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Enhancing Farmers' Productivity and Farmers' Livelihood for Food Security: Findings from 8 Social Impact Studies across Asia and Africa

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Abstract
Projections indicate that the global population will surpass 9 billion by 2050, making food security and poverty alleviation critical challenges. Smallholder farmers, who produce a significant proportion of the world's food, are particularly vulnerable to climate change and face rising temperatures, unpredictable weather patterns, and water scarcity, which threaten their farm productivity and livelihoods. This study investigates the social impacts of targeted agricultural interventions, including hybrid seeds, intercropping, knowledge transfer, and weather insurance, on small-scale vegetable farmers in India, Kenya, the Philippines, and Pakistan. On the basis of data from more than 2,000 vegetableseed customers gathered through standardized surveys from 2022 to 2024, the research shows that farmers perceive these interventions as improving their farming practices, increasing crop production, income, and quality of life. In absence of control groups, the farmers compared their perceived outcomes to their farming and livelihood results before the intervention. The results highlight the importance of obtaining both subjective and objective measures of agricultural success from farmers to design effective, scalable interventions. This study underscores that even small, targeted interventions can have a large impact. They offer scalable ways to make smallholder farmers more resilient and contribute to achieving Sustainable Development Goals 1 (No Poverty) and 2 (Zero Hunger). Targeted policies and investments in agricultural innovation may be essential to sustain these gains and ensure resilience in the face of escalating climate risks.

Keywords: Food Security, Smallholder Farmers, Climate Resilience, Agricultural Interventions, Poverty Alleviation, Social Impact

Introduction

Food security and poverty reduction are critical global challenges that require innovative solutions to eradicate malnutrition. In 2020, it was estimated that approximately 690 million people were undernourished, most of whom were living in developing countries where poverty exacerbates food insecurity [1].

Agriculture, a cornerstone of food security and poverty alleviation, faces an unprecedented global challenge, as climate change threatens the very basis of crop production [2,3]. Research suggests that human-induced climate change has led to a reduction of approximately 21% in total global agricultural productivity since 1961. This decline is equivalent to the productivity growth lost over the last nine years [4]. Rising temperatures, unpredictable weather patterns, and an increase in pest and disease outbreaks threaten crop yields globally, with a particularly severe impact on vegetable crops

[5]. A major threat is also the lack of water, since 70% of the world's freshwater is used by agriculture, and competition for this limited resource is growing because of population growth and industrial needs [6].

Within this broader context, vegetable production emerges as a critical sector for both nutrition and economic resilience in rural communities. In fact, the global value of the production of fruits and vegetables is greater than the value of all food grains combined [7,8]. In developing nations, vegetable production provides a promising economic opportunity for reducing rural poverty and unemployment and is a key component of farm diversification strategies [8]. Smallholder vegetable farming systems are widely recognized as essential for improving household food security and income. Vegetable production plays a critical role in farmers' livelihoods across various farm types, often generating income that exceeds their immediate food requirements [7].

Smallholder farmers are central to vegetable production and global food systems, yet they remain highly vulnerable to climate and economic pressure. Producing approximately 35% of the world's food on only 24% of agricultural land, these farmers, often managing less than two hectares of land, contribute significantly to the local food supply, especially in low- and middle-income countries, where they provide up to 80% of the essential nutrients [9,10]. However, their ability to respond effectively to climate disruptions is constrained by limited access to modern agricultural innovations and technologies, such as high-quality seeds and agricultural inputs, resulting in declining crop yields and an increased risk of poverty [11-13]. As a result, small-scale vegetable farmers, in particular, operate in low- input, low-output systems, mainly due to financial constraints and lack of technical knowledge [14,15].

Addressing these challenges requires targeted and sustainable interventions that strengthen smallholder resilience and productivity. Such efforts are essential to achieving the United Nations Sustainable Development Goals (SDGs), particularly SDG 1 (No Poverty) and SDG 2 (Zero Hunger). Interventions that improve access to high- quality seeds, agricultural inputs, and digital advisory services can help smallholder farmers overcome constraints, enhance food security, and build climate resilience in regions where smallholder farming is vital.

While numerous studies have examined agricultural interventions aimed at improving livelihoods, there remains a need for comprehensive research that analyzes the combined impacts of these interventions on smallholder farmers, particularly in Asia and Africa [13]. In countries such as Nigeria, Tanzania, and Uganda, improved seed systems for legumes (e.g., cowpea and chickpea) increased productivity, income, and market access for smallholder farmers. The key factors included innovative partnerships, capacity building, and small seed packages to reach more farmers [16]. In South Africa, the adoption of climate-smart irrigation increased crop productivity and resilience. Critical to success were factors such as training, extension services, and awareness campaigns [17]. Smallholder farmers in Nepal have adopted strategies such as crop diversification, improved soil and water management to cope with climate change. These measures increased resilience and diversified income sources, improving livelihoods in vulnerable agroecological zones [18]. This study significantly contributes by addressing the lack of a clear understanding of how agricultural innovations support climate resilience, improve livelihoods, and enhance food security [12,19]. Its originality fills this gap by including farmers' direct perceptions and qualitative insights. This is an important aspect often overlooked in studies that depend on secondary data. By doing this, the study offers a more complete view of the real impact on farmers' lives. It also provides practical insights for smallholders, policymakers, and the agricultural community [20-23].

This study specifically focuses on Asia and Africa, two regions with large smallholder populations that play pivotal roles in both regional and global food security. These areas are also among the most vulnerable to climate change, which makes effective interventions urgently necessary [24]. By examining parts of these regions, this study aims to generate insights that can guide future policies and practices in areas where smallholder resilience is essential for sustainable development.

Through a synthesis of findings from eight impact studies across Asia and Africa, this paper examines farmer perceptions of selected agricultural interventions, such as hybrid seeds, intercropping, knowledge transfer, and weather insurance, chosen for their relevance to small-scale vegetable farming and potential to affect farmers' climate resilience, livelihood security, and food production capacity. The impact studies were performed in the selected countries based on the country's high relevance to global food security due to their large populations of smallholder farmers and their vulnerability to climate and market shocks. Vegetable production plays a key role in all four farming systems and, specifically, for smallholders relying on subsistence farming to feed their families. At the same time, they face challenges regarding limited access to modern inputs as well as agronomic education and advisory, which impacts their livelihoods and food security outcomes. Frequent adverse weather events make resilience-building interventions particularly critical.

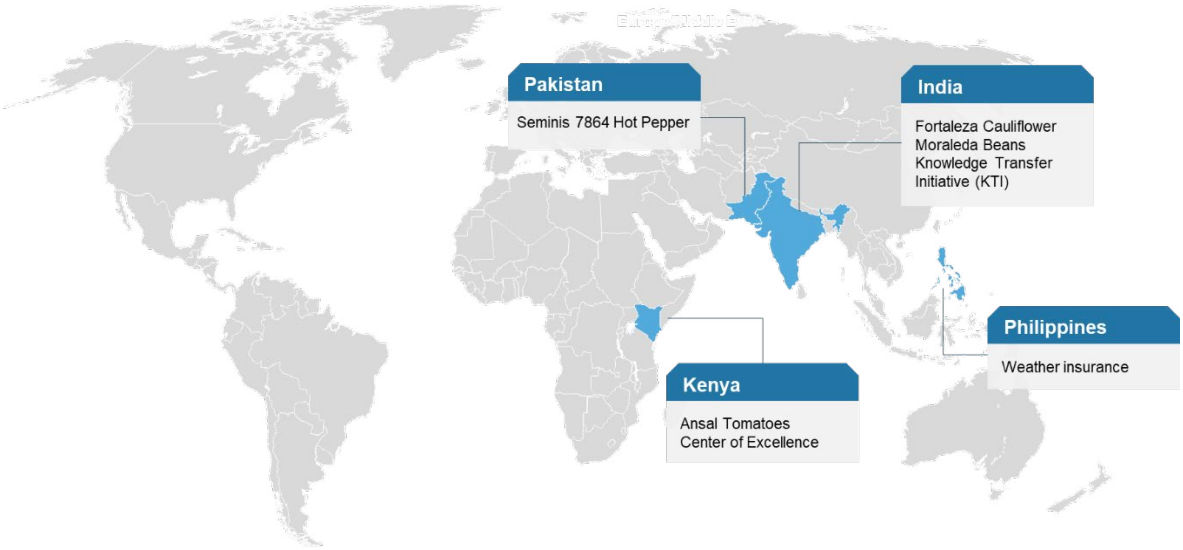

Figure 1: Impact Study Locations

This study aims to explore whether farmer-perceived benefits of interventions, such as hybrid seeds, intercropping, digital advisory or insurance services, correlate with self-reported improvements in their way of farming, crop productivity, farmer income and quality of life. We hypothesize that farmers who adopt such interventions perceive improvements in the listed impact metrics, which in turn contribute to adaptive agricultural production, enhanced livelihoods and food security under their specific production conditions.

Figure 2 depicts the expected impacts of adopting agricultural interventions on food security and farmers' livelihoods. The framework centers on small-scale vegetable farmers who face multifaceted challenges, including the impacts of climate change, restricted access to high-quality seeds, knowledge, and water scarcity. The introduction of targeted agricultural interventions facilitates transformative impacts. These interventions increase crop productivity, the adoption of better farming practices, and incomes, which together lead to improved quality of life. Equipping farmers with agricultural interventions strengthens their resilience and enables their contribution to global food security, thereby enhancing the livelihoods of both the farmers and their families [25].

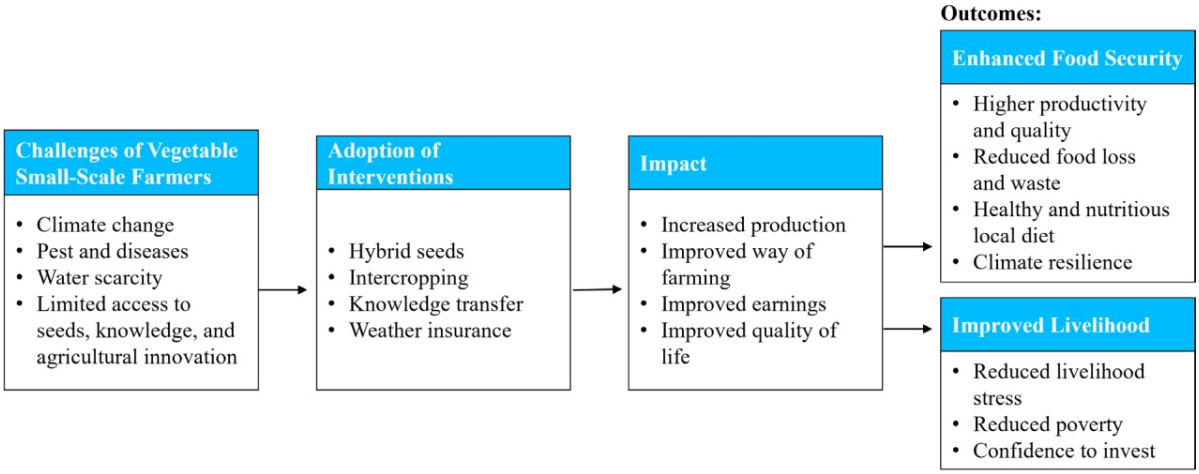

Figure 2: Conceptual Framework

This paper is divided into five sections: (1) the methodology and data used to assess the social impact of selected agricultural interventions are explained; (2) the selected impact studies in India, Kenya, Pakistan, and the Philippines are described; (3) the most relevant results from the surveys conducted with farmers to assess the impact of the agricultural interventions are presented; and (4) the results with existing literature are discussed and; (5) finally, results and a future direction are presented.

Methodology

Gathering reliable data on the social impact of agricultural interventions is widely acknowledged to be difficult, but the near ubiquity of mobile phones offers the possibility of direct communication with farmers even in isolated rural areas. Short phone surveys and other features such as interactive voice response provide effective and efficient ways to collect important social data directly from farmers [26].

For this study, a Lean Data approach, originally developed by the nonprofit organization Acumen and currently implemented by 60 Decibels was followed because of its relative simplicity and flexibility (Acumen, 2019; Dichter et al., 2016), The methodology was initially motivated by a social enterprise in India that was providing ambulance services but lacked reliable data to know if they were reaching the most vulnerable people in the region [26,27]. To solve this problem, call center workers were taught how to ask a simple set of questions drawn from the Poverty Probability Index ® (PPI®) to randomly chosen survey respondents. The questions were formulated in a simple form to administer the survey during a brief phone interview (Dichter et al., 2016). The innovation of this approach lies in the use of efficient and fast data collection methods and technologies, while maintaining the statistical accuracy essential for transforming data into actionable information for decision-making (Dichter et al., 2016) [26].

The Lean Data approach has evolved since, with 60 Decibels conducting extensive research in the agricultural sector to identify key topics that are both relevant and easily understood by farmers. Over the years, they have identified recurring themes and designed questions around those themes by conducting thousands of surveys across 80+ countries. As part of this effort, 60 Decibels has enabled farmer-reported outcome measures (FROMs), which provide a more robust framework for assessing the social impact of interventions in the agricultural sector. This iterative learning process has been further enriched by alignment with global frameworks such as the Sustainable Development Goals (SDGs) and the Impact Management Project (IMP). The resulting set of standardized questions is designed to generate actionable insights that inform program improvements. The questions are designed to be easy to understand, minimizing the risk of misinterpretation or misunderstanding. By integrating both quantitative and qualitative questions, these studies provide a comprehensive, farmer-focused evaluation [28].

To ensure cultural sensitivity, trained researchers conducted the surveys by phone in local languages. The surveys integrate both quantitative and qualitative elements to provide a comprehensive, farmer-centered assessment. On average, the interviews lasted approximately 16 minutes. Farmers were randomly selected from a Bayer customer database, aiming to achieve a confidence level of 90% and a 5% margin of error. The sample may, therefore, not represent the broader smallholder population in the country and study findings may not be applicable to farmers outside the database. The customer database reflects historical patterns of engagement, e.g., male-dominated customer lists, and is therefore limited in representing the impact experience of female farmers.

The measurement approach is focused on learning about the impact of interventions by listening to beneficiaries' voices. It is intentionally based on their perceptions to monitor impact performance based on their lived experiences. The survey design provides the respondents with the opportunity to share their expected and unexpected experiences as well as the mechanisms through which these were realized. The study approach differs from a randomized controlled trial (RCT), with treatment and control groups, that measure the achievement of a pre-defined outcome over the long-term. RCTs do not allow easy comparison across programs and geographies, as with this measurement approach. In the lean data studies participants are asked to compare a specific impact metric now versus the time before joining the program, effectively assessing their livelihood with and without the intervention. As study results rely on self-reported perceptions from farmers without a control group, findings reflect perceived changes since the introduction of interventions rather than empirically measured causal effects. This approach allows for results to be available within a relatively short time frame of up to 12 weeks, supporting actionable steps to further optimize impact generation while the program is continuously ongoing. It also allows for comparison of results across different projects and versus local and regional agriculture benchmarks established by the provider, based on all previous impact studies in the sector using the same methodology. This allows program leads to place their results in the context of the industry they operate in and measure program performance over time.

Farmer-expressed values are still lacking at the core of understanding the impact of agricultural interventions [29]. Therefore, the surveys were designed to capture farmers' perceptions of the implementation of one or more of the abovementioned agricultural interventions [30,31]. The results of the impact questions can be categorized as percentages of the surveyed sample having improved their way of farming, having increased their production, having increased their earnings, having improved their quality of life, reporting challenges and specific questions to the intervention.

For specific varieties, in-house field trials were conducted to evaluate the performance of the hybrid seeds, which were compared with those of competing seeds in terms of yield, resource management, shelf time, food supply resilience, biotic stress management, abiotic stress management, and climate change adaptation. The results of these studies were used to support the findings of the surveys and establish a link between product performance and the observed social impact outcomes.

Intervention: Use of High-Yielding Hybrid Seeds

The selected interventions demonstrate scientifically validated strategies for sustainable agriculture. The first intervention, the use of high-yielding hybrid seeds, significantly increases productivity, with crops such as maize and bitter gourd showing improved yields under controlled environments such as insect-proof netting. These seeds also provide resistance to pests and diseases while effectively adapting to local climatic conditions, optimizing crop yields [32].

Intervention: Introduction of Intercropping as an Agricultural Practice

The next intervention, the introduction of intercropping as an agricultural practice, increases yields by approximately 30% compared with monocultures, taking advantage of resource efficiency and biodiversity benefits such as pest control and nitrogen fixation [33]. Studies have shown that, compared with traditional monocultures, intercropping can increase net farm income by 39.2% while reducing the environmental impact by 17.3% [34]. For example, intercropping maize with field beans has resulted in significant increases in total protein yield, ranging from 24% to 39% higher than that of maize alone [35]. This practice reduces the dependence on synthetic inputs and promotes long-term environmental sustainability [36]. Research by highlights the importance of selecting compatible crop combinations to maximize resource use efficiency and ecological benefits [37]. Intercropping is particularly effective in resource-constrained environments, where land use optimization is critical. Its success is influenced by the choice of crop combinations and farmers' understanding of complementary crop interactions, highlighting the importance of local knowledge and training.

Intervention: Knowledge Transfer to Enhance Farmers' Agricultural Knowledge and Practical Skills

The next intervention, knowledge transfer to improve farmers' agricultural knowledge and practical skills, emphasizes participatory approaches that promote knowledge cocreation. These methods encourage innovation and the adoption of techniques such as intercropping, which are tailored to specific contexts [38]. Sasidhar (2013) highlights the critical role of agricultural training in rural development [39]. Effective training equips farmers with essential knowledge and skills, enabling them to adopt innovative practices, increase productivity, and improve their livelihoods. He emphasizes the importance of well-structured training programs tailored to the specific needs of rural communities to facilitate sustainable agricultural development and economic growth. The train-the-trainer approach, as implemented by CARE in Tanzania, exemplifies how cascading knowledge sharing can extend the benefits of agricultural interventions beyond the immediate participants [40]. Research by on farmer field schools illustrates how experiential learning can empower communities to sustain agricultural practices on their own [41]. The effectiveness of this intervention depends on the quality of the training and the cultural relevance of the knowledge shared. It is particularly effective in promoting community-wide adoption of sustainable practices, creating a multiplier effect.

Intervention: Weather Insurance Offering Financial Compensation to Farmers Suffering from Climatic Extremes

Finally, weather insurance, which provides financial compensation to farmers facing extreme climatic events, provides critical financial security. By mitigating crop losses and thereby stabilizing incomes, it builds resilience to climate variability. Public subsidies to cover premiums further support accessibility for smallholder farmers [42]. Together, these integrated strategies strengthen sustainable agricultural development and adaptive capacity. The effectiveness of these interventions depends on the availability of accurate climate data, efficient application processes, and farmers' trust in the system. Research by Carter et al. suggests that bundling weather insurance with other agricultural inputs, such as seeds and fertilizer, increases the uptake and impact among smallholder farmers [43]. This approach is particularly valuable in regions prone to extreme weather events, where traditional risk management strategies may be insufficient.

This study integrates case examples from geographically diverse regions, including India, Kenya, the Philippines, and Pakistan. This diversity demonstrates the global importance of agricultural interventions while also highlighting the need to address region-specific challenges posed by intensifying climate drivers [44]. For example, the Philippines faces increasing risks from typhoons and extreme weather events, requiring adaptation strategies to protect smallholder farmers [45]. On the other hand, Pakistan experiences prolonged droughts that exacerbate food insecurity and demand the adoption of climate-resilient crops and practices [46]. In order to account for these different contexts, the Lean Data approach allowed for structured comparisons to be made within their respective local contexts. The study prioritized overarching indicators such as farming practices, productivity gains, income improvements, and quality of life while accounting for specific regional vulnerabilities. This nuanced approach shows both similarities and differences between situations, emphasizing the important role that agricultural interventions play in reducing the uneven effects of rising climate risk [47]. By combining standardized methodologies with localized insights, this study advances both global and region-specific strategies for sustainable agricultural development.

Presentation of the Case Studies

The case studies presented in this research are the result of extensive fieldwork, capturing the diverse experiences of more than 2,000 farmers across four different countries. As the studies were not designed to examine gender-related dynamics, the findings do not include gender-disaggregated analyses. Reflecting the depth of engagement and the richness of the data collected, approximately 24 days of interviews were conducted. This multilingual effort, carried out in seven different languages, underscores the project's inclusivity and commitment to cross-cultural understanding.

Fortaleza Cauliflower – India

Cauliflower production is highly important in India and contributes significantly to the country's economy. According to the FAO, India ranks second in terms of cauliflower production, highlighting its critical role in supporting domestic food security and economic growth [48]. The steady increase in cauliflower production over the years reflects the growing importance of the crop and concerted efforts to improve its cultivation across the country. These advances have led to the development of Cauliflower Fortaleza, a robust hybrid seed with strong and exceptional outer leaves for better protection and adaptability to different climatic conditions, making it particularly suitable for winter harvests. This variety

was commercially launched in 2017 and is favored for its quality and comprehensive disease resistance.

Between March and April 2024, a randomized survey was conducted among 281 farmers cultivating Fortaleza seeds across four states in India. The sample was randomly drawn from a population of 1,682 farmers. The study cohort comprised exclusively male participants (100%), with a median age of 40 years and a median engagement duration of two years with the intervention. Approximately 24% of the cauliflower farmers in the sample were living on less than $3.65 per day.

Ansal Tomato – Kenya

Post-harvest food losses are a major challenge in Africa, especially in regions with high temperatures and during harvest seasons when crops are most vulnerable. The long transport times required to move produce from fields to supermarkets, often without access to refrigerated transport systems, exacerbate these losses. Collectively, these factors result in substantial economic losses for farmers and contribute to food insecurity [49]. This led to the development of the tomato hybrid Ansal, which is suitable for longer transportation. Ansal is a square-round tomato hybrid developed for use in an open-field environment and was launched in 2019. This variety has an extended shelf life of 20 days, nearly doubling the typical range of 10–14 days. This trait offers significant potential for reducing food waste during long-distance transportation (WBCSD, 2019) [50]. In addition, Ansal tomatoes present increased disease resistance, improved climate resilience, and greater fruit firmness.

The longitudinal survey focused on understanding the impact of Ansal tomatoes on beneficiary farmers in Kenya and their experiences over time. A baseline study was conducted in 2022, and a follow-up study was conducted one year later in October 2023. A total of 418 farmers participated in the baseline study, of whom 82% were male and 18% were female. Most participants (53%) reported a tenure commitment of two years or more.

One year later, all 418 farmers from the baseline study conducted in 2022 were contacted, with 211 interviews successfully completed. Information on farmer age, household size, and tenure was drawn from the baseline study. The overall demographic profile of the follow-up sample closely aligned with that of the baseline cohort. However, there was a slight decrease in the representation of female farmers, from 18% at baseline to 9% at follow-up. The average age of respondents remained largely unchanged between the two rounds of the study (42 years in the follow-up phase compared with 41 years in the baseline phase), and tenure did not change significantly when the time elapsed between the data collection phases was considered.

Moraleda Bean – India

Globally, beans are widely consumed and are a rich source of fiber, B vitamins, and plant-based protein. Their consumption is associated with several health benefits, such as cholesterol reduction, blood sugar regulation, and the promotion of the growth of beneficial gut bacteria [51]. In addition to these human health advantages, legumes, such as beans, play versatile roles in intercropping systems by fixing biological nitrogen and thus improving soil health, increasing protein yield outputs, and increasing functional diversity [52]. A study in Tanzania found that including intercrops, maize, and common beans is a promising option for sustainable food production on smallholder farms [53].

In February 2020, the Moraleda pole bean variety was launched with the aim of creating added value for farmers and the planet. Moraleda is a pole bean suitable for both protected and open field cultivation. These seeds can achieve relatively high yields and relatively good resilience to pests and diseases. Farmers tend to practice relay cropping of Moraleda beans with other crops because of nitrogen fixation.

Between May and June 2024, 60 Decibel researchers conducted interviews with 262 tomato farmers from Maharashtra, India, who cultivate Moraleda beans. The sample size for the survey was drawn from a total frame of 776 farmers. The sample consisted entirely of male participants (100%), with a median age of 37 years. The participants had been involved with Moraleda for a median of two years, and approximately 25% of the Moraleda farmers lived on less than $3.65 per day, which was slightly below the national average in India.

Seminis 7864 Hot Pepper – Pakistan

Nutrition- and hunger-related problems in Pakistan are alarming, particularly in the aftermath of the 2022 floods, which have exacerbated the country's vulnerability to climate change, ranking it as the 8th most affected nation. Almost half of a household's expenditure is allocated to food, yet 82% of the population lives below the multidimensional poverty line, making it difficult for them to afford a healthy diet. For many, vegetable farming serves as a primary source of income and employment [54]. To enhance food security and build resilience, it is essential for farmers to have access to high-performing seeds that are climate- resilient. These seeds can significantly increase yields and incomes while improving the availability and diversity of nutritious foods. Ultimately, this will contribute to greater food security and foster improved agricultural practices in the face of changing climatic conditions.

In 2016/2017, a high-yielding pepper variety was introduced in the Punjab and Sindh regions of Pakistan. This variety has relatively high resistance to pests and climatic shocks and high yield. The years 2022 and 2023 were challenging for farmers because of extreme climatic events such as floods. Between August and September 2024, 275 farmers were

interviewed from a sample frame of 874 farmers growing Seminis 7864 peppers. All participants in this study were male, with a median age of 40 years. They had been involved in the intervention for an average of 3 years. Notably, 37% of Bayer Seminis farmers live on less than $3.20 per day, which is similar to the national average in Pakistan (34%).

Knowledge Transfer Initiative – India

Smallholder farmers often face limited access to critical agricultural knowledge, which hinders their ability to maximize yields and build climate resilience [55]. The so-called Knowledge Transfer Initiative (KTI) in India is a digital platform that provides tools to empower farmers by enhancing their agricultural knowledge and practical skills. This initiative aims to improve education, farming productivity, income, and efficiency. To achieve this objective, three delivery modes were implemented: (1) standard advisory, including an 11-part series on modern agricultural techniques hosted on YouTube and accessed via WhatsApp and other social media platforms launched in 2023; (2) key opinion leaders providing crop-specific expert advice hosted on YouTube and accessed via WhatsApp and other social media platforms launched in 2024; and (3) WhatsApp chatbot launched in 2023 was enhanced further in 2024 to provide product recommendation, where to buy, weather updates and most importantly crop stage wise agronomy best practices and solutions to pest, disease, virus management through proper Crop Protection recommendation and is currently available for 17 crops in 10 local languages. WhatsApp chatbots providing price and weather information accessed via WhatsApp QR codes launched in 2024.

The program aims to increase crop production and promote sustainable farming by focusing on effective resource management. The videos address essential topics such as the management of abiotic stress, helping farmers understand how to mitigate the effects of drought, excessive rainfall, and temperature fluctuations. Additionally, biotic stress management techniques are highlighted, enabling farmers to combat pests and diseases that have been devasting their crops. This initiative equips farmers with the knowledge needed for adaptation of climate change and strengthens food supply resilience in their communities. The program uses visual learning to make essential information readily available and comprehensible, thus enabling farmers to apply these practices successfully. In the end, the knowledge transfer program contributes to a more sustainable agricultural landscape, providing benefits for farmers and the wider food system.

Between September and October 2024, out of a database of 1,086 farmers, 281 who use KTI offerings were interviewed. These interviews were conducted across three regions of India. The participants in this study were predominantly male, with only 1% female representation. The median age was 33 years, while the median duration of engagement with the knowledge initiative was five months. In terms of participation in the intervention, 55% of the farmers had access to all three offerings, 31% received two offerings, and 14% received one. The crop distribution among the participants included 48% tomato farmers, 11% cultivating hot pepper and cauliflower, 6% growing beans, and 34% involving other vegetables.

Bayer's Centers of Excellence – Kenya

Recent studies have demonstrated that smallholder farmers experience significant productivity increases when provided with both tools and training. A study in Tanzania found that farmers who received training and had access to irrigation had more than doubled the yield compared to farmers who did not receive training [56]. In Uganda, extension training for female smallholder livestock farmers led to improved productivity and economic status [57].

To promote agricultural innovation and provide farmers in Kenya with tailored solutions to address evolving agricultural challenges, Bayer has established the Centers of Excellence (CoE). Local centers in Rumuruti, Mwea, Kajiado, and Mbita serve as vital hubs for empowering farmers with knowledge and tools to address key agricultural challenges. Focusing on enhancing yield and resource management, the CoE provides hands-on training in seed selection, crop protection, and efficient farming practices to promote food supply resilience. By introducing hybrid seed varieties, such as the Ansal tomato, which resists bacterial wilt, CoE helps manage biotic stresses such as pests and diseases. To address abiotic stresses, such as drought and poor soil health, the CoE emphasizes climate-smart solutions such as drip irrigation, soil conservation, and optimal fertilizer use. Leveraging Bayer's research, they offer tailored guidance on climate change adaptation, recommending resilient seed varieties capable to withstand harsh conditions such as high temperatures, droughts. Through real-time simulation and data- driven decision-making tools, farmers learn sustainable practices that mitigate the impacts of climate variability, enhance productivity, and improve resource efficiency. This comprehensive approach fosters increased food security, boosts economic empowerment, and strengthens farmers' capacity to adapt to evolving environmental challenges.

Between November and December 2024, 286 farmers from a sample frame of 2,086 engaged with the CoE were interviewed. The majority of the interviewed farmers were male (82%), with a median age of 42 years. On average, farmers had been engaging with the CoE for approximately one year.

Weather-Based Parametric Insurance – Philippines

The Philippines ranks highest in the Worldwide Risk Report, with a risk index of 46.86, underscoring the country's extreme vulnerability to climate change-induced natural disasters [58]. The agricultural sector, particularly small- and medium-scale vegetable farming, is disproportionately affected by adverse weather conditions, such as tropical cyclones and

droughts [59]. Smallholder farmers often experience substantial financial losses during such events and rely primarily on personal savings or high-interest loans to sustain their farms. Crop destruction exacerbates their financial burdens, compelling many to incur additional debt. In the future, this is expected to occur even more frequently, as climate change and increasing water and heat stress are likely to lead to lower crop yields, increased pest and disease outbreaks and a shift in crop production [60].

To address these challenges, weather-based insurance has been integrated into the purchase of Bayer Seminis seeds at accredited partner agri supply stores. The program offers coverage for climate-related risks, including typhoons, excessive rainfall, and droughts, which have significantly impacted the country. In the case of adverse weather, individual losses are evaluated according to the severity of the event, and farmers receive reimbursement in the form of vouchers that can be used to buy Seminis products. Bayer partners with one of the leading insurance companies in the Philippines manage this risk. The program is mostly paperless and requires only an enrollment form, which makes it attractive for smallholder farmers. This initiative supports farmers in addressing climate change challenges in one of the world's most vulnerable countries by providing a solution that promotes resilient food systems in climate-sensitive regions.

Between March and April 2024, 243 farmers using Seminis seeds were interviewed, which were selected from a database of 555 Bayer Seminis farmers. All participants had registered or enrolled at no additional costs for insurance as part of their Seminis seed purchase. Questions related to weather insurance were posed only to this subset of farmers.

The sample consisted of 21% female and 79% male participants, with a median age of 44 years.

Table 1 shows the summarized data for the agricultural interventions, sorted by their respective measures.

Name	**Fortaleza**	**Ansal Baseline**	**Ansal Follow-up**	**Moraleda**	**Pepper**	**KTI**	**CoE**	**Weather Insurance**
Intervention	Hybrid seeds	Hybrid seeds	Hybrid seeds	Seeds and intercropping	High-yield variety	Digital advisory	Farm advisory	Weather insurance
Crop	Cauliflower	Tomato	Tomato	Pole beans & tomato	Hot pepper	Several vegetables	Several vegetables	Cabbage & watermelon
Location	India	Kenya	Kenya	India	Pakistan	India	Kenya	Philippines
Language	Hindi	English, Swahili	English, Swahili	Marathi	Sindhi, Punjabi	Hindi	Swahili	Tagalog
Sample size (n)	281	418	211	262	275	281	286	243
Response rate	41%	81%	62%	44%	58%	42%	60%	58%
Average time per interview	17 mins	16 mins	17 mins	16 mins	12 mins	17 mins	16 mins	16 mins
Confidence level	90%	95%	90%	90%	90%	90%	90%	90%
Margin of error	4%	4%	4%	4%	4%	4%	5%	5%
Time period	Mar – Apr 2024	October 2022	October 2023	May – Jun 2024	Aug – Sep 2024	Sep – Oct 2024	Nov – Dec 2024	Mar – Apr 2024
Note: The targeted sample size of 275 was calculated using a 90% confidence level and 5% margin of error, assuming a population proportion of 0.5 and based on random sampling from the company's customer database.								

Table 1: Summary Data of the Agricultural Interventions

All social impact studies under review inherently address the outcomes of enhanced food security and improved farmer livelihoods. Through meaningful impacts of the interventions on a farmer's way of farming, production, earnings, and quality of life, the impacts often co-incur and are interconnected (cf. Figure 2: Conceptual framework). We therefore opted for an integrated approach and present each study's findings individually. Any specifics of each study beyond the social impact, for instance a dedicated focus of the intervention on climate resilience, is highlighted in the appropriate study section.

Results

The results of this study focus on the farmers' perceptions of the implemented agricultural interventions rather than empirically measured causal effects (cf. limitations mentioned in the Methodology section). Table 2 shows the main results for the selected farmer-expressed core impact indicators. Production and earnings were selected as proxies of farmers' economic viability supporting better livelihoods, and way of farming and quality of life serve as indicators of the long-term sustainability of their farm production and overall farmer resilience. All the values in this section are expressed as the percentage of farmers within the sample group (without gender disaggregation) who perceived positive changes

in the respective indicators since engaging with the intervention.

Case	Increased production (%)	Improved way of farming (%)	Improved quality of life (%)	Improved earnings (%)
Fortaleza	Slightly = 51 Very much = 42 No change = 1 Decrease = 6	Slightly = 50 Very much = 34 No change = 14 Decrease = 2	Slightly = 53 Very much = 35 No change = 9 Decrease = 3	Slightly = 53 Very much = 39 No change = 1 Decrease = 7
Ansal Baseline	Slightly = 36 Very much = 50 No change = 9 Decrease = 5	Slightly = 40 Very much = 33 No change = 23 Decrease = 4	Slightly = 37 Very much = 52 No change = 6 Decrease = 5	Slightly = 36 Very much = 55 No change = 3 Decrease = 6
Ansal Follow-up	Slightly = 33 Very much = 59 No change = 3 Decrease = 5	Slightly = 33 Very much = 28 No change = 34 Decrease = 5	Slightly = 42 Very much = 52 No change = 5 Decrease = 1	Slightly = 40 Very much = 50 No change = 6 Decrease = 4
Moraleda	Slightly = 48 Very much = 46 No change = 1 Decrease = 5	Slightly = 52 Very much = 42 No change = 1 Decrease = 5	Slightly = 44 Very much = 48 No change = 5 Decrease = 3	Slightly = 56 Very much = 38 No change = 1 Decrease = 5
Hot Pepper	Slightly = 34 Very much = 41 No change = 7 Decrease = 18	Slightly = 31 Very much = 25 No change = 33 Decrease = 11	Slightly = 39 Very much = 34 No change = 14 Decrease = 13	Slightly = 36 Very much = 38 No change = 7 Decrease = 19
KTI	Slightly = 40 Very much = 37 No change = 21 Decrease = 2	Slightly = 56 Very much = 30 No change = 14 Decrease = 0	Slightly = 44 Very much = 31 No change = 24 Decrease = 1	Slightly = 45 Very much = 29 No change = 24 Decrease = 2
CoE	Slightly = 29 Very much = 63 No change = 6 Decrease = 2	Slightly = 29 Very much = 67 No change = 3 Decrease = 1	Slightly = 35 Very much = 58 No change = 7 Decrease = 0	Slightly = 36 Very much = 48 No change = 14 Decrease = 2
Weather insurance	Slightly = 62 Very much = 10 No change = 22 Decrease = 6	Slightly = 41 Very much = 6 No change = 53 Decrease = 0	Slightly = 65 Very much = 8 No change = 24 Decrease = 3	Slightly = 65 Very much = 8 No change = 24 Decrease = 3

Table 2: Summary of the Main Results for all Case Studies for Selected Farmer-Reported Impact Indicators

Fortaleza Cauliflower – India [108]

The majority of farmers (83%) confirmed that none of their Fortaleza harvest was rejected by buyers after long transport times. This finding aligns with what the company's own field tests have shown: the Fortaleza cauliflower hybrid seeds have a curd maturity period of 75–80 days, which is the same as or longer than that of other hybrid varieties and competitors. Furthermore, 80% of the farmers identified zero harvest waste from cauliflowers, reflecting improved produce quality. Around 80% of farmers report that both rejection and wastage rates are lower with Fortaleza compared to other cauliflower varieties.

The vast majority of farmers (84%) perceived improved farming practices, primarily attributed to timely access to farm advice (46%), better management of crop diseases (18%), and reduced fertilizer use (17%):

"Field agents guided us on farming patters to be followed, such as how much fertilizer and water to be used." (Male, 56, Rajasthan)

"With Fortaleza seeds, fewer pests like caterpillars attack, and hence the crop production is very good." (Male, 35, Haryana).

These observations are consistent with internal field trials, which demonstrated that chemical costs, fertilizer costs, field preparation costs, harvesting costs, and irrigation costs were about 8-10% lower for Fortaleza than for other cauliflower varieties.

93% of farmers reported an increase in production, most of them (57%) managed to attain increased yields on the same land, which indicates productivity growth. Additionally, 92% of the farmers reported increased earnings due to increased median yields (8,500 kg compared with 7,500 kg for regular cauliflower) and increased median prices for their produce (INR 19.5 per kg for Fortaleza against INR 16.5 per kg for competing variety). These outcomes are supported by internal field trials showing that, compared with other cauliflower hybrids, Fortaleza has a 1381% increase in ROI. Farmers reported that their earnings increased because of increase in volume sold (82%), reasonably better prices

(59%), and decreased costs (10%). These results are corroborated by field trials that recorded a 16% higher produce price per kilogram, number of plants, average weight per plant, and yield of Fortaleza than other products.

The perceptions of an improved quality of life were predominantly positive, with 88% of the farmers reporting benefits such as increased savings (49%), increased farm investments (18%), and the ability to afford household assets (17%). The participants often commented that their improved earnings allowed them to afford more, leading to an enhanced quality of life.

"The profit from Fortaleza was very good. I deposited some money as savings in my bank account." (Male, 40, Rajasthan)

"I have purchased additional land for agriculture because of the increased production from Fortaleza." (Male, 56, Rajasthan)

Nearly all of the farmers (90%) reported that their stress levels decreased because of Fortaleza.

"Life is less stressful after using these seeds because we need to not worry about rejections and wastage." (Male, 50, Delhi)

Ansal Tomatoes – Kenya (60 Decibels, 2022, 2023)
Both the baseline (73%) and follow-up (61%) studies highlighted farmers' perceptions of improved farming practices. A male participant from the follow-up described how his farming practices improved because of Ansal tomatoes.

"I apply smaller amounts of fertilizer and more manure to reduce soil acidity. I spray my farm twice a month to avoid over spraying. I also space my crops well to increase flowering and production."

In the baseline, key improvements included the use of better farm inputs (24%), reduced pesticide and insecticide usage (18%), and enhanced irrigation techniques (15%). In contrast, follow-up respondents cited improved pest and disease management (30%), better crop spacing (26%), and more effective fertilizer application (23%) as the primary outcomes. A total of 34% of the farmers who did not notice improvements in the follow-up period attributed this predominantly to their unwillingness to change their existing methods (37%). Training played a significant role, as farmers who received training within the last 12 months were more likely to report substantial improvements in farming practices (38%) than those who did not receive instructions (24%).

Farmers perceived an increase in production during both the baseline and follow-up studies. The results of internal field studies support this finding, showing a greater yield per plant for Ansal tomato hybrid seeds than for competitor varieties. Ansal seeds also had more plants per hectare than did competitor seeds. This was determined by multiplying the number of plants planted (20,000 plants/ha) by the percentage of plants that survived problems such as bacterial wilt (BW), nematodes, and transplanting shock. In the follow-up study, a greater proportion of farmers reported increased production (92%) than at baseline (86%). Notably, farmers who received training within the past 12 months were significantly more likely to report substantial production increases (70%) than those who had not received instructions (55%).

Postharvest waste levels remained stable between the two periods, with 79% of the farmers in the baseline period and 80% in the follow-up period reporting lower waste. On average, tomatoes spoiled 16 days after harvest, which is consistent with the findings of field trials showing that Ansal tomatoes had a storability of 21 days, outperforming competitor seeds, which exhibited storability of 10 and 14 days. Across both datasets, the majority of farmers reported wasting less than 25% of their harvest, underscoring the reduced postharvest losses associated with Ansal.

The proportion of farmers reporting increased earnings was similar between the baseline (91%) and the follow-up (90%). Increased production volumes (97%), better prices (26%), and cost reductions (10%) primarily drove income growth in the follow-up. This finding aligns with the field trial results, which revealed an ROI of 172% for Ansal. However, fewer farmers in the follow-up period cited price increases and cost reductions as contributors to their income growth compared with the baseline.

In the follow-up, 94% of the farmers perceived an improvement in their quality of life, compared with 89% at baseline. The key factors contributing to improved quality of life during follow-up included better farming outcomes or higher yields (43%), the ability to better afford education (40%), and improved capacity to cover household expenses (35%). Similarly, baseline respondents most frequently cited increased income (49%) and the ability to afford household bills and basic needs (44%), as well as investments in housing or property (15%) as factors improving their quality of life. A total of 90% of the farmers reported that their level of stress in meeting their family's basic needs decreased with Ansal tomatoes, which was a solid improvement since the baseline (80%) was reached. 32% of the farmers feel more prepared to face future climate shocks:

"I have been able to take my kids to school because of Ansal. I also eat well and dress well now. We even built a house with the money we earned." (Female)

"Ansal doesn't require too much water to produce fruits. This is favorable during a drought, and it will help me recover faster." (Male)

The percentage of farmers who received training decreased from 49% at baseline to 30% at follow-up. In the follow-up, training was primarily delivered through on-farm visits (65%), participation on field days (27%) or attendance of demonstration farms (25%). Baseline respondents reported receiving training predominantly through word-of-mouth communication with other farmers (18%) or on-farm visits (12%)

92% of the farmers in the baseline group said that training helped them learn more about, for instance, how to use pesticides and insecticides (32%), prepare the land for planting (22%), properly space crops (14%), and conserve and irrigate water (10%). In the follow-up, 81% of the trained farmers confirmed to apply all or most of the knowledge gained from training; application barriers to all training information constitute of lack of funds (46%) or the unavailability of recommended materials or equipment (27%).

Moraleda Beans – India [109]

The vast majority of the farmers (94%) reported improved farming practices, which was attributed primarily to reduced labor and effort (40%) and the adoption of intercropping with tomatoes (33%). Additionally, lower water usage (20%) was perceived by farmers as described by one of them:

"Irrigation has improved as we use less water to grow crops in the summer when there is a shortage of water supply." (Male, 42)

Furthermore, farmers also reduced their use of fertilizers (90%) and pesticides (88%). These improved practices contributed to enhanced tomato yield (94%) and better tomato quality (92%), which in turn improved farmer livelihoods through increased earnings (94%). This farmer highlighted the positive impact of Moraleda beans on both his farming production and income:

"I made good money from beans and tomatoes after using Moraleda seeds as we get two crops in a short time, so there is double profit. The Moraleda beans produce much more yield than other seeds." (Male, 40)

The improved yield was corroborated by field trials, which demonstrated that the yield per plant was greater for Moraleda than for other hybrid seeds. Additionally, Moraleda had a greater return on investment (ROI) in field trials, with a 55% increase in ROI due to the higher yield in kilograms.

Farmers reported an improvement in their quality of life (92%), largely driven by increased investments in their farms (34%), investment in personal assets such as household items and home renovations (26%), and higher savings (21%). These advancements were made possible by higher earnings, attributed to an increase in the volume of tomatoes sold (95%), better prices (92%), and cost reductions (48%). Nearly all intervention participants (92%) noted decreased stress levels, which they attributed to the adoption of Moraleda seeds, highlighting the broader positive impact on farmer well-being and resilience:

"Life is better and stress-free now with the extra income from Moraleda seeds. Now, if I need money immediately, I don't have to worry or borrow from others." (Male, 43)

Seminis 7864 Hot Pepper – Pakistan [107]

A total of 56% of the farmers reported improvements in their farming practices, whereas nearly 33% experienced no significant changes. Among those who identified improvements, 61% mentioned adopting modern farming practices, such as the use of hybrid seeds and land levelling. Additionally, 30% reported reduced pesticide and fertilizer use, and 28% highlighted lower water usage:

"I now use hybrid seeds and modern techniques like land leveling for better results with [Seminis 7864]." (Male, 36)

"[Seminis 7864] require less water, saving me from paying extra labor costs for irrigation." (Male, 25)

These findings align with those of field trials, which revealed that the irrigation and chemical costs for Seminis 7864 were lower than those for other seeds. 75% percent of the farmers perceived an increase in production, 75% of whom achieved this increase on the same amount of land. This observation was supported by field tests, which revealed that Seminis 7864 had higher yields than other hot pepper hybrid seeds. Almost three quarters (74%) reported higher earnings related to an increase in sales volume (100%), price (40%) and cost reduction (25%). A farmer explained that the good yield and higher weight of the chilies result in increased earnings:

"This seed provides good yields, and of the chilies are sold after turning red, they have good weight and bring in higher earnings. This has resulted in substantial profits for me." (Male, 33)

These results are consistent with the field trial data, which indicated that the total investment for Seminis 7864 was lower, the ROI was higher and increased by 477%. This improvement was driven by a higher produce price per kilogram, greater average weight per plant, and higher total yield than those of the other seeds.

73% of the farmers reported an increase in their quality of life, and the main drivers mentioned were increased income (68%), improved ability to afford household expenses (32%), and reduced stress (30%). 72% of the farmers noted a decrease in stress levels when prompted, which they attributed to the adoption of Seminis 7864.

Furthermore, 30% of the farmers had experienced flooding as one of the most common climate shocks in Pakistan, followed by irregular weather patterns (14%) or droughts (12%). Almost a third of the affected farmers (32%) feel better prepared for future shocks, crediting this to resilient seeds (98%).

"[Seminis 7864] is very resilient and doesn't deteriorate easily due to weathering. This gives me the confidence to tackle unexpected problems, and I am always mentally prepared for any issues that may arise in the chili crop." (Male, 37)

Knowledge Transfer Initiative – India [105]
The study revealed that a majority of the farmers (86%) reported an improvement in their farming practices as a result of the Knowledge Transfer Initiative (KTI), with 30% noting significant improvements:

"Earlier, I planted tomatoes without any specific techniques. Now, I use the staking method, mulching, and drip irrigation. I also apply high-quality pesticides." (Male, 22)

Among the farmers who identified improvements, 49% mentioned better application of fertilizers or pesticides, 29% highlighted improved irrigation techniques, and 22% reported the adoption of mulching practices. A survey participant explained his improved application of fertilizer:

"Previously, I didn't know the correct quantity of fertilizer to use for my field area. After watching a video, I learned the proper method and quantities for applying fertilizer." (Male, 26)

A total of 77% of the farmers reported an increase in farm production due to KTI, with higher yields achieved in the same land area (77%), indicating improved productivity. Notably, compared with those who received one or two offerings, farmers who accessed all three KTI offerings were significantly more likely to report that their production had "very much increased" (44% vs. 29%).

In terms of economic impact, 74% of the farmers reported an increase in crop earnings due to KTI, with 29% reporting a significant increase. The higher earnings were attributed primarily to an increase in the volume of crops sold (89%), an increase in crop prices (53%), and a reduction in costs (12%). Additionally, 84% of the farmers reported increased confidence in investing in agriculture following their engagement with KTI, with 41% saying this has "very much increased".

The initiative also contributed positively to the quality of life of the farmers, as a male participant expressed:

"Previously, there was a lack of water but now I have installed a tube well. My house, which was once made of raw materials, is now gradually being rebuilt." (Male, 35)

A total of 75% of the respondents noted improvements; among those, 49% highlighted increased crop production, 43% cited higher income, and 40% mentioned an enhanced ability to invest in farm equipment or infrastructure as the driver of improved quality of life. Stress reduction was another significant outcome, with 79% of the farmers reporting a decrease in their stress levels:

"The tips from the videos on keeping crops safe have been very helpful. I apply them and get good results. My crops stay safe, and I no longer worry about damage." (Male, 28)
The high proportion of farmers accessing such an offering for the first time (88%) along with the relative lack of good alternatives suggests that KTI is providing a unique service to an underserved farmer base.

Bayer's Centers of Excellence – Kenya [104]
The engagement with the Centers of Excellence demonstrated substantial benefits for farmers, with 98% receiving training onsite, 90% obtaining product recommendations and information, and 69% accessing personalized services such as farm visits or phone calls. One male intervention participant described the benefit of Bayer's Centers of Excellence on his life:

"After gaining knowledge through their training, I now truly believe there is a method to practicing farming. Sometimes I wonder how much more I could have accomplished in life if I had known about Bayer's [CoE] three years ago." (Male, 40)

Nearly half of the farmers (49%) visited the CoE at least twice in the past year, with those receiving personalized services being more likely to make multiple visits than those without personalized services (63% vs. 37%).

Farmers found the advisory provided by the CoE both novelly and accessible, with 71% reporting that "all" or "most" of the advisory was new to them and 94% finding it easy to understand. While 71% of the farmers implemented "all" or "most" of the advice on their farms, financial constraints were the primary barrier for the complete application (67%).

The impact on farming practices was profound: 96% reported improvements driven by enhanced pest management techniques (49%), the use of better-quality seeds (34%), and improved fertilizer application (33%). A female intervention farmer described how CoE changed her way of farming:

"This harvest, my production has significantly increased compared to the previous one. This is because I followed the advice provided on farming activities and product recommendations, including certified seeds and chemicals, from farm preparation to harvesting." (Female, 30)

Consequently, 92% of the farmers noted a change in production, with 63% reporting a significant increase. Most achieved these gains on the same amount of land (73%), indicating improved productivity. Among those with increased production, 71% reported increases of up to 50% since engaging with the CoE. These gains translated into financial benefits, with 84% of the farmers reporting an increase in earnings, driven by higher volumes sold (98%), reduced costs (13%), and better prices (12%).

93% of Farmers also reported broader improvements in their quality of life. One farmer described how the training allowed him to earn enough money through farming to meet the family's basic needs:

"Through the trainings and from applying what I've learned, I have stopped juggling too many things to make ends meet. Now, farming provides enough money to meet all my needs and those of my family." (Male, 50)

Improved farm production and income (83%), increased farming knowledge (49%), and increased ability to afford household expenses (24%) were cited as key contributors to improved quality of life.

"I have noticed a significant improvement in my production. Harvesting more means I can sell more and earn more." (Male, 47)

Confidence in farming investments also increased markedly, with 95% of the farmers reporting greater confidence, specifically those farmers who had received personalized services.

Weather-Based Parametric Insurance – Philippines [106]

In total, 47% of the farmers perceived an improvement in their way of farming. A male participant explained how he was able to improve his farming practices by reducing the amount of fertilizer used:

"We were able to use only a small amount of fertilizer because it is not hard to take care of crops from Seminis seeds." (Male, 39)

The main reasons for this improvement were better use of fertilizer and pesticide (43%), improved pest management (42%), and practicing crop rotation (19%). A total of 72% of the respondents reported that the total production of their main crop increased due to Seminis/Jardine, with 79% planting on the same amount of land. 61% of the farmers surveyed reported higher earnings due to an increase in volume sold (82%), price (50%), and reduced cost (15%):

"Seminis is more durable than other varieties. Because of this, we can harvest more and increase our income. We can buy food for the family." (Female, 40)

A total of 73% of the farmers reported that their quality of life improved, as described by this participant:

"Because of the money we earned from cabbage, we were able to invest in essential machinery for the farm, such as an electric water pump for irrigation and a tractor to expedite land preparation, reducing our labor costs and increasing efficiency." (Female, 33)

Fifty-eight percent of the farmers mentioned that their quality of life improved due to increased income (58%), their ability to afford household expenses (47%), and their ability to better afford their children's education (38%). For these reasons, 58% of the farmers reported a reduction in their stress levels.

In the past two years, nearly all communities faced climatic extremes, including typhoons (76%), drought (44%), flooding (22%), irregular rainfall (12%), and landslides (4%). Fifty-three percent reported having recovered at least at the same level as before the climatic event, whereas 46% reported still recovering. Among all the farmers, 44% said that they feel better prepared for future extreme weather events because of the intervention, and 47% would expect their recovery timelines to be shorter. The main reasons they provided for perceived resilience were good-quality seeds (53%), agronomic support and training (32%), and the adoption of resilient practices (28%).

Challenges

As shown in Table 3, only a small number of farmers reported challenges, with the highest prevalence observed in Ansal, where challenges were mentioned by 51% of the farmers at baseline and 35% at follow-up. The lowest proportion of challenges was identified in KTI (8%), followed by Fortaleza (11%) and Moraleda (13%). The reported challenges can be clustered into four key areas: crop health and resilience, yield and productivity, input quality and effectiveness, and knowledge and support.

Case	Farmers report experiencing challenges (%)	Top challenges of farmers facing challenges
Fortaleza	11%	Bad quality of produce = 56% Lack of support from agents = 41% Poor resistance to pests = 16%
Ansal Baseline	51%	Infestation by pests = 40% Leaves yellowing or drying = 39% Low tomato production = 18%
Ansal Follow-up	35%	Yellowing of plants or blight = 43% Inconsistent yield = 26% High prices of Ansal seeds = 15%
Moraleda	13%	Poor resistance to high temperatures = 26% Poor resistance to pests = 20% Poor beans yield = 11%
Hot Pepper	28%	Poor climate resilience = 51% Poor yield = 38% Poor pest or disease resistance = 16%
KTI	8%	Incorrect or incomplete information = 41% Lack of relevant information = 41% Recommended product authenticity concerns = 18%
CoE	16%	Limited stock of recommended products = 26% Suggested products being ineffective = 26% High cost of recommended inputs = 22%
Weather insurance	38%	Poor seed germination = 33% Pest and disease infestations = 19% Vulnerability to weather changes = 12%

Table 3: Overview of Challenges Reported by Farmers Facing Challenges

The variation in reported challenges across cases suggests that local conditions, crop types, and support systems significantly influence farmer experiences. While Ansal showed the highest prevalence of challenges, particularly related to pest pressure and plant health, other cases like KTI and Fortaleza reported fewer issues, often linked to information gaps or input quality. These findings underscore the importance of context-specific support and interventions. However, it is important to note that the data reflects self-reported perceptions from farmers who experienced challenges and does not include a control group for comparison. As such, the interpretation of challenge prevalence and severity should be approached with caution.

While many farmers reported challenges related to crop health, input quality, and climate resilience, this does not contradict the overall positive perception of the interventions. Although seed cost was noted as a challenge, farmers still reported higher earnings, suggesting that input costs were outweighed by gains in yield and quality; interpreting such findings requires consideration of farmer characteristics and production contexts. These findings reflect the complexity of farming systems, where improvements in yield, income, and quality of life can coexist with persistent or emerging challenges. Farmers may perceive net benefits despite facing specific issues, suggesting that the interventions are seen as valuable but not without limitations. This highlights the importance of continuous support and adaptation to local conditions.

Discussion

Reducing poverty and ensuring food security remain major global challenges, especially as the world's population grows and the effects of climate change become more apparent [61,62]. Smallholder farmers, responsible for producing a

significant portion of the world's food, are at the forefront of these challenges. To address these challenges, targeted interventions are essential. However, improving the livelihoods of smallholder farmers is inherently complex, as it involves addressing multiple, interconnected barriers along the value chain [63]. This study synthesizes findings from eight impact studies to evaluate the perceived impact of targeted agricultural interventions - hybrid seeds, intercropping, knowledge transfer, and weather insurance - on the farm productivity and livelihood of small-scale vegetable farmers across India, Kenya, the Philippines, and Pakistan. As outlined in the methodology section, the study findings may not be applicable to the broader smallholder population in the countries. The analysis focuses on both subjective and objective farmer- reported outcomes to provide a comprehensive understanding of the impacts of these interventions. While comprehensive interventions across the entire value chain are ideal, this study demonstrates that even focused measures, such as hybrid seeds and practical, localized capacity building, can yield significant benefits. Across all case studies, key outcomes included considerable improvements in farming practices, production, earnings, and quality of life. These findings underscore the importance of scalable and accessible innovations in improving farmer resilience.

Improved Farming Practices

The adoption of targeted innovations such as hybrid seeds, intercropping, and knowledge transfer initiatives has significantly improved farming practices. Farmers gain access to tools and techniques that enable them to adapt to changing agricultural conditions, improving both productivity and resilience. For example, in India, farmers using Fortaleza hybrid cauliflower seeds reported enhanced disease management and reduced fertilizer use. In Pakistan, farmers growing hot pepper have adopted modern farming practices such as land levelling and highlighted lower water usage. Such interventions empower farmers to adopt modern practices, which are crucial for overcoming climate and resource challenges [64]. Furthermore, they empower smallholder farmers to compete with larger agribusinesses, fostering economic growth and social development in farming communities [65]. These examples highlight the value of integrating innovations and capacity building into local farming contexts to empower smallholder farmers. While innovations such as hybrid seeds and intercropping improve farming methods, their broader impact is reflected in increased productivity. For instance, evidence from climate-resilient agriculture (CRA) interventions in southern Malawi shows that farmers who adopted CRA practices achieved significantly higher maize yields, underscoring the productivity benefits of such approaches [66]. Research further suggests that intercropping may increase soil fertility via observed increases in soil organic matter, total nitrogen and macro-aggregates when comparing intercropped with monoculture soils to enhance soils, contributing to both crop production and its long-term sustainability [67]. Combined with the right training interventions, this can create ripple effects on improvements in the way of farming. For example, in India, a higher share of Ansal tomato farmers who received respective training reported a significantly better way of farming compared to their untrained peers (38% vs. 24%). The following section examines how these interventions contribute to higher yields and why knowledge transfer plays a pivotal role in sustaining these gains.

Increased Productivity and the Importance of Knowledge

The study also demonstrated that targeted agricultural interventions can significantly increase productivity. For example, as observed across the impact studies, hybrid seeds played a pivotal role in achieving higher crop yields. These results are consistent with the literature that has demonstrated the positive impact of hybrid seeds on smallholder productivity [68].

The increased availability of vegetables resulting from higher production positively impacts individual farmers but also local communities, addressing food security at a broader systemic level [69]. This dual benefit highlights the far-reaching effects of increased production through agricultural interventions on both immediate nutritional needs and regional food supply chains [70]. However, increasing vegetable output does not always result in improved regional food supply chains because of postharvest losses, according to a study by The majority of these losses are due to the accumulation and spoilage of produce during the wholesale-to-wholesale trade [71]. This underscores the importance of ensuring that vegetables have a long shelf life such as the Ansal tomatoes to compensate for challenges in the supply chain.

The role of knowledge transfer was particularly pronounced in boosting productivity as well as reducing stress levels and increasing confidence among farmers to invest in agriculture in the future. This underscores the importance of aligning technological solutions with enabling conditions to unlock their full potential for smallholder farmers. Evidence from Zambia further supports this, showing that conservation agriculture technologies can significantly improve household welfare when interventions are designed to overcome key constraints, particularly limited access to knowledge and inputs, thereby reinforcing the importance of integrated support systems [72]. Farmers who received training under initiatives such as the KTI in India and CoEs in Kenya reported substantial productivity increases. These results reinforce the importance of integrating innovative agricultural inputs with practical, localized training to increase farm productivity [30,73,74]. Knowledge transfer, as evidenced by the KTI and CoE programs, emerges as a critical factor in helping farmers to not only access educational information but to also adopt the learnings and maximize the benefits of their production. These findings align with evidence showing that extension services and training programs enable farmers to thrive in evolving agricultural landscapes, particularly under climate stress [75]. Cost-benefit analyses of agricultural extension and knowledge systems have shown that the benefits such as increased yields, improved input efficiency, and reduced crop losses often outweigh the costs of information provision, particularly when programs are well-targeted and context-specific, such as digital agricultural extension. A study by highlights how mobile-based agricultural extension services can deliver tailored information to smallholder farmers at scale, with significantly lower costs compared to

traditional methods [76]. These digital systems have shown positive returns by improving input use and crop yields, demonstrating a favorable cost-benefit ratio in various contexts.

Despite these successes, barriers to the full adoption of interventions remain a concern. Financial constraints, limited access to credit, and the unavailability of necessary resources hinder implementation. These findings align with earlier research highlighting the importance of addressing financial and resource limitations alongside the provision of knowledge [56,77]. To maximize the effectiveness of these interventions, comprehensive support systems that address both financial and knowledge-based challenges are essential. Recent evidence from Malawi suggests that structured stakeholder engagement, such as agricultural panels, can play a pivotal role in overcoming these constraints by facilitating the diffusion of innovations and enhancing the adoption of post-harvest loss reduction practices [78].

The next section explores how these interventions translate into higher income levels, with transformative impacts on households and communities.

Increased Income

The study clearly shows that increased income was one of the key outcomes of the interventions, as observed in the literature [68,79,80]. Increased crop volumes, improved market prices, and reduced costs primarily drove farmers' reported higher earnings across all impact studies. This finding reinforces the idea that equipping farmers with the tools and techniques necessary to navigate both production and market dynamics is pivotal for achieving income stability [81]. The study results do not equate increased incomes solely with higher prices, as these may be offset by inflation; instead, the results underscore that enhanced productivity plays a critical role in mitigating income losses resulting from harvest shortfalls. Higher earnings allow farmers to invest in household assets, education, and healthcare, thereby improving their overall quality of life and financial resilience [82,83].

In rural areas where public health services are often scarce or inaccessible, financial stability enables farmers to afford better medical care, contributing to greater household resilience and well-being [84]. Additionally, surveyed farmers reported being able to send their children to school, a finding that aligns with literature emphasizing the intergenerational benefits of educational investments as a pathway out of poverty [85,86]. Education not only improves the prospects for the next generation but also creates opportunities for long-term economic growth and development in farming communities [87]. Moreover, increased income allowed surveyed farmers to reinvest in their farms, adopt innovative practices, thereby strengthening their resilience against external challenges, such as climate variability and market fluctuations. This observation corroborates previous research highlighting the role of increased earnings in creating a positive feedback loop that drives agricultural development and breaks poverty traps [88]. These findings further demonstrate how targeted agricultural interventions can foster systemic changes that enhance both individual livelihoods and broader community resilience.

Higher incomes also increase families' ability to afford healthier and more diverse diets, directly contributing to improved nutritional status and overall food security [89]. However, a study by showed that higher farmer incomes lead to better diet quality and nutrition, but can also increase the risk of obesity and overweight [90]. Diversifying agriculture toward high-value crops such as fruits and vegetables are highlighted as a key strategy to improve dietary diversity.

The following section discusses how these economic improvements lead to enhanced quality of life, reduced stress, and greater confidence in farming.

Improved Quality of Life

In addition to improved farming practices, agricultural productivity, and income, the study highlights significant improvements in the quality of life of farmers, which are driven mainly by increased financial stability. Greater access to household resources, enhanced savings capacity, and increased investments in farm infrastructure reflect these improvements. For example, in Kenya, nearly all of the CoE intervention participants reported a higher standard of living, noting improvements in education opportunities for their children and increased ability to meet household expenses. In India, KTI participants highlighted reduced stress levels, greater confidence in farming, and better access to essential resources as key contributors to their enhanced quality of life.

The improvement in farmers' quality of life has direct implications for long-term agricultural engagement. Financially stable and satisfied farmers are more likely to remain committed to agricultural activities, which are essential for longterm food security [91]. As the FAO (2014) suggests, improving farmers' economic well-being is crucial for maintaining their engagement in agriculture, particularly as they face increasing climate risks [92]. In contrast, the study by Wojewódzka-Wiewiórska et al. found that economic circumstances had a substantial detrimental effect on mental health [93]. In the study, they assumed that hard work, which limits leisure time and increases stress levels, often leads to a favorable financial situation in a farmer's household. Therefore, providing farmers with agricultural interventions that ease their workload and reduce stress levels is highly important, as demonstrated in our case studies.

Another critical outcome of the interventions was the significant reduction in stress levels reported by farmers. While often overlooked in discussions on agricultural sustainability, stress reduction plays a pivotal role in ensuring that farmers

remain engaged in their work. Reduced stress not only improves mental and emotional well-being but also has tangible impacts on productivity (Divya [94,95]. Research has demonstrated that lower stress levels enhance decision-making capabilities and increase resilience, making farmers more likely to invest in and sustain their agricultural activities over the long term [96]. The findings of this study underscore the need to create supportive environments that address both the physical and emotional challenges faced by farmers. Interventions that reduce stress, such as providing financial security through weather insurance and offering knowledge-based support, or that improve climate resilience through respective crop traits, allowing farmers to feel better prepared for future climate shocks, contribute to fostering a sense of stability and confidence. These efforts enable farmers to focus on long-term planning and innovation, further strengthening their role as key contributors to sustainable agricultural systems and global food security.

While the study highlights the potential of small-scale interventions, it also identifies critical limitations that must be addressed to ensure scalability and inclusivity. The following section discusses these challenges and offers insights into future research.

Limitations

While the findings of this study underscore the substantial benefits of targeted agricultural interventions, several limitations must be acknowledged. The sample population showed a significant overrepresentation of male respondents, indicating continuing gender inequalities in access to agricultural resources and decision-making roles. This highlights a critical shortcoming in the design and implementation of interventions. The development of targeted strategies to better engage and empower women farmers is essential, as they often encounter unique barriers, such as restricted land ownership and limited access to credit. Addressing these challenges is crucial for fostering gender-inclusive agricultural development. Moreover, bridging these disparities would not only promote gender equity but also amplify the overall effectiveness of interventions, given the indispensable role that women play in agricultural production, household nutrition, and community resilience.

Although this study focused on interventions in a wide range of cultural and geographical settings, it might not have fully taken into account the differences in local conditions, such as differences in soil quality, market access, or climate problems that affect different areas. These contextual factors can significantly influence the effectiveness of agricultural interventions. Future research should prioritize a deeper exploration of location- specific dynamics to refine and tailor interventions, ensuring their relevance and maximizing their impact. By incorporating these localized insights, interventions can be adapted to better address the unique challenges experienced by smallholder farmers in different regions, which will eventually enhance their efficacy and sustainability. The next section outlines key policy recommendations for inclusive and sustainable agricultural development.

Policy Implications

The policy implications of these findings are clear: investing in agricultural innovation targeted at smallholder farmers is essential for reducing poverty and ensuring global food security [97]. Policymakers must prioritize the creation of enabling environments where innovation can thrive, ensuring that farmers have access to the tools, resources, and knowledge necessary for sustainable agricultural practices. As Som Castellano and Moroney (2018) argue, adaptation strategies must account for sociodemographic factors and regional variability to ensure inclusivity and effectiveness, particularly in reaching underrepresented groups such as smallholders at the rural–urban interface [98].

To be effective, agricultural policies must also recognize the complex decision-making processes within smallholder households, where production, consumption, and labor allocation are deeply interconnected. Agricultural household models have long emphasized the need to consider these dynamics when designing interventions (Singh, Squire, & Strauss, 1986), reinforcing the importance of integrated approaches that address both economic and agronomic constraints.

First, governments should implement financial assistance programs to mitigate the cost of inputs through access to affordable credit and to support climate resilience as well as financial stability through agri-insurance coverage for smallholder farmers. Public–private partnerships can play a pivotal role in expanding access to these tools while sharing risks and rewards across sectors. Second, policymakers should invest in developing and sharing knowledge transfer platforms, such as digital advisory services and community-based training programs, to provide farmers with the necessary skills to effectively adopt climate-smart techniques. Digital agricultural extension services have demonstrated significantly lower costs per farmer reached compared to traditional in- person methods, while still delivering tailored and actionable information at scale [76]. Third, adaptation strategies must account for sociodemographic factors and regional variability to ensure inclusivity, with a focus on reaching underrepresented groups such as smallholder farmers at the rural–urban interface.

Finally, national agricultural policies should integrate climate adaptation and resilience. Governments must prioritize research and innovation that address region-specific challenges posed by climate change while ensuring scalability and practicality. Evidence from Malawi demonstrates that climate-smart agriculture aid investments can lead to significant yield improvements, reinforcing the importance of targeted support for smallholder farmers in climate-vulnerable regions (Amadu, Miller, & McNamara, 2020). Evidence from rural Pakistan shows that farmer-led adaptation to extreme weather

conditions can significantly improve farm performance, underscoring the importance of enabling and supporting locally relevant adaptation strategies. Such findings underscore the need for policies that not only promote innovation but also ensure that investments are strategically directed to maximize impact.

To summarize, this study underscores the indispensable role of smallholder farmers in ensuring global food security (SDG 2) and reducing poverty (SDG 1). By focusing on farmers' subjective evaluations, this research provides critical insights into the dimensions of their experiences, emphasizing the importance of aligning agricultural interventions with their perceptions and lived realities. The findings demonstrate that empowering farmers through tailored, innovative solutions not only improves farming practices, productivity, and income but also contributes to enhanced quality of life and long-term resilience. Especially in the face of escalating climate risks, such approaches are essential to address the twin challenges of food security and poverty reduction. This research highlights that agricultural interventions designed with a holistic understanding of farmers' experiences can foster sustained engagement, strengthen community welfare, and enhance the capacity to meet both immediate needs and future challenges, contributing to a more equitable and sustainable agricultural landscape.

Conclusion and Future Directions

This study highlights the transformative potential of targeted agricultural interventions in enhancing smallholder farmers' farming practices, farm productivity, income, and livelihoods to contribute to global food security. Farmer self-expressed perceptions, which were collected through independent and innovative survey methodologies, provide critical insights into the social impacts of interventions. Interventions such as hybrid seeds, intercropping, weather insurance, and knowledge transfer emerged as key drivers of improved farming methods, increased productivity, higher incomes, and better quality of life.

Hybrid seeds and intercropping strongly affect yields and input efficiency, optimizing resource utilization while increasing production. Knowledge transfer, implemented through both scalable digital platforms and localized, hands-on approaches, empowered farmers to adopt climate-smart techniques and improve their farming practices sustainably. Weather insurance offered essential financial security. Collectively, these interventions improved farming and production methods, enhanced production and income stability, and contributed to improved quality of life, with farmers reporting reduced stress and greater capacity to invest in their farms, homes, and children's education.

The findings emphasize that even small, focused interventions can yield disproportionately large benefits without requiring a comprehensive overhaul of agricultural systems. By aligning interventions with farmers' lived realities and perceptions, stakeholders can ensure sustainable and impactful outcomes.

While the results are promising, systemic barriers remain a challenge to scaling these interventions. Financial constraints limit access to tools and technologies, particularly for marginalized groups underline the need for inclusive and accessible solutions. Gender disparities were evident, with male farmers being the predominant participants. Addressing this imbalance will require targeted efforts to include and benefit female farmers, who often face additional barriers in accessing agricultural resources. Future research should explore these gender disparities and focus on designing interventions that benefit women as equally as men do. It is also crucial to examine region-specific challenges, such as climatic conditions and socioeconomic factors, while maintaining the scalability of interventions.

The findings of this study underscore the critical role of smallholder farmers in securing the global food system and in achieving the SDGs 1 (No Poverty) and 2 (Zero Hunger). Policymakers and stakeholders must prioritize investments in scalable agricultural solutions, such as hybrid seeds, weather insurance, and knowledge transfer platforms, to address the combined challenges of food insecurity, poverty, and climate change. The interconnections among improved livelihoods, reduced stress levels, and sustained agricultural productivity underscore the importance of farmer-centric approaches.

An improved livelihood directly correlates with farmers' ability to continue producing relevant crops, contributing to both regional and global food security. By fostering an environment where innovation and inclusiveness drive progress, stakeholders can empower smallholder farmers to navigate the growing challenges of climate change, ensuring their pivotal role in advancing food security and sustainable development. Targeted interventions, though seemingly small, hold the potential to create far-reaching and transformative impacts across farming communities, ensuring their resilience and productivity for future generations [99-109].

Declaration of competing interests

The studies were sponsored by Bayer AG Division Crop Science. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in the paper.

Author contributions

VK Kishore: Conceptualization, Methodology, Supervision, Writing
Constance Spitzer: Methodology, Project administration, Writing
Reshma Menon: Project administration, Writing

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