those in tins, and branded maize shows higher vigour than unbranded maize. Overall, all seed types from the sample had at least an "excellent" germination rate and a "good" vigour rate.

Most importantly, for our purpose, is a comparison of seed quality across trustworthiness levels of agrodealers. Our quality tests do not support the hypothesis that agrodealers perceived as highly trustworthy supply better seed than their less-trustworthy peers. There is no clear ranking in terms of germination rate or vigour as we move from agrodealers with low to medium and eventually high trustworthiness. Differences in performance are small and likely to 'get lost' under real-life production conditions where production also depends on factors like soil type and weather outcomes.

Result 3: Seed quality in terms of germination and vigour is consistently good to excellent across seed samples, and does not vary much by state, packaging, or trustworthiness of the source (agrodealer).

Farmers therefore behave rationally by bidding the same amount for seed from different agrodealers. Notwithstanding the attention for fake and adulterated agro-inputs, the quality of seed supplied by the agrodealers in our sample is uniformly high. Concerns about low quality of agro-inputs in Africa are not always supported by objective measurement. Similarly, Michelson et al. (2021) analysed fertilizer quality in Uganda and found no support for concerns about fake or adulterated fertilizers. Barriga and Fiala (2020) examined the maize seed supply chain in Uganda and found also no evidence of large-scale faking or adulteration—reporting consistently high levels of seed purity throughout the supply chain. However, we note that our agrodealer sample may not be representative of the full set of seed sellers. Qualitative data suggested that low quality seed may enter the market via mobile salesmen – not shop-owners as included in this sample.

7.5.5 Validating agrodealers' trustworthiness

Farmers form perceptions about agrodealers' trustworthiness based on visible signals and traits, but this does not affect their valuation of seed, which is consistent with high quality. Are there other spheres of interaction between agrodealers and farmers where trustworthiness does matter? To probe this issue, we consider a specific type of interaction where, according to informal discussions, trustworthiness is more relevant. Agrodealers are at the frontline of input distribution and their recommendations are an important determinant of farmer choices with respect to input use. In particular, there are standard (imported) and sub-standard (locally-produced) agro-chemicals available on the market. Almost all farmers growing vegetables in our study region use insecticides, and every agrodealer supplies both standard and sub-standard varieties. While there is a standard price for the sub-standard pesticide, some agrodealers try to increase profits by selling the sub-standard product as if it were the standard one. Untrustworthy sellers may try to sell the local product for the same price as the foreign product if they believe they are interacting with an uninformed farmer. To test whether there is indeed variation in dishonesty and whether that correlates with perceived trustworthiness, we implemented a second mystery shopper task. This part of the research project was not pre-specified.

We sent an enumerator acting as 'somebody who is new to farming' to the 45 agrodealers of Dealer Sample 2. One agrodealer closed his business in the meantime, so the sample was reduced to 44 dealers. We used male enumerators and made sure these persons were appropriately dressed as farmers. This mystery shopper picked up a sub-standard insecticide product and asked for the price. We collected two dependent variables; the initial asking price and the lowest (or final) price, after negotiating, for which the seller was willing to offer the product. We explore whether there

is a correlation between the degree of perceived trustworthiness and these two prices using specification (6a). Results are summarized in Panel A of Table 7.5.

Table 7.5: Perceived trustworthiness and displayed honesty

	Panel A		**Panel B**	
	(1)	(2)	(3)	(4)
	Final Price	Initial Price	Die rolling experiment	Die rolling experiment
Perceived trustworthiness	-528.4*	-591.8*	1.460*	1.016
	(263.8)	(306.0)	(0.819)	(0.684)
Controls (age)	Yes	Yes	Yes	No
State fixed effects	Yes	Yes	Yes	Yes
Enumerator fixed effects	Yes	Yes	No	No
Constant	8,159.6***	8,578.4***	7.428***	7.630
	(773.4)	(939.7)	(2.703)	(2.748)
Observations	44	44	43	43
R-squared	0.155	0.336	0.041	0.034

Notes: Robust standard errors in parentheses, *** p<0.01, ** p<0.05, * p<0.1. We used one enumerator per state for the die-rolling experiment, so state fixed effects also capture enumerator fixed effects.

The results in Panel A indicate that agrodealers perceived to be trustworthy initially charge a lower price than their less-trusted peers, and also agree on a lower final price. This suggests that some agrodealers seek to benefit from inexperienced farmers by over-charging for a low-quality input; perhaps by passing low-quality pesticides for high-quality pesticides. Farmers appear to be able to distinguish between trustworthy and not-so trustworthy agrodealers along this particular dimension by observing the signals that they send.

To further probe this issue, we played a standard die-rolling game with this same subsample of agrodealers, a few weeks later. On average, agrodealers claimed they rolled 11.9 pips, or an over-reporting rate of almost 15%, consistent with mild cheating behaviour. In a recent review of the literature and meta-analysis about honesty experiments, Gerlach et al. (2019) report an average over-reporting rate of 30% (a result based mainly on student samples in industrialized countries). Our die-rolling data (and using specification (6b)) do not support the hypothesis that especially untrustworthy agrodealers over-report the number of pips they rolled. In contrast, according to Panel B of Table 7.5, agrodealers who are perceived to be trustworthy report a higher number of pips than their not-so trustworthy peers. However, this result is not robust. Omitting control variables, for example, implies that the coefficient associated with perceived trustworthiness is no longer statistically significant (col. 4).

Result 4: Honest behaviour in a professional task by agrodealers correlates with perceived trustworthiness. Honest behaviour in a die-rolling experiment does not robustly correlate with perceived trustworthiness.

The lack of a correlation across honesty experiments is consistent with Gerlach et al. (2019), who emphasize heterogeneity across approaches to measure dishonest behaviour. They mention several explanations for differences in measured dishonesty. For example, the exchange in the mystery shopper task is a zero-sum game (the farmer's loss is the dealer's gain) whereas it is left unspecified what happens to money unspent after the die-rolling experiment. It is also possible that the die-rolling game raised suspicion among agrodealers which may "heighten the sense among

participants that socially undesirable behaviours are being observed, thus possibly promoting [them] to behaviours that make them look good in the eyes of observers" (p. 18). Since the die-rolling experiment resembles "gambling", our Muslim participants were even more wary and cautious (one agrodealer refused to roll the die).

Finally, a key situational difference between the two dishonesty measures is that the agrodealer interacted with a 'farmer' in the insecticide task (business as usual) and with an experimenter in the die-rolling game. Experimental and meta-analytic evidence suggests that dishonest behaviour is moderated by the social context in which it occurs and specifically, whether a concrete other is harmed by the dishonest act. In tasks where dishonesty affects an identifiable victim, individuals tend to behave more honestly (e.g., Köbis et al., 2019). Our findings are consistent with the hypothesis that agrodealers who are perceived to be untrustworthy feel less inhibitions to harm farmers by engaging in cheating behaviour.

7.6 Conclusion and discussion

Agricultural input markets in low-income countries suffer from information asymmetries between sellers and buyers. This could lead to "market for lemons" scenarios where poor-quality inputs dominate the market, lowering trust of farmers and discouraging the adoption of innovations. Improving market transparency has potential to mitigate these issues, enhancing market performance. The literature has focused on formal approaches to increasing transparency (e.g. certification and accreditation). In this chapter we explore the potential of informal approaches. We ask whether agrodealers are able to credibly signal their type (and, hence, the quality of their products) through informal channels to farmers seeking to buy modern inputs, and how this matters for market outcomes.

We combined several research methods to address multiple questions. First, we asked whether agrodealers are able to send signals about their trustworthiness to farmers, and which signals are used for this purpose. We found that farmers associate certain (unobservable) traits with trustworthiness. These include religiosity, experience and wealth. To signal these traits to potential buyers, agrodealers can invest in gaining (body) weight and in traditional yet costly clothes. Second, we asked whether perceived agrodealer trustworthiness matters for how much farmers value the seed offered by sellers. We did not find that farmers are willing to pay more for seed sourced from trustworthy agrodealers. Accordingly, we found that seed is consistently of high quality, and that there is little meaningful variation in terms of germination and vigour across (shop-owning) agrodealers. This finding is consistent with other recent research casting doubt on the common narrative of extensive problems with adulteration and "fake" products on agricultural input markets. However, farmer perceptions of seller trustworthiness did correlate with another measure of agrodealer dishonesty that is relevant to farmers; the propensity to overcharge for agrochemicals and perhaps pass low-quality inputs for high-quality ones. If this finding extends to other spheres of seller-buyer interactions, then distinguishing between more and less trustworthy agrodealers is meaningful to farmers.

In sum, farmers can infer something about unobservable agrodealer traits by observing signals, and based on their own experiences are able to rationally act upon this information. This suggests that informal approaches to mitigate information asymmetries on input markets succeed in

improving market transparency. Such skills may be particularly useful in the absence of effective formal mechanisms and may attenuate the need to introduce these. Future research could further explore which spheres of seller-buyer interactions suffer from information asymmetries, and identify which factors inhibit ago-dealers from credibly signalling their type to prospective clients. Moreover, such research could focus on differences between more urban and more remote areas, as well as between mobile and stationary agrodealers, as these characteristics are associated with higher risk.

Appendix

Appendix 7.1: Samples of farmers and agrodealers

Sample	(1) Sample size	(2) Purpose
Farmer Sample 1	116 farmers Kaduna: 20, 16, 20 Kano: 20, 20, 20	Focus group discussions
Farmer Sample 2	289 farmers Kaduna: 161 Kano: 128	Individual rankings of pictures
Farmer Sample 3	560 farmers Kaduna: 280 Kano: 280	BDM auctions, each farmer made 12 bids (3 agrodealers × 4 products)
Farmer Sample 4	585 farmers Kaduna: 295 Kano: 290	BDM auctions, each farmer made 2×16 bids (four agrodealers × four products each for first and second order beliefs)
Dealer Sample 1	78 agrodealers Kaduna: 32 Kano: 46	Semi-structured interviews
Dealer Sample 2	45 agrodealers Kaduna: 20 Kano: 25	Portrait pictures, mystery-shopper task (pesticide), die-rolling experiment
Dealer Sample 3	6 agrodealers Kaduna: 3 Kano: 3	Portrait pictures for BDM and seed purchases
Dealer Sample 4	36 agrodealers Kaduna: 18 Kano: 18	Seed samples

Appendix 7.2: Contrasting pairs of AI-generated agrodealers



(old age)



(young age)



(cheap cloth)



(expensive clothes)



(thin body type)



(big body type)



(traditional/religous clothes)



(modern clothes)

Appendix 7.3: Overview of variables

Stage 2: Ranking exercise			
Source	**Indicator**	**Form**	**Expected impact WTP**
Ranking signals	Body type (slim to fat)	Range 1-5	+
	Age (young to old)		+
	Clothing type (traditional to modern)		-
	Clothing cost (cheap to expensive)		+
Ranking traits	Trustworthiness (low to high)	Range 1-5	+
	Religiosity (low to high)		+
	Wealth (low to high)		+
	Experience (low to high)		+
Generated	Predicted trustworthiness (low to high) based on signals	Range 1-5	+

Stage 3: BDM I			
Type	**Indicator**	**Form**	**Expected impact WTP**
WTP	Farmers' own WTP for seed	Naira	
Signals	Body type (slim to fat)	Average rank	+
	Age (young to old)		+
	Clothing type (traditional to modern)		-
	Clothing cost (cheap to expensive)		+
Traits	Trustworthiness (low to high)	Average rank	+
	Religiosity (low to high)		+
	Wealth (low to high)		+
	Experience (low to high)		+

Stage 4: BDM II			
Type	**Indicator**	**Form**	**Expected impact WTP**
WTP	First order: farmers' own WTP for seed Second order: farmers' estimation of peers' WTP	Naira	
Signals	Body type: slim	Dummy	-
	Body type: fat		+
	Age: young		-
	Age: old		+
	Clothing type: modern		-
	Clothing type: traditional		+
	Clothing cost: cheap		-
	Clothing cost: expensive		+

Appendix 7.4: Summary statistics for agrodealer sample 2 and different farmer samples

Agrodealer sample 2					
Variable	Obs	Mean	Std. Dev.	Min	Max
State	45	.556	.503	0	1
Agrodealer gender (male = 1)	45	.978	.149	0	1
Age	45	31.311	8.525	16	50
Role of agrodealer: Shop owner (yes = 1)	45	.511	.506	0	1
Role of agrodealer: Manager (yes = 1)	45	.267	.447	0	1
Role of agrodealer: Salesperson (yes = 1)	45	.222	.420	0	1
Number of years of shop existence	45	11.578	9.176	1	30
Farmer sample 2					
Variable	Obs	Mean	Std. Dev.	Min	Max
Farmer gender (male = 1)	286	.955	.209	0	1
Age	286	39.122	12.926	18	73
Education level (primary = 1)	286	.643	.48	0	1
Buys seed (yes = 1)	286	.948	.223	0	1
Farmer sample 3					
Variable	Obs	Mean	Std. Dev.	Min	Max
Farmer gender (male = 1)	560	.954	.211	0	1
Age	560	37.473	12.798	17	75
Education level (1= primary or higher)	560	.57	.496	0	1
Total land size (acre)	560	4.591	4.267	0	24.7
Cultivates tomato (1 = yes)	560	.204	.403	0	1
Cultivates maize (1 = yes)	560	.832	.374	0	1
Cultivates none (1 = yes)	560	.045	.207	0	1
Buys tomato seed (1 = yes)	560	.186	.389	0	1
Improved tomato variety (1 = yes)	560	.118	.323	0	1
Buys maize seed (1 = yes)	560	.307	.462	0	1
Improved maize variety (1 = yes)	560	.159	.366	0	1
Sub-sample: tomato growers					
Buys tomato seed (1 = yes)	170	.612	.489	0	1
Improved tomato variety (1 = yes)	170	.388	.489	0	1
Part of tomato harvest sold (%)	170	86.465	16.886	0	100
Sub-sample: maize growers					
Buys maize seed (1 = yes)	522	.33	.47	0	1
Improved maize variety (1 = yes)	522	.17	.376	0	1
Part of maize harvest sold (%)	522	47.907	30.276	0	100
Farmer sample 4					
Variable	Obs	Mean	Std. Dev.	Min	Max
Farmer gender (male = 1)	585	.978	.148	0	1
Age	585	39.439	13.017	18	75
Education level (1= primary or higher)	585	.55	.498	0	1
Total land size (acre)	585	5.267	4.696	0	24.7
Cultivates tomato (1 = yes)	585	.229	.421	0	1
Cultivates maize (1 = yes)	585	.742	.438	0	1
Cultivates none (1 = yes)	585	.024	.153	0	1
Buys tomato seed (1 = yes)	585	.267	.443	0	1
Improved tomato seed (= yes)	585	.198	.399	0	1
Buys maize seed (1 = yes)	585	.308	.462	0	1
Improved maize seed (1 = yes)	585	.185	.388	0	1
Sub-sample: tomato growers					
Buys tomato seed (1 = yes)	250	.624	.485	0	1
Improved tomato seed (= yes)	250	.464	.5	0	1
Part of tomato harvest sold (%)	250	86.94	17.415	0	100
Sub-sample: maize growers					
Buys maize seed (1 = yes)	550	.327	.47	0	1
Improved maize seed (1 = yes)	550	.196	.398	0	1
Part of maize harvest sold (%)	550	46.289	32.569	0	100

Appendix 7.5: Summary statistics outcome variables

Stage 2: ranking exercise					
Full sample					
Variable	Obs	Mean	Std. Dev.	Min	Max
body rank	1440	3.178	.739	1	5
age rank	1440	2.528	.79	1	5
modern rank	1440	2.847	1.093	1	5
expensive rank	1440	3.138	.802	1	5
religion rank	1440	3.647	1.12	1	5
wealth rank	1440	3.172	.838	1	5
knowledge rank	1440	3.591	1.063	1	5
trust rank	1440	3.688	.979	1	5
Stage 3: BDM I					
Full sample					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	1680	2653.036	2276.059	0	20000
Maize unbranded	1680	2278.482	2128.528	0	20000
Tomato can	1680	6789.405	5928.827	0	20000
Tomato pouch	1680	2807.798	3185.749	0	20000
High trust					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	560	2616.518	2254.719	100	20000
Maize unbranded	560	2265.089	2214.299	0	20000
Tomato can	560	6780.714	5943.470	0	20000
Tomato pouch	560	2783.393	3175.305	0	20000
Medium trust					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	560	2733.393	2525.348	0	20000
Maize unbranded	560	2309.375	2297.340	0	20000
Tomato can	560	7879.107	6171.346	0	20000
Tomato pouch	560	3002.946	3336.044	0	20000
Low trust					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	560	2609.196	2022.127	500	13000
Maize unbranded	560	2260.982	1850.883	0	16000
Tomato can	560	5708.393	5459.677	0	20000
Tomato pouch	560	2637.054	3033.744	0	20000
Stage 4: BDM II first-order beliefs					
Full sample					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	2340	2507.543	2031.646	0	21000
Maize unbranded	2340	2106.564	1682.079	0	21000
Tomato can	2340	6929.893	6331.687	0	21000
Tomato pouch	2340	2802.949	2948.289	0	21000
Expensive clothing					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	294	2488.265	2033.060	0	21000
Maize unbranded	294	2064.626	1688.444	0	20000
Tomato can	294	6969.388	6219.973	0	21000
Tomato pouch	294	2724.558	2695.802	0	21000
Cheap clothing					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	291	2540.893	2039.911	0	15000
Maize unbranded	291	2188.316	1826.859	0	15000
Tomato can	291	6921.821	6469.137	0	21000
Tomato pouch	291	2837.285	3127.579	0	20000
Traditional clothing					

Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	294	2531.122	2092.395	0	21000
Maize unbranded	294	2069.49	1688.531	0	21000
Tomato can	294	6930.952	6308.219	0	21000
Tomato pouch	294	2795.748	2844.456	0	21000
Modern clothing					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	291	2519.931	1923.820	0	15000
Maize unbranded	291	2164.261	1677.157	0	10000
Tomato can	291	6971.924	6445.257	0	21000
Tomato pouch	291	2847.766	3158.263	0	20000
Full body type					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	291	2559.622	2098.742	0	15000
Maize unbranded	291	2134.364	1668.818	0	10000
Tomato can	291	6979.897	6414.956	0	21000
Tomato pouch	291	2876.117	3168.869	0	20000
Slim body type					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	294	2438.776	2028.381	0	21000
Maize unbranded	294	2026.701	1463.781	0	12000
Tomato can	294	6823.707	6164.907	0	21000
Tomato pouch	294	2718.98	2669.334	0	21000
Old age					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	294	2420.408	1939.299	0	20000
Maize unbranded	294	2055.884	1701.174	0	20000
Tomato can	294	6834.864	6189.047	0	21000
Tomato pouch	294	2737.415	2741.246	0	21000
Young age					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	291	2562.887	2108.889	400	15000
Maize unbranded	291	2151.031	1735.079	0	12000
Tomato can	291	7008.247	6509.983	0	21000
Tomato pouch	291	2888.144	3157.319	0	20000
Stage 4: BDM II second-order beliefs					
Full sample					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	2340	2691.829	1961.046	0	22500
Maize unbranded	2340	2238.829	1572.196	0	15000
Tomato can	2340	8428.077	6912.897	0	22500
Tomato pouch	2340	3191.624	3041.601	0	22500
Expensive clothing					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	294	2687.075	2338.318	300	22500
Maize unbranded	294	2218.908	1623.928	9	15000
Tomato can	294	8452.041	6877.429	300	22500
Tomato pouch	294	3173.98	2948.783	200	22500
Cheap clothing					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	291	2743.471	1859.864	400	15000
Maize unbranded	291	2303.436	1561.919	350	10000
Tomato can	291	8461.856	6976.435	0	22500
Tomato pouch	291	3214.089	3162.053	0	20000
Traditional clothing					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	294	2668.197	1928.956	300	15000
Maize unbranded	294	2181.463	1665.753	500	15000
Tomato can	294	8440.816	6937.086	300	22500
Tomato pouch	294	3244.898	2998.622	200	22500

Modern clothing					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	291	2699.656	1834.713	0	15000
Maize unbranded	291	2296.048	1576.649	0	10000
Tomato can	291	8388.832	6946.369	0	22500
Tomato pouch	291	3150.172	2991.622	0	18000
Full body type					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	291	2736.942	1966.355	500	20000
Maize unbranded	291	2295.017	1547.986	400	10000
Tomato can	291	8350.172	6920.122	0	22500
Tomato pouch	291	3161.512	3073.992	0	18000
Slim body type					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	294	2634.014	1937.425	300	16000
Maize unbranded	294	2172.279	1515.733	500	12000
Tomato can	294	8467.007	6926.506	300	22500
Tomato pouch	294	3208.673	3050.267	200	22500
Old age					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	294	2658.503	1927.733	500	15000
Maize unbranded	294	2162.075	1525.880	500	13000
Tomato can	294	8475	6924.552	300	22500
Tomato pouch	294	3168.878	3049.625	200	22500
Young age					
Variable	Obs	Mean	Std. Dev.	Min	Max
Maize branded	291	2708.007	1866.789	500	15000
Maize unbranded	291	2283.677	1564.080	350	10000
Tomato can	291	8387.629	6876.256	0	22500
Tomato pouch	291	3210.481	3089.446	0	18000

Appendix 7.6: WTP by observable signals and product type (first-order beliefs)

	(1)	(2)	(3)	(4)
	Unbranded Maize	Branded Maize	Tomato Pouch	Tomato Can
Expensive clothing	37.925	49.490	5.578	145.680**
	(44.179)	(41.383)	(55.426)	(72.735)
Chubby	-16.667	-3.265	-12.027	-28.351
	(44.406)	(41.596)	(55.711)	(73.109)
Traditional clothing	42.789	92.347**	76.769	107.245
	(44.179)	(41.383)	(55.426)	(72.735)
Old	29.184	-18.367	18.435	11.156
	(44.179)	(41.383)	(55.426)	(72.735)
Cheap clothing	37.285	-21.993	-50.859	-86.426
	(44.406)	(41.596)	(55.711)	(73.109)
Modern clothing	13.230	-42.955	-40.378	-36.323
	(44.406)	(41.596)	(55.711)	(73.109)
Respondent FE	Yes	Yes	Yes	Yes
Position FE	Yes	Yes	Yes	Yes
Mean WTP	2,107	2,508	2,863	6,230
StDev	1,682	2,032	2,948	6,332
Observations	2,340	2,340	2,340	2,340
R-squared	0.002	0.006	0.002	0.004
Farmers	585	585	585	585

Notes: Robust standard errors, clustered at the farmer level in parentheses. Right-hand-side variables are binary variables, e.g. expensive clothing = 1. Position FEs control for the position of each bid (1st, 2nd, …). WTP is measured in Naira (1,440 Naira ≈1 USD). *** p<0.01, ** p<0.05, * p<0.1. WTP.

Appendix 7.7: WTP by observable signals and product type (second-order beliefs)

	(1) Unbranded Maize	(2) Branded Maize	(3) Tomato Pouch	(4) Tomato Can
Expensive clothing	46.629	53.061	-34.694	-14.966
	(30.666)	(47.233)	(50.913)	(79.792)
Chubby	11.340	28.935	-48.969	-37.457
	(30.824)	(47.475)	(51.175)	(80.202)
Traditional clothing	9.184	34.184	36.224	-26.190
	(30.666)	(47.233)	(50.913)	(79.792)
Old	-10.204	24.490	-39.796	7.993
	(30.666)	(47.233)	(50.913)	(79.792)
Cheap clothing	19.759	35.464	3.608	74.227
	(30.824)	(47.475)	(51.175)	(80.202)
Modern clothing	12.371	-8.351	-60.309	1.203
	(30.824)	(47.475)	(51.175)	(80.202)
Respondent FE	Yes	Yes	Yes	Yes
Position FE	Yes	Yes	Yes	Yes
Mean WTP	4,107	4,142	4,078	4,224
StDev	4,594	4,650	4,691	4,859
Observations	2,340	2,340	2,340	2,340
R-squared	0.002	0.001	0.003	0.001
Farmers	585	585	585	585

Notes: Robust standard errors, clustered at the farmer level in parentheses. Right-hand-side variables are binary variables, e.g. expensive clothing = 1. Position FEs control for the position of each bid (1st, 2nd, …). WTP is measured in Naira (1,440 Naira ≈1 USD). *** p<0.01, ** p<0.05, * p<0.1. WTP.

Appendix 7.8: Sample of Best Cypermethrin insecticide



Appendix 7.9: Summary statistics of seed germination and vigour tests: 36 agrodealers sampled

Seed packages	N	Mean	SD	Min	Max
Panel A: Germination test					
Maize branded	22	94.591	3.081	89	100
Tomato pouch	36	97.944	1.881	94	100
Tomato tin	36	93.833	5.593	81	100
Maize unbranded	36	93.639	4.486	83	100
Panel B: Vigor test					
Maize branded	22	79.955	5.038	70	87
Tomato pouch	36	78.056	3.935	69	86
Tomato tin	36	76.75	5.277	61	84
Maize unbranded	36	76.222	4.323	67	83

Data source: Seed Technology Laboratory, Institute for Agricultural Research, Ahmadu Bello University, Samaru, Zaria.



Synthesis

8.1 Revisiting the research objectives

As set out in the introduction, the overarching objective of this thesis is to analyse how a market-driven approach impacts the development of vegetable seed systems in sub-Saharan Africa (SSA), and how this shapes farmer seed sourcing, livelihoods, and sector performance. In doing so, the thesis responds to two gaps in the literature: the absence of a focus on vegetable crops in academic research and the limited understanding of what it means, practically and normatively, to rely on a market-driven approach in a development context with private actors taking the lead. Three underlying objectives are addressed in the chapters of this thesis to contribute to the overarching objective, namely:

- Objective 1: To contribute to an improved understanding of the business models of the private vegetable seed sector in a development context.
- Objective 2: To assess the impact of a large-scale intervention in the vegetable seed sector by a corporate foundation on technology adoption and livelihood outcomes amongst different groups of farmers.
- Objective 3: To evaluate the extent to which product and agrodealer characteristics influence farmers' trust in quality seed and seed purchasing decisions.

The thesis addresses these objectives from complementary angles, moving from upstream questions of plant breeding and private-sector strategy to farmer-level interventions, and ultimately to last-mile seed distribution by agrodealers. First, Chapter 2 shows that private seed companies are willing to make substantial investments in hybrid breeding programmes when these are deemed commercially viable, and it becomes clear that vegetable crops are generally suitable candidates. Subsequently, Chapter 3 illustrates that seed companies are also prepared to invest in market development for their innovations, most notably hybrid varieties, through farmer capacity-building activities, thereby cultivating demand for their products. Chapter 4 then provides empirical evidence that hybrid (now referring to a public-private approach) market-driven agricultural extension services can stimulate vegetable cultivation as well as the adoption of improved varieties and good agricultural practices in the challenging context of northern Nigeria. This chapter further indicates positive income effects of commercial vegetable cultivation for farmers. Chapter 5, however, shows that treatment effects remain confined to directly targeted farmers, underscoring the limitations of relying on spillovers for broader diffusion. Chapter 6 explains how product and agrodealer traits represent key mechanisms to build trust along the value chain, encouraging farmers to invest in quality seed. Finally, Chapter 7 assesses how these mechanisms influence actual seed purchasing decisions of farmers, finding no such effect, as seed quality is generally high and seed markets appear to function effectively. Below, I synthesize contributions and implications around the three objectives, before drawing cross-cutting lessons.

Objective 1: To contribute to an improved understanding of the business models of the private vegetable seed sector in a development context.

The first objective of this thesis is addressed by Chapters 2 and 3. Together, these chapters contribute to a grounded understanding of the vision of the private seed sector on vegetable seed sector development. As profit-driven actors, the actions of all seed companies are shaped by

commercial feasibility. However, despite their shared profit-driven nature, seed companies are heterogeneous and specialize in different seed system functions based on advantages or constraints. Such constraints are particularly salient in decisions about breeding programmes to generate improved varieties, which require substantial resource investments. The findings of Chapters 2 and 3 are aligned: Chapter 2 explains the high costs of hybrid breeding and private sector decision-making processes based on biology and economics; Chapter 3 then explains the market dynamics based on the experiences of seed companies with variety development being an impossible investment for some.

These insights matter for SSA because they imply that private incentives to invest will be stronger in crops and segments where R&D and seed production costs can be recovered from the seed market, often aligning with higher-value, more commercialized production systems. This explains why vegetable breeding for SSA remains limited: most local seed companies continue to import vegetable seeds and barely any vegetable breeding is done in SSA by local or global companies (Afari-Sefa et al., 2012; Schreinemachers et al., 2021). Farmer demand for quality seed of improved varieties remains limited, and a consistent, sizeable market only exists for tomato and onion seed. Furthermore, the chapters show that the dominant private vision on vegetable seed sector development is a linear hybrid-oriented trajectory. In this regard, the vision of the private sector seems very much aligned with the traditional perspective on seed sector development of Douglas (1980) and the original pro-innovation theory of Rogers (1962). Open-pollinated varieties are not considered an end point, but rather a steppingstone on the path towards hybrids. Farmers are expected to gradually move towards more advanced seed types, and it is assumed that once they have crossed that bridge, they will also stick with more advanced seeds. Moreover, it is generally considered that the 'natural' property rights protection offered by hybrid varieties is required for seed markets to function as companies are reluctant to invest in open-source technologies.

This links back to the excludability-rivalry matrix discussed in the introduction confirming that the private seed sector invests in private (or club) goods underlying the need for exclusion. These results matter for policymakers and development practitioners because interventions should be designed to complement private sector activities, for example, by supporting viable business models for niche markets and less commercially attractive transitions. Several authors have highlighted the potential of informal commercial actors, which may target different crops and different farmers (Borman et al., 2025; Sperling & Almekinders, 2023). This sets up the next question: when formal private-sector actors invest in vegetable seed sector development, what impacts follow?

Objective 2: To assess the impact of a large-scale intervention in the vegetable seed sector by a corporate foundation on technology adoption and livelihood outcomes amongst different groups of farmers.

The second objective of this thesis is addressed by Chapters 4 and 5. Both chapters evaluate an agricultural extension programme focused on commercial vegetable production in northern Nigeria using a randomized controlled trial. The trial was conducted on agricultural extension services (AES) delivered by a corporate foundation (East-West Seed Knowledge Transfer) linked to a seed company (East-West Seed). The intervention was thus carried out by a public-private

partnership, as AES is co-funded by the seed company and public sector. There were two treatment groups: one only received training, whilst the other group also completed a test at the end of training and subsequently received a certificate during a public ceremony. The results indicate that such 'hybrid' market-driven approaches have potential, while simultaneously highlighting their limitations. The largest impact in Chapter 4 is observed in vegetable cultivation, which increases by 15 percentage points. Achieving this effect requires the foundation to target non-vegetable farmers, which lowers the efficiency of the intervention for the vegetable seed company in terms of targeting potential customers. Nonetheless, a positive and meaningful impact was also observed on the adoption of quality seed, good agricultural practices (GAP) and vegetable revenues.

The discussion further notes that while East-West Seed has strengthened its market position, it does not attain market dominance. Instead, the company shares the expanded market for quality seed with competitors, reflecting the public-good nature of the knowledge shared with farmers. Furthermore, Chapter 4 shows that the impact of the intervention was driven by a small group of commercial crops, reiterating the conclusions of Chapters 2 and 3 that market-driven approaches work for a limited group of crops and farmers. Both Chapters 4 and 5 focus on estimating average effects and do not explicitly account for heterogeneity across farmers. Chapter 4 shows a low increase in the average total number of GAP adopted (0.6 practice), while the increase in the percentage of farmers adopting more than 5 GAP is relatively high (11 percentage points). This suggests that a smaller group of farmers has adopted a larger number of practices, which may imply that, rather than diffusing broadly through communities, adoption initially is concentrated among a limited group of farmers. In turn, this could help explain why no spillover effects are detected in Chapter 5. Previous research underlined the heterogeneous impact of technology adoption with profitability being higher for some farmers and lower or non-existent for others (Suri, 2011). While we do not measure profitability differences for farmers, this would be one potential explanation for the observed results.

Furthermore, Chapter 5 shows that AES generate limited to no spillovers from targeted to non-targeted farmers. This pattern is consistent with the phased adoption process described by Rogers (1995), which emphasized that different types of knowledge are required at different stages of adoption. The findings also point to the complementary roles of didactic, social, and experiential learning mechanisms identified by Stone (2016). While targeted farmers in Chapter 4 progress through these stages, non-targeted farmers in Chapter 5 rely primarily on social learning, effectively bypassing didactic instruction. Conley and Udry (2010) demonstrated that farmers learn from their peers, particularly from close neighbours, but that such learning is often localized and incomplete, even when a technology is profitable. Consistent with this, Chapter 4 shows that targeted farmers adopt profitable technologies, whereas Chapter 5 shows non-targeted farmers do not follow suit, at least within the study period.

Chapters 4 and 5 further show that public certification neither increased adoption among targeted farmers nor enhanced spillovers to non-targeted farmers, raising questions about its effectiveness in strengthening didactic learning or signalling proficiency to peers. Previous research suggests that both monetary and social incentives can motivate AES providers to intensify diffusion efforts (Balew et al., 2023; BenYishay & Mobarak, 2018; Shikuku et al., 2019). However, Shikuku et al.

(2019) showed that such increased diffusion efforts do not necessarily translate into higher adoption among other farmers. Taken together, this suggests that while social incentives may influence diffusion efforts, they may not be sufficient to increase adoption among either recognized farmers or those exposed to such recognition. For the overarching objective of this thesis, these results imply that market-driven development approaches can be effective but are not inherently self-scaling; achieving broader impact requires deliberate design choices in seed system interventions to extend benefits beyond direct participants.

Objective 3: To evaluate the extent to which product and agrodealer characteristics influence farmers' trust in quality seed and seed purchasing decisions.

While the previous chapters establish how private incentives and extension shape adoption, Chapters 6 and 7 turn to a core mechanism that may constrain market-driven seed sector development: trust. Concerns about the quality of agricultural inputs sold in sub-Saharan African markets have received considerable attention in both the popular media and the scientific literature. Moreover, actors within the private seed sector have expressed concern that counterfeit seed may undermine market development (Keller & Csörgo, 2024). Even when farmers are willing and able to invest in improved seed, distrust in products supplied through market channels may discourage adoption. On the one hand, the findings of Chapters 6 and 7 are aligned in identifying meaningful variation in the trustworthiness of agrodealers. Both chapters suggest that farmers rely on a combination of formal signals (e.g., packaging, branding, certification) and informal cues (e.g., seller appearance, shop characteristics, and reputation) when making seed purchasing decisions. These patterns are consistent with environmental learning, whereby farmers draw on their own experiences, as well as social learning, as they observe where their peers choose to purchase inputs. Together, these findings challenge the common distinction between formal seed systems as regulated value chains and informal systems as socially embedded, showing instead that trust and relationships remain central even within formal markets.

On the other hand, the two chapters appear to yield partly divergent conclusions. While Chapter 6 documents seed quality concerns in the market, the seed quality tests reported in Chapter 7 suggest that seed quality is generally high. A potential explanation for these differences is the limited sample of agrodealers used in Chapter 7, which may have not included the most untrustworthy types who really sell counterfeit seed and operate in the shadows: agrodealers who engage in opportunistic behaviour are unlikely to maintain permanent shops or long-standing customer relationships. The findings of Chapter 6 suggest that farmers engage in screening behaviour that mitigates adverse selection in seed markets. They prefer agrodealers with stationary and nearby shops, as these characteristics are associated with accountability. By selecting such sellers, farmers reduce the risk of purchasing low-quality seed.

In addition, Chapter 6 shows that farmers are roughly evenly split between those who prefer to purchase seed from a familiar agrodealer and those who do not. By contrast, Chapter 7 finds no evidence that farmers' bids differ by agrodealer trustworthiness. This discrepancy may be driven by the experimental setting: in the BDM auctions, farmers may have focused on the research team organizing the transaction rather than on the identity of the agrodealer. In this case, the performative nature of the auction made it unsuitable to mirror a real-life situation (Kilwinger,

Spielman, et al., 2025). Also, limited seed availability and access may have made the experimental setting where seed was accessible at relatively low cost particularly attractive, thereby attenuating differences in preferences.

Importantly, Chapter 6 highlights the influential role of agrodealers beyond that of input suppliers. It describes how many agrodealers maintain long-term relationships with farmers, who return season after season. While Chapter 7 does not detect an effect of agrodealer signals on willingness to pay, the role of these social relationships warrants further investigation, potentially through experimental designs that incorporate familiar and unfamiliar agrodealers. Moreover, Chapter 6 shows that more vulnerable farmers are more reliant on agrodealers, who provide services such as repackaging seed into smaller quantities or offering credit. These practices, however, may not persist in more formalized market environments, where repackaging is often restricted by regulation or company policy. As a result, while formal quality assurance mechanisms may strengthen over time, they may also reduce access for more vulnerable farmers.

8.2 Synthesis

In this section, I respond to the overarching objective of this thesis to analyse how a market-driven approach impacts the development of vegetable seed systems in SSA, and how this shapes farmer seed sourcing, livelihoods, and sector performance. What emerges is not a single verdict which states that "market-driven approaches for seed sector development work" or "do not work" but a more conditional and policy-relevant synthesis.

Concerning farmer seed sourcing, market-driven approaches may expand farmers' choices, but they can also constrain these choices by steering farmers in a particular direction. As outlined earlier, seed sector development is commonly framed as increasing the availability, access, and use of quality seed. The private sector often frames this objective as "supporting farmer seed choices" (ISF, 2018), while the development sector emphasizes "seed diversity" enabling farmers to select preferred varieties from a broader range of options (Nabuuma et al., 2020). In practice, market development can indeed widen choice as more seed companies enter the market and offer different varieties at different price points. Chapters 2 and 3 reflect the private sector view that farmers remain in the lead because adoption only occurs when a variety offers perceived value. Chapter 7 further shows that farmers trust and value options accessed through market channels. At the same time, market-driven approaches often rest on an implicit assumption that there is a single desirable direction for farmers, namely: the uptake of quality seed of improved varieties. Chapter 3 illustrates how seed companies envision a linear progression towards more advanced seed types.

However, empirical evidence suggests that farmer practices are more dynamic. Farmers frequently mix and match seed sources and types to manage risk and meet diverse production, market, and consumption needs (Almekinders, Hebinck, et al., 2021). While Chapter 4 does not examine seasonal differences in the use of seed types, Chapter 6 provides qualitative evidence that alternating between buying and saving vegetable seed remains common. This indicates that the linear trajectory assumed by seed companies does not fully reflect farmer realities. Nevertheless, this trajectory may describe a subset of farmers: evidence from Chapters 6 and 7 suggests that farmers can become increasingly oriented towards specific seed products and brands, using them

as proxies for quality assurance. As seed markets develop, quality may become more strongly associated with private standards and branding. In sum, market-driven seed sector development appears to both broaden farmer options and channel farmer behaviour.

Regarding impacts on farmer livelihoods, market-driven approaches can quickly drive change when profitability and farmer capability align. Seed system transformation is embedded in broader food system change, which is typically slow and complex (Borman, 2025). Changes in seed use are therefore not isolated but intertwined with shifts in farming systems and market system (ter Steeg & Gildemacher, 2023). Variety choice, for instance, shapes market participation by influencing whether farmers target informal markets, supermarkets, or export chains. Market prices in turn affect farmers' willingness and ability to invest in seed and complementary inputs. Such investments require cost recovery through either higher volumes or higher output prices. Moreover, yield and quality gains often depend on more intensive cultivation practices, which demand additional labour, time, and management. Farmers must weigh these interlinked factors, and perceived risk or limited resources may very well lead to non-adoption.

Across the chapters, two conditions emerge as central to adoption: profitability and capability. Farmers must perceive a viable economic opportunity and possess the means to act on it. This highlights the role of market-driven agricultural extension in helping farmers recognize and pursue market opportunities. While Chapter 4 finds that measured financial gains are still modest, the rapid expansion of vegetable cultivation and uptake of improved practices is likely driven by perceived profitability and newly gained capability. However, Chapter 5 shows that scaling is not automatic or immediate: even if farmers have witnessed the profitability of technologies following adoption by their peers, they might not have the capabilities to adopt the same practices. Hence, market incentives alone are insufficient; impact ultimately hinges on the interaction between economic opportunity and farmer capacity.

Furthermore, while it seems like market-driven seed sector development is well suited to contribute to poverty alleviation, it seems less fit to contribute to food and nutrition security. Existing evidence shows that horticultural commercialization can raise farm incomes, indicating that market-driven approaches have the potential to contribute to poverty reduction (Muriithi & Matz, 2015; Rao & Qaim, 2011). Consistent with the literature, Chapter 4 contains some evidence that vegetable production improves financial wellbeing. However, no impact was observed on household food and nutrition security, reinforcing earlier findings that commercial horticulture interventions do not necessarily translate into improved nutritional outcomes (Gosa et al., 2024; Kubitza et al., 2024). It seems like the commercial orientation of market-driven approaches may constrain their broader impact. Chapters 2 and 3 confirm that seed companies prioritize commercial farmers and commercial vegetable crops in their investment and market development strategies. While these farmers certainly benefit from company investments, they do not constitute the most vulnerable group. Moreover, Chapter 3 shows that tomato and onion seed account for a substantial share of seed company revenues, a finding echoed in Chapter 4, where the total value of production of the top three vegetables, tomato, onion, and chili pepper, is nearly equal to that of all other vegetables combined.

As mentioned in the introduction, vegetables are frequently categorized as crops, which are well-served by formal seed systems or "commercialized seed delivery models" (Louwaars & de Boef, 2012; Mausch et al., 2021). However, this seems to apply only to a rather narrow set of commercial vegetables. Many or most vegetables will likely remain dependent on farmers' own initiatives or public-sector involvement. Both seed companies and commercial farmers tend to focus on crops for which market demand already exists and there is sufficient scale. Consequently, market-driven approaches will likely only increase the production and availability of a limited number of vegetables at the household and market level. Most studies still consider vegetables as one food group, whilst the diversity of nutrients within the food group makes vegetables such a crucial component of healthy diets (Harris et al., 2022). Moreover, vegetables are not equally nutritious, and markets seem to favour the less nutritious vegetables: tomatoes and onions (Di Noia, 2014; Steenhuijsen Piters et al., 2021). Higher incomes increase financial access to diverse diets, but the limited availability of diverse vegetables may constrain physical access. Broader impact depends on both incentivizing farmers to diversify crop production and strengthening consumer demand for these crops underscoring the need for complementary supply- and demand-side interventions (Harris et al., 2023). Moreover, it underlines an inherent tension between private and public interests: markets prefer scale and uniformity, while healthy diets require diversity.

In terms of sector performance, the chapters converge on a similar conclusion: market-driven approaches can strengthen sector performance, but their benefits tend to be selective rather than broadly inclusive. This reflects a structural tension between public policy objectives such as widespread access to quality seed and contributions to food and nutrition security and the commercial interests of private actors, which depend on excludability and rivalry to sustain viable business models. Chapter 2 shows that private breeding efforts concentrate on a limited range of crops and prioritize hybrid breeding systems, which provide built-in protection against seed recycling and thus support commercial returns. Chapter 3 reinforces this pattern, demonstrating that companies mainly target commercially oriented farmers and crops. While firms (co-)invest in market development for hybrids, similar investments are less common for open-pollinated varieties. In line with this logic, the interventions assessed in Chapters 4 and 5 centre on introducing hybrid tomato varieties (and to a lesser extent improved onion and chili varieties). These chapters also focus on the promotion of good agricultural practices, but the leitmotif to do so is to unlock the potential of improved varieties. Chapters 6 and 7 further indicate that private quality assurance mechanisms can provide certainty regarding seed quality for farmers who are willing and able to pay.

These findings suggest that while seed sector performance may improve, access is differentiated: market-driven approaches tend to serve farmers and crops with the strongest commercial potential, whereas performance gains are limited for others. This echoes the concern raised in the introduction that market-driven approaches risk leaving behind farmers or crops that do not align with commercial priorities and who falls behind is left behind (Westengen et al., 2023). An alternative trajectory has been proposed by Beumer et al. (2022) who challenge the dominance of market-based approaches and explore how the principles of reciprocity, redistribution and subsistence can also effectively drive the diffusion of agricultural technologies. Such trajectories do not focus on the promotion of expensive agricultural inputs, but on alternative methods to raise productivity. Taken together, the chapters suggest that market-driven approaches improve sector

performance where commercial incentives are strong, but they are not neutral in their distributional effects. Strengthening overall sector performance therefore requires a mix of market-based and non-market approaches to ensure that efficiency gains do not come at the expense of inclusiveness.

A final point that needs to be emphasized is the central role of the public sector in market-driven seed sector development. As outlined in the introduction, the public sector needs to facilitate the private sector in market-driven seed sector development because markets are not yet functional. Accordingly, a consistent pattern emerges across the chapters, which shows how the private sector depends on public investments and institutions. For variety development, Chapter 2 and 3 note the dominance of seed companies in vegetable breeding while also highlighting the importance of public–private partnerships (Dhillon et al., 2020). A public research organization, the World Vegetable Center, maintains breeding programmes for open-pollinated varieties and provides genetic resources to seed companies in SSA (Schreinemachers et al., 2017). Chapter 3 explains that these seed companies focus on seed production as they lack the resources to initiate breeding programmes themselves, reinforcing their reliance on public research. In seed dissemination, evidence from Chapter 7, which finds generally good seed quality in market samples, suggests that quality assurance systems are at least partially effective. Regulatory oversight remains necessary here to deter fraud. Still, Chapter 6 shows that farmer concerns regarding seed quality are persistent underling the importance to improve farmer literacy regarding seed products. Finally, regarding seed use, Chapter 3 stresses that stimulating demand for quality seed of improved varieties requires public and private investments in farmer training and awareness raising. Such activities are often qualified as 'pre-commercial' and co-funding is required to persuade private actors to target such undeveloped markets. Chapters 4 and 5 illustrate this complementarity through a hybrid intervention, which is co-funded by public and private actors. Overall, this thesis suggests that market-driven seed sector development is underpinned by public involvement mostly in research, regulation, and farmer capacity building.

In summary, this thesis demonstrates that market-driven vegetable seed sector development can foster technological innovation, improve access to such technologies, and contribute to farmer livelihood improvements. Yet, market-driven trajectories tend to be selective, narrowing the set of farmers, crops, and market segments that are served. Moreover, market-driven approaches require the presence of practical support for farmers to unlock the potential of these technologies as well as profitable opportunities to gain a return on their investment in quality seed. Finally, effective market-driven seed systems rely on a combination of formal and informal trust and quality assurance mechanisms that enable farmers to purchase quality seed with confidence. This implies that the effectiveness of market-driven approaches hinges on the alignment of three elements: a viable business case for technology development and service provision, farmers' capacity to capture economic gains from the technology, and farmer trust in product markets.

8.3 Implications for policy, private-sector strategy, and development practice

The findings of this thesis carry several implications for policy, private-sector strategy, and development practice in market-driven seed sector development. First, they underscore the importance of treating the private seed sector as a heterogeneous rather than homogeneous group

of actors. All seed companies are profit-driven entities, but Chapter 3 shows that firms perform distinct functions within seed systems, ranging from variety development and seed production to distribution and farmer engagement. While some companies focus on open-pollinated varieties, others exclusively sell hybrid varieties; while some participate in seed tenders, others deliberately avoid them, as they oppose the free distribution of seed; while some have corporate foundations to build farmer capacity, others only target on the most advanced farmers skimming the cream off the top. Policymakers and development actors should therefore avoid generic assumptions about "the private seed sector" and instead assess which specific functions are provided by which private-sector actors in specific contexts to identify suitable development partners. Also, they should assess which functions are still underprovided to determine their subsequent course of action.

Second, the results highlight the importance of farmer capacity building in any (vegetable) seed sector development trajectory. Evidence from agricultural extension services in Chapter 4 demonstrates that investments in farmer knowledge and production practices can meaningfully increase the adoption of improved vegetable varieties and associated technologies. Chapter 5 then underlines that diffusion cannot be assumed: dissemination may require deliberately designed mechanisms. Chapters 6 suggests that the importance of farmer capacity building with respect to seed product literacy. In the absence of effective enforcement systems, farmers' ability to distinguish between high- and low-quality seed can contribute to fraud-resistant markets. Farmer capacity building should therefore be recognized as an essential component of seed sector development strategies. Moreover, the focus of capacity building should not be limited to 'growing the crop' and 'finding a product market' but can also contribute to solving other issues such as recognizing seed quality.

Third, inclusivity needs to be made explicit and operational in market-driven seed sector development strategies if broader development objectives are to be achieved. Public actors need to clearly define their development objectives and identify which farmer groups they aim to serve, recognizing that these groups may not always coincide with the private sector's target markets. As shown in Chapters 2 and 3, market-driven approaches naturally prioritize commercially attractive crops and farmer segments. This focus thus requires additional efforts to support less profitable crops, production systems, and farmer groups. Addressing these gaps may require the public sector to move beyond a market-fixing role towards a market-creating role. While such efforts may reduce the commercial pull for private actors and likely require greater public investment, they can lead to more inclusive market development over time. Importantly, pursuing inclusion does not imply abandoning a market orientation; rather, it involves sequencing and supporting market development so that underserved segments can eventually become viable market participants. The guiding principle is complementarity: public interventions should target areas where private action is unlikely to emerge on its own, while avoiding duplication in commercially viable segments.

Fourth, trust is a prerequisite for seed markets to function and as seed prices increase, so does the financial risk associated with purchase decisions. Efforts to promote more technologically advanced seed therefore need to be accompanied by stronger and more credible quality assurance mechanisms. Chapter 6 shows that farmers may opt out of market participation altogether when perceived risks are high, preferring to rely on farm-saved seed because its quality is predictable. Also, it shows that seed companies do succeed in building strong brands and some farmers feel

sufficiently confident to rely on such product signals. Together, Chapters 6 and 7 show that quality uncertainty and trust are not peripheral issues, but shape how farmers engage with input markets and how they read products and sellers. Private actors can look to the public sector to enforce seed regulations, but this may remain challenging. Interventions that strengthen accountability and farmers' ability to recognize credible quality signals (like certificates) may therefore be as important as varietal innovation and distribution expansion. Vegetable seed companies can partially take matters into their own hands and invest in securing and differentiating their products using packaging, branding, and traceability mechanisms. In addition, companies should collaborate with public actors and NGOs to invest in farmer awareness of seed quality. Strengthening these mechanisms is essential for ensuring the effective functioning of seed markets: market-driven approaches that fail to attend to the social and institutional conditions underlying trust risk underperforming.

8.4 Questions for future research

This section identifies key directions for future research, reflecting both the methodological constraints of this thesis and the technological landscape of the seed sector. During the research process, additional questions came into view that fell beyond the scope of the present study. First, there are two practical limitations, which spark additional questions: the geographic focus of this thesis and its limited time horizon. In terms of contextual variation, Chapters 4-7 all draw from data from northern Nigeria, providing insights into this specific setting. Additional comparative studies would help clarify whether the findings are location specific or more broadly applicable. In particular, the findings related to trust may be shaped by local culture and social norms. Moreover, northern Nigeria represents a context characterized by insecurity and political instability. These factors complicated both project implementation and research activities. One consequence is the disruption of input and output markets: vegetable seed imports may be constrained, and farmers may face difficulties accessing output markets for their produce. Future studies could compare the impacts of similar programmes implemented in more stable settings. Another practical limitation is the limited time horizon of the analyses. Chapters 4 and 5 provide evidence on technology adoption, livelihood impacts and diffusion within the evaluation period. However, some impacts, particularly those related to farmer livelihoods and diffusion, may only materialize over longer time horizons. This could explain the modest financial impact of the treatment on targeted farmers in Chapter 4 as well as the absence of spillover effects in Chapter 5. Longer-term follow-up studies would be useful to assess whether initial adoption is sustained, how the intervention impacts household welfare over time and whether spillovers emerge gradually.

Other questions concern the comparability of different approaches to seed sector development. This thesis focuses on market-driven approaches, in which the private sector takes the lead while the public sector plays a facilitating role. Although the thesis provides evidence on the effectiveness of market-driven agricultural extension services in northern Nigeria, it does not allow for a direct comparison between market and non-market approaches. Such a comparison would be valuable for several reasons. First, the technological focus of interventions could differ. As discussed earlier, market-driven approaches tend to promote technologies linked to commercial input markets, since these align with private-sector business models (Beumer et al., 2022). Chapter 3, for instance, shows that seed companies are more inclined to invest in farmer capacity building when it supports

the uptake of hybrids. Accordingly, the intervention examined in Chapters 4 and 5 centres on the introduction of hybrid vegetable varieties. By contrast, non-market approaches may place greater emphasis on low-cost practices (and non-excludable goods) that do not depend on repeated input purchases. Second, market and non-market approaches may reach different types of farmers. Market-driven initiatives are more likely to focus on farmers who represent potential customers for seed and other inputs. In line with this, the communities selected for Chapters 4 and 5 were chosen by the foundation based on their vegetable production potential. Non-market approaches might instead prioritize more resource-constrained farmers, for whom barriers to adoption are (even) higher. Third, non-market approaches may put stronger emphasis on crop diversity. Whereas market approaches often concentrate on a limited set of commercially attractive crops, non-market interventions may be better positioned to support minor crops or diversified production systems. These considerations suggest that different development approaches may not be substitutes but play complementary roles: research can help clarify their relative strengths, trade-offs, and potential synergies. In addition, the thesis focuses primarily on vegetable seed sector development, which limits the scope for cross-crop comparison. Although Chapter 7 includes both maize and tomato seed allowing for comparison, the other chapters focus exclusively on vegetables. Future research could address these limitations through study designs that explicitly compare different approaches across a range of crops.

Furthermore, there is the question of gender dynamics in vegetable production. In SSA, home gardens for vegetable production are often considered a "women's domain" (Kramer & Trachtman, 2024). On the contrary, commercial vegetable production seems to be more of a male domain in northern Nigeria. Chapter 3 already highlights the distinction between commercial and subsistence vegetable production systems with commercial systems. Still, Chapter 4 and 5 might have failed to grasp certain gender dynamics. Michler et al. (2019) note how knowledge- and management-intensive technologies are frequently managed by specific household members, often women. This makes labour inputs difficult to observe and easy to underestimate. Given the labour-intensive nature of vegetable farming, future studies should account for labour costs when assessing profitability (Steenhuijsen Piters et al., 2021). Moreover, these studies should pay particular attention to the role of women: is commercial vegetable production still profitable if all additional hours of labour of (female) household members are considered? Chapter 4 and 5 cannot answer this question as hours of labour per household member were not recorded. Furthermore, Chapter 6 and 7 show that gender dynamics shape seed sourcing practices. Chapter 6 highlights that women frequently rely on their husbands to source vegetable seed on their behalf. This dependence is particularly pronounced in more remote communities. As a result, the decision was made in Chapter 7 to largely exclude women from the experiment. Consequently, while Chapter 6 provides some qualitative insights into gendered dynamics in seed sourcing, Chapter 7 does not offer quantitative evidence to compare seed purchasing decisions between men and women. Future research can address this gap by designing methods that capture women's preferences and constraints in seed markets.

The final question concerns the relationship between seed sector development and broader food system transformation. Earlier in this section, the interdependence between seed, farm, and market systems was highlighted; these linkages are not always mutually reinforcing. In many contexts, the intensification of farming systems has been associated with increased pest and disease pressure

(Gould et al., 2018). Farmers tend to respond by adopting more technologically advanced inputs, including pesticides and more resistant varieties. This dynamic has been frequently described as an agricultural "treadmill," in which rising input use contributes to biodiversity loss and agroecosystem simplification, thereby reinforcing dependence on external inputs (Bakker et al., 2020; Vialatte et al., 2025). Emerging breeding approaches, including new genomic techniques, may help introduce resistance traits more quickly and precisely. Yet these innovations still leave us on the treadmill. Whatever humans design: "natural selection is likely to result in a response" (Gould et al., 2018). This raises a broader question, namely: to what extent do current innovation trajectories address root causes rather than symptoms? Most technologies help farmers cope within the existing system, rather than redesigning the systems to reduce vulnerability. Market-driven seed sector development can both reinforce and alleviate these dynamics. On the one hand, severe pest or disease pressure may push farmers toward improved varieties with stronger resistance traits. As noted in Chapter 4, for instance, certain traditional tomato varieties in Kenya are no longer used because they cannot withstand current disease pressures. On the other hand, resistant varieties sold by private actors are more expensive, and when output prices remain low, farmers may continue using older varieties that require higher chemical use. Food system transformation likely requires combining market and non-market approaches with greater public steering toward low-input and system-level solutions. Moreover, non-market approaches are likely better suited to address certain systemic environmental challenges (Beumer et al., 2022). Accordingly, Silva et al. (2021) have advocated public investments aimed at achieving "the same outputs with fewer inputs" for sustainable intensification.

8.5 Conclusion

By examining private-sector business models, evaluating a large-scale seed system intervention, and studying trust in seed markets, this thesis develops a nuanced and policy-relevant understanding of the impact of market-driven approaches on vegetable seed sector development in SSA. Market-driven approaches can stimulate technological innovation and contribute to increase of commercial vegetable production and technology adoption where commercial opportunities are strong. However, market-driven seed sector development will (initially) only target certain crops, seed types and farmers. Moreover, market-driven trajectories do not automatically scale through diffusion, do not guarantee livelihood gains across multiple outcome dimensions, and depend on market environments in which quality is effectively managed. There appears to be a structural tension between public policy objectives of inclusion and the private sector's need for excludability and rivalry to sustain viable business models.

Regarding the first objective, the thesis demonstrates that the private seed sector is not homogeneous. Companies differ in their roles, capacities, and strategic orientations. The dominant private-sector vision follows a linear, hybrid-oriented trajectory that assumes farmers will gradually progress toward more advanced seed types. Yet farmer realities are often more dynamic, with continued reliance on mixed seed sourcing strategies. Regarding the second objective, the impact assessment shows that market-driven extension models can increase the adoption of agricultural technologies and can support income gains from commercial vegetable production. However, these effects are not self-scaling: adoption tends to be concentrated among a subset of farmers, and spillovers to untargeted farmers are limited. Concerning the third objective, the thesis shows

that trust is a foundational condition for market-based seed systems. Although the evidence suggests that seed quality in the studied markets is generally high and that formal quality assurance can sometimes substitute for interpersonal trust, risk perceptions at continue to shape farmer decision-making.

Across these strands, one cross-cutting insight emerges: market-driven approaches to vegetable seed sector development depend on sustained public involvement in research, regulation, and capacity building. Market-driven approaches do not replace public action; they build on it. The implication is therefore not to choose between private and public interventions, but to combine them strategically. The private seed sector clearly has a role to play, yet complementary public initiatives remain essential for achieving robust and inclusive vegetable seed systems in SSA. A "hybrid" approach referring here to a combination of public and private strategies rather than hybrid seed appears most promising. This involves leveraging private-sector dynamism where incentives align, while directing public resources to areas where market incentives are weak. Such efforts are particularly relevant for plant breeding, farmer capability development, and last-mile quality assurance systems. Under these conditions, market-driven seed sector development can be part of a strategy that realizes the potential of vegetable crops for smallholder livelihoods.



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Summary

This thesis examines how a market-driven approach shapes the development of vegetable seed systems in sub-Saharan Africa (SSA), and how this affects farmer seed sourcing, livelihoods, and sector performance. It addresses a blind spot in the literature at the intersection of two underexplored areas. First, despite their importance for nutrition and income generation, vegetable crops have received far less scholarly and policy attention than staple crops such as cereals. Second, although private actors are increasingly expected to drive seed sector development, there is still limited understanding of what reliance on market-based approaches means in practice. Against this background, the thesis investigates how a market-driven approach impacts the development of vegetable seed systems in SSA, and how this shapes farmer seed sourcing, livelihoods, and sector performance.

Three underlying objectives guide the analysis. The first is to improve understanding of the business models of vegetable seed companies operating in a development context. The second is to assess the impact of a large-scale intervention in the vegetable seed sector by a corporate foundation on technology adoption and livelihood outcomes among different groups of farmers. The third is to evaluate the extent to which product and agrodealer characteristics influence farmers' trust in seed quality and seed purchasing decisions. To address these objectives, the thesis combines multiple methods and perspectives. It moves from upstream questions of breeding feasibility and company strategy to farmer-level intervention effects, and finally to the last mile of seed distribution. The research design combines literature review, qualitative methods, a randomized controlled trial (RCT), and experiments. Across the chapters, the analysis draws on data from SSA more broadly and from northern Nigeria, with four chapters focusing specifically on vegetable seed systems in Kano and Kaduna states.

The first part of the thesis examines how private incentives shape vegetable seed sector development. Chapter 2 analyses the conditions under which commercial plant breeders invest in hybrid breeding programmes for food crops. Hybrid breeding is often associated with technological progress because it can increase yields, improve product quality, and strengthen resistance to biotic and abiotic stresses. At the same time, it remains socially and politically contested, especially where it is seen as aligned primarily with high-input, commercial agriculture. By combining insights from breeding science and business economics, the chapter shows that the feasibility of hybrid breeding depends on both biological and economic conditions. Whether hybrid breeding is commercially attractive varies by crop and business case. The chapter concludes that the most important constraint is often the high cost of seed production. This finding helps explain why commercial breeding efforts are concentrated in some crops and not in others, and why public or donor support may remain necessary for crops that are technically possible to improve but commercially unattractive. For the broader argument of the thesis, the chapter demonstrates that market-driven seed sector development starts from a logic of commercial feasibility rather than from public goals such as inclusion or nutrition.

Chapter 3 extends this analysis by examining the business models of leading vegetable seed companies operating in SSA. Based on in-depth interviews with company representatives, it demonstrates that the private seed sector is not a homogeneous group of profit-driven actors with a single strategy. Using ideal-type analysis, the chapter identifies a set of business model typologies and shows that these different models jointly shape seed sector development. The chapter shows

how seed companies in SSA have specialized in the four seed system functions: variety development, seed production, seed dissemination, and seed use. These specializations mean that firms currently play complementary roles with different companies applying different business models and serving different market segments. At the same time, the chapter finds that companies broadly share a common vision of seed sector development as a linear transition in which farmers gradually move towards increasingly advanced seed types, especially hybrids. In this view, open-pollinated varieties are often treated as transitional products rather than endpoints in themselves. Moreover, whilst companies are investing in breeding and market development for hybrid seed, they tend to not invest in open-pollinated varieties because these do not allow them to gain a return on their investments. Companies tend to be focused on commercial crops and commercial farmers who can invest in quality seed based on their market sales. The chapter therefore contributes two important insights. First, the private sector is heterogeneous and second, despite this diversity, the dominant private-sector vision remains oriented towards commercially viable crops, commercially oriented farmers, and seed types that allow firms to recover investments. Together, Chapters 2 and 3 show that private-sector engagement can stimulate innovation and market formation, but that it is selective by design.

The second part of the thesis evaluates whether such market-driven trajectories generate meaningful benefits for farmers. Chapters 4 and 5 study a large-scale agricultural extension programme implemented by East-West Seed Knowledge Transfer (EWS-KT) in northern Nigeria. This programme is particularly relevant because it combines development and commercial logics. This extension programme is 'market-driven' because it contributes to the development of a viable product market for East-West Seed as well as other seed companies. Moreover, the programme focuses on commercial vegetable production and hence, farmer attendance is also driven by commercial motives. Both chapters draw on a RCT implemented in 150 communities, with a control group, a treatment group receiving agricultural extension, and a second treatment group receiving extension combined with a test-based public certification component.

Chapter 4 assesses the direct effects of this intervention on targeted farmers. The results show that the intervention led to a substantial increase in the number of farmers cultivating vegetables, the adoption of improved vegetable varieties and the uptake of good agricultural practices. In addition, targeted farmers experienced gains in vegetable revenues, which seem primarily driven by tomato, onion, and chili pepper production. Amongst targeted farmers, test-based public certification did not generate consistent additional gains in technology adoption. Furthermore, no program effects were detected for vegetable cultivation in home gardens or for household food and nutrition security outcomes. This finding confirms that interventions focused on commercial vegetable production primarily serve poverty alleviation rather than directly strengthening food security. This chapter may constitute the core empirical contribution of the thesis: it confirms that market-driven seed sector development can shift behaviour under real-world conditions. Farmers adopt both the low-cost good agricultural practices as well as expensive practices like the use of improved vegetable varieties, which then translates into financial gains. However, while commercial vegetable production may improve economic outcomes, broader effects on food and nutrition are not automatic or immediate.

Subsequently, Chapter 5 tests whether the benefits of market-driven interventions extend beyond direct beneficiaries through social learning. While Chapter 4 focuses on the comparison of targeted farmers in treatment communities with farmers in control communities, Chapter 5 focuses on the comparison of untargeted farmers in treatment communities with farmers in control communities. Moreover, it checks whether the test-based certification treatment might have enhanced spillover effects among untargeted farmers by signalling which farmers have received training. However, we find little evidence that the intervention led to meaningful diffusion of technologies to non-targeted farmers within the study period, indicating that social learning mechanisms were insufficient. Alternatively, it could be the case that the one-year timeline is simply insufficient for spillover effects to occur. There was no significant effect on vegetable cultivation, use of improved seed, use of government-certified seeds, or the adoption of GAPs among untargeted farmers. Moreover, public certification did not meaningfully enhance diffusion, apart from a small effect on the use of government-certified seed. These findings challenge the assumption that knowledge generated through market-driven interventions will automatically spread through communities. Still, the absence of observable spillover effects should not be interpreted as evidence that social learning or certification mechanisms are inherently ineffective. Rather, the findings suggest that diffusion processes may require more time or interventions must facilitate information exchange more explicitly. Taken together, Chapters 4 and 5 indicate that market-driven approaches can work, but that they are not self-scaling. Impact tends to remain concentrated among directly targeted farmers, at least in the short run.

The third part of the thesis turns to the role of trust in seed markets. This is an important addition because even where improved seeds are available and potentially profitable, adoption may remain low if farmers do not trust the quality of the products being sold. Chapters 6 and 7 therefore analyse how trust operates in the last mile of vegetable seed distribution, with a particular focus on agrodealers. Chapter 6 uses a qualitative research design to examine how farmers assess seed quality and decide where to purchase seed in northern Nigeria. It shows that farmers rely on a combination of product signals and seller characteristics when making purchasing decisions. Product-level signals include packaging, branding, and labelling. Agrodealer-level signals include reputation, knowledge, shop appearance, social embeddedness, and accountability. The findings further show that trust develops gradually through repeated interaction. Moreover, it shows that agrodealers are not merely input suppliers: they often provide information, offer credit, and adapt products to farmer needs, for example by repackaging seed into smaller quantities. The chapter also finds that trust in product brands can partially substitute for trust in the seller, especially where farmers are familiar with specific seed products. Overall, the chapter demonstrates that vegetable seed markets are socially embedded rather than purely transactional. This matters for seed sector development because it implies that last-mile distribution, retailer reliability, and farmer literacy regarding product signals are central to market functioning.

Chapter 7 investigates these issues experimentally. It examines whether farmers distinguish between more and less trustworthy agrodealers, whether perceived trustworthiness influences willingness to pay for seed, and whether formal and informal signals help farmers navigate quality uncertainty. The study finds that farmers do use observable agrodealer characteristics to distinguish between more and less trustworthy sellers, and that these perceptions correlate with actual agrodealer trustworthiness as measured through a mystery shopper exercise regarding a sub-

standard insecticide. However, the analysis does not find that perceived agrodealer trustworthiness affects farmers' willingness to pay for maize or tomato seed. This result is consistent with the seed quality tests conducted in the study, which suggest that seed quality was generally high across agrodealer types. In other words, while farmers appear to screen sellers and use trust-related signals, actual differences in product quality were limited in the sample studied. Together, Chapters 6 and 7 suggest that trust remains central to farmer decision-making, but also that its role may be more about enabling participation in input markets than about generating price differentiation under conditions where product quality is already reasonably assured.

The synthesis across chapters leads to a nuanced conclusion. The thesis does not support a simple claim that market-driven approaches either succeed or fail. Rather, it shows that their effects are conditional. Market-driven vegetable seed sector development can stimulate innovation, promote technology adoption and improve some farmer livelihood outcomes. At the same time, these effects are uneven and selective. They are strongest where three conditions align: first, where there is a viable business case for private investment; second, where farmers have the capability to capture gains from the technology; and third, where trust and quality assurance mechanisms allow farmers to engage with seed markets confidently. This synthesis has several implications. In terms of farmer seed sourcing, market-driven approaches can expand options by increasing the availability of improved seed and strengthening retail channels. Yet they can also narrow trajectories by steering farmers towards particular crops, varieties, and brands. The private-sector vision documented in the thesis assumes a relatively linear progression towards more advanced seed types, especially hybrids. However, farmer practices are often more flexible. Farmers combine seed buying with saving and manage risk through diversification. Market-driven development therefore both broadens and channels farmer choice.

With respect to livelihoods, the thesis finds that market-driven interventions can support income generation, particularly where technologies are profitable, and farmers can adopt them. However, these gains do not automatically translate into broader food and nutrition security outcomes. This reflects a deeper tension in market-driven seed sector development. Commercial actors tend to prioritise crops and farmer segments where demand is already strong, and returns can be recovered. In practice, this often means a focus on a relatively narrow set of vegetables and on more commercially oriented farmers. Similarly, regarding sector performance, the thesis shows that market-driven approaches can improve efficiency, strengthen innovation, and contribute to the emergence of functional markets for quality seed. However, performance gains are also selective rather inclusive. The thesis therefore highlights a structural tension between public objectives, such as inclusion and food security, and private incentives, which depend on excludability and rivalry to sustain business models.

A final cross-cutting insight is that market-driven seed sector development depends fundamentally on public involvement. Throughout the thesis, public action appears not as an alternative to markets, but as a precondition for their functioning. Public support remains important in breeding, especially for less commercially attractive crops; in regulation and quality assurance; and in farmer capacity building. The intervention evaluated in northern Nigeria itself illustrates this hybrid character, combining private-sector incentives with public-private funding for agricultural extension. The broader conclusion is therefore not that public actors should withdraw and let

markets take over, nor that private actors should be sidelined. Rather, the most promising pathway is a 'hybrid' approach in which private-sector dynamism is leveraged where incentives align, while public actors deliberately support functions, crops, and farmer groups that markets alone are unlikely to serve.

In conclusion, this thesis contributes to the literature by placing vegetable seed systems and private-sector development at the centre of analysis. It shows that market-driven approaches can play a meaningful role in strengthening vegetable seed systems in SSA, but that their effects are conditional, selective, and dependent on public support. Market-driven approaches are most effective where commercial viability, farmer capability, and trust in markets reinforce one another. Where one or more of these conditions is absent, their impact is likely to remain limited. The thesis therefore argues for a more differentiated understanding of market-driven seed sector development: one that recognises both its potential and its boundaries, and that treats public and private action as complementary rather than competing pathways towards inclusive and resilient vegetable seed systems.



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My PhD journey has been an odyssey: a journey full of adventure, unexpected turns and encounters. Luckily, it only took me a little longer than expected to make it home. Considering the rather dramatic ending to my years at Wageningen, quite literally falling on my face, I am especially grateful that I made it across the finish line. These past years have made one thing abundantly clear: some things matter far more than others. Above all, it is the people who surround you and make you feel heard, seen and loved. I am deeply grateful for my community, my travel companions, and I carry each of you with me in my heart wherever I go.

Being an 'external PhD' means constantly running two parallel tracks in your brain. One track represents your real-world job, offering tangible, short-term rewards. The other is your PhD, demanding years of work in exchange for a distant, rather abstract reward. In retrospect, I could certainly have made things easier for myself by focusing on just one thing, but that has never really been my vibe. I loved working with the SeedNL team, the ICFG team, and, finally, Team Tanka (tijgers). These jobs allowed me to travel (even more) and develop myself beyond academia. Moreover, they reflected the need I felt to pursue real-world impact alongside my PhD. Through these jobs, I had the opportunity to shape seed system projects across sub-Saharan Africa and, later on, manage a Europe-focused food systems grant portfolio.

The seed for this PhD was planted while I was working in Rwanda for Solynta, a hybrid potato company. I will never forget how Gertjan shoved the 'potato bible' into my hands right before we boarded a flight to Ethiopia, from where we would continue to Rwanda. Before I had any actual work experience, Gertjan believed in me and entrusted me with what was perhaps a little too much responsibility. Thus, he gave me the steepest learning curve of my career, transforming my book smarts into something more streetwise while working on agricultural projects across East Africa. Alongside elevated stress levels, Gertjan always offered wise words of advice and plenty of laughter and continues to do so today. Thank you Gertjan for kickstarting my adventurous career path.

In Rwanda, I experienced first-hand just how difficult it is to introduce a new technology in an agricultural system. Potato farmers were not only expected to adopt a new variety, but to switch to a new type of planting material. Somehow, we had to convince them that this was the way to go. Working in the field with my dear colleague, the potato powerhouse, Bonnie, I quickly realised that this was not going to be easy and not only because chimpanzees were feasting on our trail fields. New technologies rarely sell themselves, but instead they have to find (or fight) their place in(to) an existing system, and that system has an enormous advantage: it is familiar. What also became clear was that the vegetable sector was ahead in this respect: building farmers' knowledge and simultaneously growing markets for their products. I then began to wonder whether the vegetable seed sector might hold lessons for other crops.

Meanwhile, I was trying to get up to speed with the world of plant breeding, about which I knew very little. My greatest mentor in this regard was Pim: the father of the hybrid potato, though he still insists he is, first and foremost, a tomato breeder. During our first conversation, I boldly stated that Dutch tomatoes were nothing more than flavourless *wasserbomben*. Pim came to the defence of 'his' tomatoes, explaining that they were among the most commercially successful tomatoes ever developed. Fair enough. Pim then invited me to co-author my first academic paper. As a social scientist, I suddenly found myself writing alongside three plant-breeding experts about the commercial viability of hybrid breeding systems for food crops. It was the best introduction I could have wished for to this fascinating world and I think the combination of my outsider's perspective and their deep expertise, turned the paper into an accessible and interesting overview. It now forms Chapter 2 of this thesis, was published in Nature Plants and, more importantly, it convinced me to embark on this PhD journey. Thank you, Pim, for your mentorship and our

'walky-talkies', and thank you also to my fellow co-authors, Paul and Richard, for the countless interesting discussions.

My dream of doing a PhD on vegetable seed sector development became a reality thanks to four women: An, Anke, Anneke, and Maaike. Without them, I do not think it would have happened. I remember the phone call with An during which I explained the research I wanted to do: studying the impact of the business models of Dutch vegetable seed companies on smallholder livelihoods. With the support of An, Anke, Anneke, and Maaike, I managed to successfully pitch my research proposal vis-à-vis the VTZ Board of Plantum. I was waiting at the airport in Mozambique when Anke called to tell me that the board had approved it: I was incredibly relieved. So thank you, An, Anke, Anneke and Maaike, for making a dream come true. Of course, I am also deeply grateful to the VTZ Board of Plantum for providing the financial support that made this research possible.

Now that I have finally arrived at the start of my PhD, I first need to thank my team of supervisors: Erwin, Marrit, and Niels.

Erwin welcomed me into his office and, after I explained the research I wanted to do, simply said, "Okay, that works. You can start writing a proposal." This interaction pretty much illustrates Erwin's modus operandi. He is no-nonsense, efficient, direct, and a fast thinker. At first, I found his critical questions slightly intimidating, but I realized this was his way of showing that he believed in my capabilities as a researcher. Still, I was relieved to discover that he also has a fascination with 'Randstedelijke' phenomena like gellac nails and esma's. I will never forget his email, which read (in slightly less formal terms): "Hi Emily, I am reading a paper about information asymmetry and the benefits of having a sizable derrière." That email became the starting point for Chapter 7.

Marrit, you have been my *steun en toeverlaat*. While Erwin and Niels were always ready to dive into the content, you were also there for everything else: my silly economics questions (having no economics background), my research struggles (how do I fix this in Stata!?), as well as any personal matters. Our conversations covered everything from sheep to relationship therapy, feminism, and running injuries. I feel we grew close, sharing an office on Tuesdays and going on our walks. Moreover, I do not think I could have made it through these four and a half years without you. Thank you so much for always being just one metre away, working away behind your (ridiculously) large screen.

Niels, my seed-sector guru. You also played an important role behind the scenes in making this PhD possible. And once I started, you opened doors for me, allowing me to speak openly with seed companies across the sector. Most of all, I enjoyed our one-on-one meetings, which had a habit of turning into private lectures on seed sector development including plenty of anecdotes from your adventurous career. Whenever we had a meeting scheduled, I knew it would almost certainly take a little longer than planned. I always preferred meeting in person because then I could keep a close eye on your ears: whenever they started to wiggle, I know you were either particularly engaged or beginning to get a little distracted.

Then I need to thank my paranymph, Stellamaris: my academic companion on this journey. After a year of being on my own, Marrit introduced me to Maris, who was working on a large IFPRI project on EWS-KT. We ended up dividing the workload: I took the lead on the paper about technology adoption (Chapter 4), while she led the paper on technology diffusion (Chapter 5). We turned out to be a wonderfully complementary team. Maris is a Stata wizard, while I am a seed nerd. Maris loves everything that comes before the writing phase; I love the writing itself. Maris drinks tea, I drink coffee. Maris loves yams and I love plantains (actually Maris also really loves

plantains). The past few years were not exactly easy for either of us, and there was some synchrony in our love lives and stress levels. I feel very lucky to have shared this journey with you: you have a sparkle that brings a smile to people's faces and your companionship was an antidote to the loneliness of this PhD journey.

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And then there was the 8:24 train to Ede-Wageningen, where I was lucky enough to meet Julia. I still find it remarkable how quickly we became close as 'two *Amsterdammers* commuting to Wageningen.' I miss our post-journey coffee ritual (including a croissant for you) and, of course, I miss complaining to you about the travellator.

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After ICFG, I ended up working with John, who had decided to start his own foundation after all. One of its pillars would be food systems, and I was given the opportunity to shape the portfolio.

Of course I had to say yes. John sent me an email from a monastery, in which he quoted from Dune: "The proper teaching is recognized with ease. You can know it without fail because it awakens within you that sensation which tells you this is something you've always known." That email still says everything. Thank you, John, for shaking up my world.

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Just around the corner from the Tanka office is the Rootline office, where I suspect I wrote most of this thesis. It all started at the office on the Prinsengracht, where I sought refuge from the heat and cold (and mice) in my tiny studio at the Claes Claeszhofje. At the time, there were only five people in the office, all men, and they seemed to appreciate the extra company and, perhaps, also the apparent diversity hire. In return, I appreciated the air conditioning, the quiet working culture of developers, delicious lunches, and lunch conversations (e.g. about Napoleon podcasts). Nowadays, the office has grown to around forty people and yet I am still welcome. Vic once famously described me as a *straatkat*, a stray cat who wanders in every now and then to enjoy the company and food, which, I have to admit, sounds pretty accurate. Thank you so much, Anselm, Felix, Rutger, Marcus, Chronis, Sofia, Daan, Barry, Thimo, Vic, Maarten, Emma, and all other team members.

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At University College Utrecht (UCU), the very first person I met was Laura. Here, I am referring to Laura Arts: it remains a funny (and confusing) coincidence that both my sister and my bestie

are called Laura. Lau, I love you for being such an authentic, brilliant, and wonderfully complex person. I also love your sense of humour, especially when your inner evil genius makes an appearance. We are wired in radically different ways, which means you can offer me an alternative perspective. Yet somehow, your advice tends to be exactly what I need because you understand me better than most. We have shared so many struggles and joys over the years growing stronger together. I am already looking forward to our granny years enjoying retirement. In the meantime, please move back to the same country because I miss you. Jens, I am so grateful that you are Lau's life partner because you are one of the most attentive and funniest people I know.

During the UCU in Africa programme, Sanne, my fellow Steegje, and I were assigned to the same internship in Addis Ababa. This rather intense experience became the foundation of a friendship. Sanne, I love our Dutch-English conversations (especially the ones about books) and very much admire your eye for aesthetics.

Through Room for Discussion, I met Chris and Kari. Chris, you are my dushi, despite your questionable preference for putting chocolate chips in home-made banana ice cream. You and Erik are one of my favourite couples to spend time with, not just because of your excellent cooking, but because you always make me feel completely at home: thoughtful conversations and just the right amount of toxicity. Kaar, I think we both experience life with great emotional depth. Even if we occasionally lose sight of each other amidst the chaos, we can always pick up exactly where we left off.

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Vincent, when we met in Alpbach, it was friendship at first sight. You create art, but you also seem to turn life itself into an art form: hiding little notes around my house, sending me letters that always touch my heart, and reading poetry to me in Oxford cemeteries. We can talk and talk and talk, but are equally content lying next to each other in silence listening to the wind.

When I moved to Kigali, the first person I met was Diederik as I asked to borrow his phone facing a struggle with the immigration office. You love drinking tea on top of a volcano in extremely muddy boots just as much as drinking champagne in your suede loafers. And how I love doing both of those things with you. Your unfiltered opinions never fail to make me laugh, and over the years I have come to appreciate your thoughtful silences just as much, creating space for me to share whatever needs sharing. One of your wise comments: "A PhD is not the main course, but merely the appetiser." It made both writing my proposal and finishing this thesis a great deal easier.

Thijs, we eventually had to introduce one house rule: no talking about potatoes after 8 p.m. You are one of the funniest people I have ever met. The best advice you ever gave me was that when things become too stressful, you should take a break rather than simply push through. Often, that break ended with us dancing around the living room to De Jeugd. Marieke, in Kigali, we got to be office buddies for a while, which was super cosy, and I still dream of your pasta sauce using multiple bushes of basil from your garden. Yvette, thank you for making my time in Kigali extra special and making me love Rwanda even more. We need to find more time to dance together.

Juliette, Jules, you have reminded me several times of what I told you when we first met as roommates during the YEP course: "I'm not here to make friends. I already have too many." Well, that did not work out as you were simply too lovely. We discovered we shared many interests, values, and experiences working in international development and living our Amsterdam lives. Thank you for all the perfect cappuccinos and thoughtful conversations.

Moving back to Amsterdam, I found myself craving classical music and art. Fortunately, my sister introduced me to Frits, who has brought a tremendous amount of cultural joy into my life over the past few years. During our dinners, your criminal anecdotes make me laugh and you always listen to my stories without judgement. While writing this thesis, I looked at the painting of the reading girl countless times as I was reading and writing myself.

Another friend I have my sister to thank for: Lieske, a.k.a. DJ Lizzy. An incident in Poland involving multiple hair dryers briefly threatened our friendship, but our connection, built on emotional exchange and a shared sense of humour, is simply too strong. Whenever the LizEmLau app is thriving, I have hours of voice notes to listen to and wherever you are DJing, we promise to be your cheerleaders.

At Milkshake, I met Tatjana. Tat and I immediately bonded over our shared personal experiences and love of Joni Mitchell. Somehow, we grew close rather quickly, likely because there has been a lot of synchronicity in the paths our lives have taken. We are in our element either in foetus position on your couch or in the middle of the dance floor. Thank you for your sassy humour and openness.

And every Sunday evening, after another hectic week, I make my way to the Argonautenstraat in my Adidas tracksuit to watch reality TV and eat delicious vegan (and often fermented) food with a loyal crowd: Bas, Marije (Parel), Eline, Tim and Hans. In between the emotional rollercoasters featured on our favourite shows, we find time to discuss our own rollercoasters, but never for too long, otherwise Bas gets upset.

Finally, I come to my family. You have shaped my life and made me the person I am today.

First, my parents. After I put a spoon in the microwave to see what would happen, they nicknamed me *'de kleine onderzoekster'* (the little researcher). Fortunately, I now conduct my experiments a little more responsibly, but in essence I am still the same: endlessly curious and adventurous. Papsi, thank you for always encouraging me to ask every question I could think of about the universe and omega, and for instilling in me the desire to leave the world a better place. Mamsi, thank you for making me believe in myself: *"Je bent goed zoals je bent en zo moet je ook altijd blijven."* Also thank you for trying to teach me that doing my best is enough. Together, you have always encouraged me to chase my dreams and your support has also enabled me to do so. Most importantly, you taught me the greatest lesson of all: what unconditional love looks like. I love you to the moon and back (our version: *tot het einde van het universum en weer terug*).

Second, Willem, the big brother I never had, until I suddenly did. I am endlessly grateful that you and my sister met at my graduation party. While the two of us are remarkably similar in some ways, we are complete opposites in others. Those similarities and differences have resulted in a special relationship. I really admire how you never seem to do anything by halves: whether it is your work, your projects, or the people you love, you commit wholeheartedly. I love you.

Third, my goddaughter, Pia-May Emily. You have become the greatest source of joy for our entire family. Whenever I do not quite know what to do with myself, all I need is to spend time with you. I sing you to sleep, and suddenly nothing else matters. I cannot wait to watch you grow into the person we can already see emerging before our eyes: curious, attentive, strong-willed and with a deep love for nature (especially 'gaga' birds).

Fourth, my big sister, Laura, knoody. When I try to put into words what you mean to me, I find that words fall short. I cannot thank you, because I could never thank you enough. I can only say that I would not know how to live this life without you by my side. We move through life together: hand in hand, laughing and crying. There are countless precious memories we share, more recently: sashimi in Japan, manta rays in Indonesia, skinny dipping in Greece, Berghain in Berlin, a wedding in Champagne and you giving birth to Pi. You know everything there is to know about me, and I know everything there is to know about you. There was never any doubt about who my paranymph would be. You are my person.

Finally, I want to express my gratitude to those who are no longer here with us, but whom I also continue to carry in my heart. Jeanna and Glyn were my 'bonus' grandparents. They continue to inspire me through their endless wisdom and extraordinary capacity to love. Oma Gerda, my stylish Pisces grandmother, once warned me that highly educated women are more likely to end up alone. Later, she reassured me that I could have it all after all. Harry and Nuus were loving godparents and great cheerleaders for Laura and me. Jeppe taught me never to take happiness or the people I love for granted. And, thank you also, to Opa Pieter, Oma Eugenie, Oma Marie, and Opa Jan.

Education certificate

Emily M.S. ter Steeg
Wageningen School of Social Sciences (WASS)
Completed Training and Supervision Plan

Wageningen School of Social Sciences

Name of the learning activity	Department/Institute	Year	ECTS*
A) Project related competences			
A1 Managing a research project			
WASS PhD Introduction	WASS	2021	1
Writing research proposal	DEC, WASS	2021	6
'Market-driven seed sector development: leading vegetable seed companies and their contribution to sector development in low-tech markets in Sub-Saharan Africa'	WASS PhD day, Wageningen	2023	0.5
Seminar *'Market-driven transitions in the vegetable seed sector in sub-Saharan Africa.'*	Rwanda Institute for Conservation Agriculture, Kigali	2024	1
Break-out session *'Choosing the target farmer.'*	SeedNL annual event, The Hague	2024	1
Conducted 10 peer reviews for the Special Issue on Seed Systems	Agricultural Systems	2023-2025	3
A2 Integrating research in the corresponding discipline			
Impact Assessment of Policies (DEC32806)	WUR	2022	6
Design of Experiments	WIAS and PE&RC	2024	0.8
Advanced Development Economics (ECRMDE)	Utrecht University	2024	5
B) General research related competences			
B1 Placing research in a broader scientific context			
Ethics for Social Science Research	WGS	2022	0.5
Smallholder Engagement in Seed Systems	PE&RC and WASS	2022	2
Farming Systems and Rural Livelihoods Analysis	PE&RC and WASS	2023	3
Advancing Implementation Science in Nutrition	VLAG	2025	1.4
B2 Placing research in a societal context			
Member of Synthesis Committee Integrated Seed Sector Development (ISSD) Africa	ISSD Africa Conference, Kigali	2023	1
Participation in Science Diplomacy Week Immersion Program	Geneva Science Diplomacy Accelerator, Geneva	2023	1
Organising team of SeedNL annual event 'Seeds outside the Box'	SeedNL, Ede	2025	1

Organising team of the International Conference on ISSD: From scientific understanding to strengthened practice and policy	Wageningen	2025	1
C) Career related competences/personal development			
C1 Employing transferable skills in different domains/careers			
Competence Assessment	WGS	2022	0.3
Searching and Organising Literature	WUR Library	2022	0.6
Teaching: Microeconomics for development (tutorial)	WUR	2025	2
Total			**38.1**

*One credit according to ECTS is on average equivalent to 28 hours of study load

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