



Original Research

Adoption and Productivity Assessment of Zinc-Biofortified Wheat (Akbar-19) Among Smallholder Farmers in District Khyber, Pakistan

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Abstract

Micronutrient malnutrition, particularly zinc deficiency, remains a critical public health challenge in Pakistan, where wheat is the dominant staple food but inherently low in zinc. Bio-fortification offers a sustainable solution by enhancing the micronutrient content of staple crops. This study evaluates the adoption and impact of zinc-biofortified wheat (Akbar-19) among 200 smallholder farmers in District Khyber, Khyber Pakhtunkhwa, Pakistan. A mixed-methods design was employed during the wheat season of 2024–25. Two hundred farmer received certified Akbar-19 seed, fertilizers and technical guidance. Adoption behavior, seed retention, yield performance, and household food security outcomes were analyzed using descriptive and inferential statistics. Results showed that Akbar-19 achieved significantly higher yields, averaging 1700 kg acre⁻¹ compared with conventional wheat varieties (1300 kg acre⁻¹) grown simultaneously on adjacent control plots during the same season. Seed retention was high, with 86% of households saving 2–4 maunds for future planting, and 60% sharing seed within communities. Awareness of zinc's health benefits increased from 20% at baseline to 100% post-intervention. This study contributes to current knowledge by demonstrating that zinc-biofortified wheat can simultaneously improve productivity (30.77%) and nutritional awareness under real farming conditions. The findings highlight the potential of farmer-led seed saving and informal sharing networks to sustain adoption. However, as results are limited to one season and location, broader conclusions require multi-season, multi-location trials and clinical validation of nutritional outcomes.

Citation: Khalid, M., Samad, M., Elahi, S., & Fahad, S. (2026). Adoption and Productivity Assessment of Zinc-Biofortified Wheat (Akbar-19) Among Smallholder Farmers in District Khyber, Pakistan. *AgroEnvironmental Sustainability*, 4(3), 240–249. <https://doi.org/10.59983/s2026040301>

Statement of Sustainability: This study introduces zinc-biofortified wheat (Akbar-19) under real farming conditions. The main innovation lies in combining biofortified wheat introduction with farmer-led seed saving and informal seed sharing within local farming communities. This approach enhances the long-term availability of improved seed through cost-effective access and community-based diffusion systems. The study relates to SDG 2 (Zero Hunger) and SDG 12 (Responsible Consumption and Production) as general areas of relevance only, not as measured targets. Overall, it supports more sustainable and resilient smallholder farming systems with reduced dependence on external agricultural inputs.

1. Introduction

Agriculture plays a central role in sustaining food security and rural livelihoods across developing countries, where smallholder farmers account for a large share of food production. Despite their importance, smallholders often face multiple constraints such as limited access to improved technologies, certified seeds, extension services and financial resources (Reddy & Rahut, 2025). These challenges reduce productivity and restrict the adoption of innovations that could enhance both agricultural output and household well-being (Zheng et al., 2022). In recent years, increasing attention has been given to nutrition-sensitive agriculture, which aims not only to increase food production but also to improve the nutritional quality of diets among vulnerable populations (Huang, 2025).

Micronutrient malnutrition, commonly known as hidden hunger remains a major global health concern. Unlike calorie deficiency,

ARTICLE HISTORY

Received: 31 May 2026

Revised: 16 June 2026

Accepted: 22 June 2026

Published: 15 September 2026



KEYWORDS

food and nutritional security
Khyber Pakhtunkhwa
malnutrition
micronutrient
smallholder farmers
zinc biofortified wheat

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e-ISSN: 2583-942X

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hidden hunger is not always visible but significantly affects human health and development. Over two billion people worldwide are estimated to suffer a deficiency of essential micronutrients. These include zinc, iron, and vitamin A (Lowe et al., 2020; Elegbeleye et al., 2025). Children and women of reproductive age are more affected due to deficiency of these nutrients which can affect immunity, growth and cognitive development (Majumdar et al., 2025). Zinc is one of the most important micronutrients, and its deficiency can lead to abnormal immune system regulation, reproductive malfunction, neurological abnormalities and an increased risk of adverse health outcomes, particularly among vulnerable populations (Baddam et al., 2025; Lin et al., 2025).

Dietary patterns in South Asia, including Pakistan, are heavily cereal-based, with wheat (*Triticum aestivum* L.) providing the largest share of daily calories. However, the wheat varieties which we grow doesn't give much zinc and iron which are needed for body to stay healthy and also it contains high levels of phytic acid which further reduces zinc absorption in the human gut (Cakmak, 2008; Roy et al., 2022). As a result, even people eat enough food to get the calories still lack important nutrients. National surveys in Pakistan reveal that 22.1% of women of reproductive age and 18.6% of children under five are zinc deficient, with prevalence highest in rural and marginalized communities (Gupta et al., 2025). A rural community-based study in Khyber Pakhtunkhwa province reported that approximately 68.8% of adolescent girls were zinc deficient, indicating a significant public health concern in resource-constrained settings (Gupta et al., 2022).

To address micronutrient deficiencies in a sustainable manner, bio-fortification the process of breeding staple crops with enhanced nutrient content has emerged as a cost-effective and sustainable solution to hidden hunger (Bouis & Saltzman, 2017). Unlike supplementation or industrial fortification, bio-fortification leverages existing farming systems, making nutrient-rich crops accessible to rural populations with limited dietary diversity and poor access to fortified foods (VijayaKumar et al., 2025). Evidence showed that consuming bio-fortified cereals can increase daily zinc intake by 21–169% compared to conventional varieties (Gupta & Lowe, 2025; Sazawal et al., 2018). Importantly, modern biofortified wheat cultivars aim to achieve high micronutrient concentrations without sacrificing yield potential. As a result, farmers will not need to compromise on productivity when adopting varieties that are nutritionally improved (Velu et al., 2014; Cakmak & Kutman, 2017).

Pakistan has made significant progress in promoting bio-fortified wheat. Recently, a number of zinc biofortified wheat varieties have been released through partnerships between national research organizations and Harvest Plus and the International Maize and Wheat Improvement Center (CIMMYT). A good example is Akbar-19, which has high grain zinc concentration (almost 39 ppm) with high yield potential and resistances to wheat major diseases (Ahmad et al., 2020). The variety has quickly expanded and is being grown on a large area of wheat in Pakistan, producing millions of tonnes of zinc-enriched grain (HarvestPlus, 2025).

Despite this progress, the adoption of zinc-bio-fortified wheat remains uneven, particularly in marginalized rural regions. Several barriers hinder widespread adoption, including limited availability of certified seeds, weak seed distribution systems, high input costs, and insufficient awareness among farmers regarding the nutritional benefits of bio-fortified crops (GAIN, 2025). Strengthening community-based seed systems and improving access to agricultural extension services have therefore, been identified as critical factors for expanding the adoption of bio-fortified varieties (Hossain et al., 2024).

These challenges are particularly evident in District Khyber of Khyber Pakhtunkhwa province, where agriculture is predominantly rain-fed and characterized by small landholdings, poor irrigation facilities that expose famers to various social and economic vulnerabilities (Waleed et al., 2020). Such conditions contribute to persistent food insecurity and low agricultural productivity, while also limiting access to nutrient-rich foods. To tackle these issues, agricultural innovation must be linked to nutrition-sensitive development through integrated interventions.

Against this background, the present study evaluates the impact of introducing zinc-biofortified wheat (Akbar-19) among small-holder farmers in District Khyber under the project “Building Resilience Through Improved Nutrition in Sub-Urban Food Systems in KP.” Farmers who participated in the intervention were given certified zinc-enriched seeds, fertilizers and technical guidance. By examining yield performance, adoption behavior, seed retention practices and household food security outcomes, the study aims to provide empirical evidence on the role of zinc-biofortified wheat in enhancing agricultural productivity and nutritional security. These findings provide preliminary insights that may guide future research and localized interventions.

2. Materials and Methods

2.1. Study Area

This study was conducted in District Khyber, Khyber Pakhtunkhwa (KP), Pakistan, during the 2024–25 wheat cultivation season under the project “Building Resilience Through Improved Nutrition in Sub-Urban Food Systems in KP (Pak 1136). This location was purposively selected due to its high prevalence of micronutrient deficiencies (specifically zinc) and its reliance on rain-fed, cereal-based agricultural systems that are vulnerable to food insecurity. The study aimed to examine the adoption and associated outcomes of zinc-biofortified wheat variety Akbar-19 among marginalized smallholder farmers using an on-farm paired-plot design. Under this configuration, each farmer cultivated the newly introduced Akbar-19 variety on a designated plot while simultaneously maintaining their traditional conventional wheat variety on an adjacent control plot within the same landholding and same season, ensuring identical environmental conditions and resource allocation.



2.2. Research Design and Sampling

A mixed-methods design was adopted, combining quantitative surveys with qualitative interviews and field observations to capture both measurable agronomic outcomes and farmer perceptions. A total of 200 smallholder farmers were selected using a step-by-step multistage purposive sampling technique. In the first stage, Community-Based Organizations (CBOs) and Village Organizations (VOs) helped identified and poor and vulnerable household in the area. In the second stage, farmers were selected based on clear eligibility criteria such as size of landholding, live permanently in the area and be willing to try new farming methods by setting up demonstration plots. To make sure everything was fair, Monitoring, Evaluation, Accountability and Learning (MEAL) officers checked the list of selected farmers. Although the MEAL officers belong to the same organization, they operate under a completely independent management structure separate from the field implementation team. This strict separation of duties ensures that the MEAL unit acts as an independent internal auditor, removing personal conflict of interest and verifying that all selection criteria were strictly followed. Overall, this well-organized method made the study more reliable and also build trust with farmers. Because of this, farmers were willing to take part, shared their knowledge and actively participated in the study.

2.3. Intervention Package

All the participating farmers received intervention package simultaneously, including 50 kg of certified Akbar-19 seed (bio-fortified wheat variety). Along with this, they received 50 kg of urea, 40 kg of DAP and 3 kg of zinc sulphate, two trolleys of farm yard manure (FYM). The provided input package was standardized for one acre (01) of wheat cultivation. Each farmer cultivated Akbar-19 and their conventional variety on paired plots of equal size (one acre each) and the same input package was applied. This established a cumulative 200 acres (80.9 hectares) under Akbar-19 across the 200 participating farms. This ensured that yield comparisons were based on varietal performance under identical input levels and management practices, thereby minimizing confounding effects of unequal inputs rates. To help farmers to use these inputs correctly, pre-distribution orientation sessions and mid-season field days were conducted in collaboration with the Agriculture Extension Department. As a result, the study was not designed to isolate the individual effect of any single component. The observed outcomes therefore reflect the combined impact of the integrated package under real farming conditions rather than the independent contribution of specific inputs.

2.4. Data Collection and Analysis

Primary data were collected through field observations, interviews and a standardized farmer questionnaire. The researcher visited their field and asked questions about crop production, how much seeds they saved and shared with their neighbors and how they utilize basic inputs. Secondary data were collected from local Agriculture extension office, published literature to provide broader context and allow comparison with evidence on biofortification and certified seed adoption in District Khyber. Data collected were analyzed using statistical software SPSS. Inferential and descriptive statistics applied to assess the adoption of zinc-enriched wheat (Akbar-19) among smallholder farmers in District Khyber. Simple tools like frequencies, percentages and averages helped summarize farmer key information such as agronomic practices, seed retention and food security outcomes. This approach made sure that both numerical data and farmer opinions were properly analyzed. As a result, it provided strong and reliable evidence about the impact of using zinc-enriched wheat.

3. Results and Discussion

3.1. Baseline Knowledge, Adoption Patterns and Determinants of Zinc-Biofortified Wheat

Table 1 present the distribution of respondents according to their knowledge, adoption pattern and determinants of zinc biofortified wheat before intervention. The result showed that only small number of farmers about 16% of farmers are using zinc biofortified wheat while the majority (84%) had not yet adopted it. This highlights the relatively low adoption of biofortified wheat among farming communities in District Khyber, Khyber Pakhtunkhwa. The low adoption level observed in this study is consistent with previous findings that adoption of biofortified and improved crop varieties in South Asia remains limited due to weak seed systems, poor extension coverage and low farmer awareness (Bouis & Saltzman, 2017; GAIN, 2025). Regarding the factors that motivate adoption, the majority of respondents cited high yield potential (54 %), followed by reduced disease/pest incidence (30%) and improved nutritional value (16%). These results suggest that productivity are the main factors influencing adoption, whereas nutritional benefits has relatively small impact. Similar findings were reported by Bouis & Saltzman (2017) that farmers in poor and resource-limited areas focus more on yield and economic return when selecting new crop varieties. On the other hand, several challenges are stopping the farmers from adopting this technology. Limited access to certified seeds was reported by 40% respondents, high input costs (fertilizers, seed, etc.) by 25% respondents, and low literacy/awareness by 35% respondents. These barriers reflect both structural and socio-economic challenges that restrict farmers' ability to adopt new technologies. Similarly, constraints such as limited access to certified seed and high input costs have been widely reported as major barriers to technology adoption in smallholder farming systems (Reddy & Rahut, 2025). In addition, awareness about zinc and its importance is also very low with only 20% farmers knew about the benefits of the zinc, while 80% have no knowledge about it. This lack of awareness underscores the need for targeted extension services and farmer education programs.



Table 1. Distribution of respondents (N=200) according to their knowledge and adoption of zinc bio-fortified wheat before intervention of the project.

Variable	Category	Frequency (n = 200)	Percentage (%)
Zinc Biofortified Wheat	Yes	32	16
	No	168	84
Factors which Motivate Adoption	High Yield	108	54
	More Nutritious	32	16
	Low Disease/Pest Incidence	60	30
Factors which Hinder Technology Adoption	Limited access to certified seeds	80	40
	High input cost (fertilizers, seed, etc.)	50	25
	Low literacy/awareness	70	35
Awareness of Zinc Enrichment/Zinc Health Benefits	Yes	40	20
	No	160	80

3.2 Yield Performance of Zinc-Biofortified Wheat (Akbar-19) Compared to Conventional Varieties

A paired-sample t-test was conducted to determine whether there was a statistically significant difference in yield between the Akbar-19 and conventional variety grown simultaneously on adjacent plots by the smallholder farmers in District Khyber. The analysis revealed that the mean yield for the Akbar-19 variety was significantly ($t = 47.32$, $p < .001$) higher than that of the Conventional variety (Figure 1). The results clearly showed that Akbar-19 performs better in terms of production. Farmers cultivating both Akbar-19 and conventional wheat varieties under the same seasonal and farm-management conditions reported average yields of approximately $1700 \text{ kg acre}^{-1}$ for Akbar-19 compared with $1300 \text{ kg acre}^{-1}$ for conventional varieties. Across all 200 acres, Akbar-19 produced a total of 340,000 kg (340 tons) on average, while the conventional variety produced 260,000 kg (260 tons) on average. This means the new variety added an extra 80,000 kg (80 tons) of healthy food to the district. This big total increase shows that the project has a real economic value for the whole area. Because the comparison was conducted within the same farming households, the observed yield advantage is less likely to be influenced by differences in farm resources or environmental conditions. This finding indicates that the higher yield performance of Akbar-19 associated with the combined effects of improved variety characteristics and complementary agronomic inputs provided under the intervention package. Given the bundled nature of the intervention, it is not possible to isolate the specific contribution of the biofortified variety. Research showed that modern zinc enriched wheat varieties are developed to have high nutritional contents along with high yield potential, ensuring that farmers do not compromise on yield over nutrition while adopting nutritionally improved varieties (Velu et al., 2014; Cakmak & Kutman, 2017). The higher yield observed in District Khyber supports that the use of biofortification varieties can simultaneously address both agricultural productivity and nutritional deficiencies.

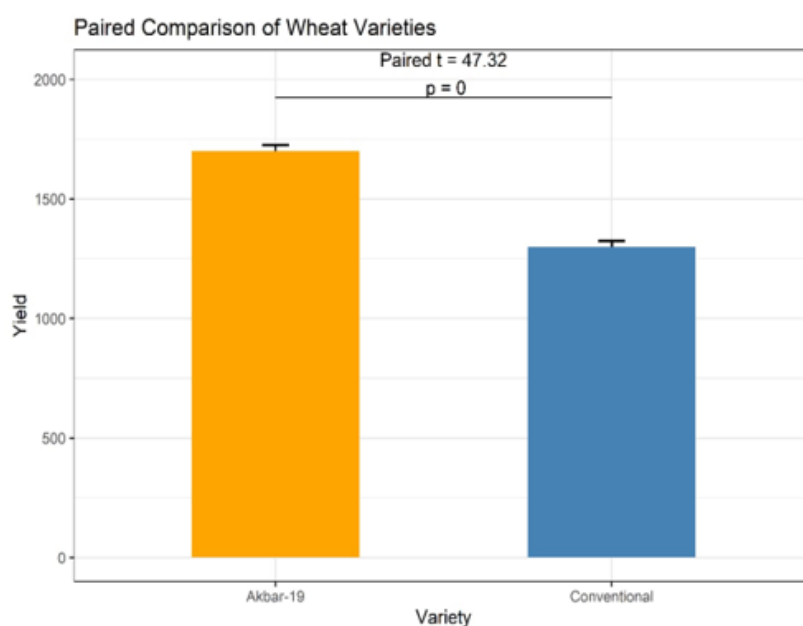


Figure 1. Average Yield (kg/acre) comparison of Akbar-19 zinc enriched wheat variety with conventional variety.



Overall, the results presented in Figure 1 demonstrated that the adoption of Akbar-19 provided dual benefits: including improved agricultural productivity and nutritional security. Such combined advantages made zinc-biofortified wheat a promising strategy for addressing both food security and micronutrient deficiencies in rural areas of Pakistan. Strengthening extension services, improved access to certified seeds, and raised awareness about the nutritional benefits of bio-fortified crops. This intervention proved essential to expand adoption and maximize the impact and adoption of this technology among smallholder farmers.

3.3. Adoption of Recommended Agronomic Practices for Zinc-Biofortified Wheat

The adoption rates of various recommended agronomic practices among smallholder farmers in District Khyber for the cultivation of Akbar-19 zinc-enriched wheat are illustrated in Figure 2. Land preparation and seed rate achieved the highest compliance (95%), followed by timely sowing (90%) and balanced fertilizer use (82%). These results reflected the strong influence of input distribution, orientation sessions and demonstration plots, which made adoption straightforward and visible. Similar findings have been reported in other biofortification programs, in those cases farmers who received trainings, certified seeds and other inputs were more likely to follow the recommended agronomic practices (Bouis & Saltzman, 2017; Gupta & Lowe, 2025). Seed treatment (65%) and organic matter application (68%) were moderately adopted. This shows that farmers understand their importance but they face challenges like limited resources or lack of knowledge. In contrast, rainwater collection (62%) and irrigation management (55%) were least practiced. This suggests that farmers in rainfed areas face major problems with water availability which makes it difficult for them to manage water effectively (Waleed et al., 2020).

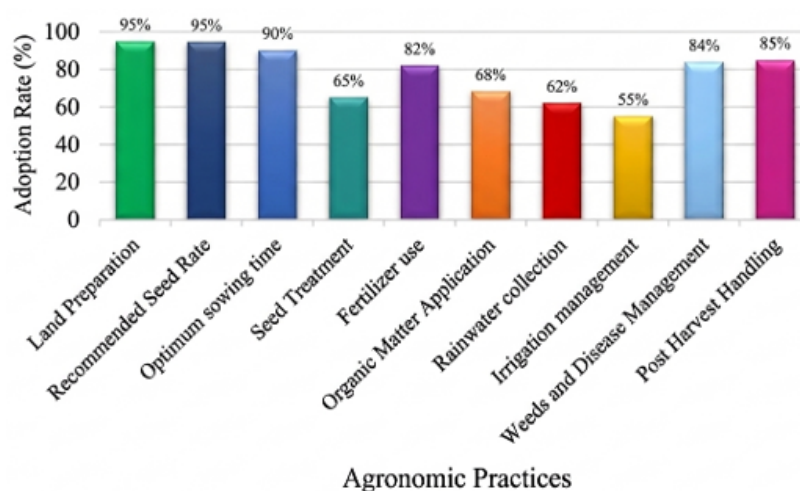


Figure 2. Adoption rate of recommended agronomic practices adopted by district Khyber farmers while cultivating zinc enriched wheat.

Overall, farmers were more likely to adopt practices that were directly supported through the provided inputs. However, more difficult and resource demanding practices were less commonly adopted. It is very important to follow the right time of sowing and fertilizer application, as these practices not only help to increase crop yield but also improve the zinc concentration in the grain, which makes food more nutritious (Velu et al., 2014). To ensure long term success, future interventions should focus on water management and involve local communities in finding practical solutions. This will help improve both productivity and nutritional benefits of zinc-biofortified wheat (Hossain et al., 2024).

3.4. Seed Retention, Sharing Behavior and Sustainability of Zinc-Biofortified Wheat

To evaluate the sustainability and community-driven diffusion of the introduced zinc-biofortified wheat (Akbar-19), seed retention and sharing behaviors were statistically modeled across distinct farmer socio-economic and awareness categories.

Figure 3 presents seed retention rates across different farmer categories. Overall, 86% of farmers retained Akbar-19 seed for the next cropping season. Seed retention was slightly higher among experienced farmers (>10 years) compared to less experienced farmers (≤ 10 years, ~78%), and among literate farmers (~90%) compared to illiterate farmers (~78%). Larger households (>6 members) also showed marginally higher retention (~88%) than smaller households (≤ 6 members, ~82%). The regression trend line ($Y = 84.86 + 0.14x$, $R^2 = 0.002$) indicates that the relationship between these socio-economic categories and seed retention is negligible, suggesting that seed retention behaviour was consistently high and relatively uniform across all farmer groups. This reflects broad satisfaction with Akbar-19 variety performance regardless of farming experience, literacy, or household size (Gupta & Lowe, 2025; Lowe et al., 2022). However, the 14% of farmers who did not retain seeds suggest some challenges such as lack of proper storage facilities, post-harvest losses or the use of harvested crop for immediate household consumptions. Addressing these constraints



through community seed banks and improved storage technologies could strengthen long-term adoption.

Figure 4 shows seed sharing rates across the same socio-economic categories. Overall, 60% of farmers shared Akbar-19 seed with neighbors and relatives. Illiterate farmers exhibited slightly higher sharing rates (~65%) compared to literate farmers (~56%), while farmers from larger households (>6 members) shared marginally more (~63%) than those from smaller households (~59%). Sharing rates were comparable between more experienced (>10 years, ~62%) and less experienced (≤ 10 years, ~59%) farmers. The regression equation ($Y = 59.14 + 0.32x$, $R^2 = 0.05$) confirms that socio-economic categories explain only a minor proportion of variance in seed sharing behaviour, indicating that informal seed exchange was widespread and not confined to any particular farmer group. These findings highlight the emergence of community-driven seed diffusion networks, consistent with farmer-managed seed systems reported in South Asia (Lowe et al., 2022; Hossain et al., 2024). The observed seed retention rate of 86% and farmer-to-farmer sharing rate of 60% indicate strong acceptance of the introduced variety and suggest a high likelihood of continued cultivation beyond the project period.

Overall, the large number of farmers who saved and shared seeds of Akbar-19 variety in District Khyber showed that this wheat variety is no longer just a project-based intervention but has become increasingly embedded within local farming systems.

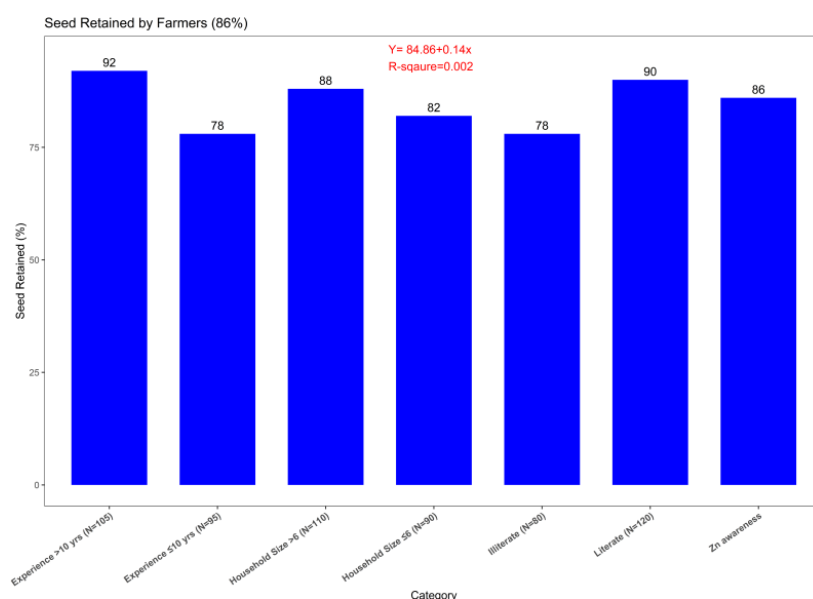


Figure 3. Percentage of zinc-biofortified wheat (Akbar-19) seed retained by smallholder farmers (N = 200) for the upcoming cropping season across socio-economic categories and farmer awareness levels.

3.5. Post-Intervention Impacts of Zinc-Biofortified Wheat (Akbar-19) on Awareness, Adoption, Food Security, and Perceived Health Outcomes

Table 2 summarizes the post-intervention changes in socio-educational, behavioral, seed system, and perceived health and nutritional outcomes associated with the adoption of zinc-biofortified wheat (Akbar-19) among smallholder farmers in District Khyber. The result showed that, the intervention achieved complete awareness among participating farmers regarding zinc enrichment in Akbar-19 variety, with all respondents (100%) acknowledging that the wheat they cultivated contained enhanced zinc levels. Similarly, 100% of the farmers reported awareness of the health benefits associated with zinc consumption following the training and extension activities conducted. This showed a clear improvement from the baseline situation where only 20% (40 farmers) had prior knowledge of zinc benefits. The increase in awareness reflects the combined effect of providing biofortified seeds along with farmer training on the importance of zinc in diet. Similar findings have been reported in nutrition-sensitive agriculture literature, where extension services significantly improve farmer knowledge and adoption behavior in biofortification programs (Hossain et al., 2024; Bouis & Saltzman, 2017).

In terms of behavioral change, adoption of Akbar-19 increased from 16% (32 farmers) at baseline to 100% (200 farmers) after intervention. Community seed retention practices, which were previously negligible, increased significantly to 86% (172 farmers), while informal seed sharing networks expanded to 60% (120 farmers). Similar patterns of farmer-led seed saving and informal exchange have been reported in South Asia, where such systems play an important role in diffusion of improved crop varieties (Gupta & Lowe, 2025; Lowe et al., 2022).

Regarding food security outcomes, the average household wheat sufficiency duration ranged between 4–5 months, indicated that

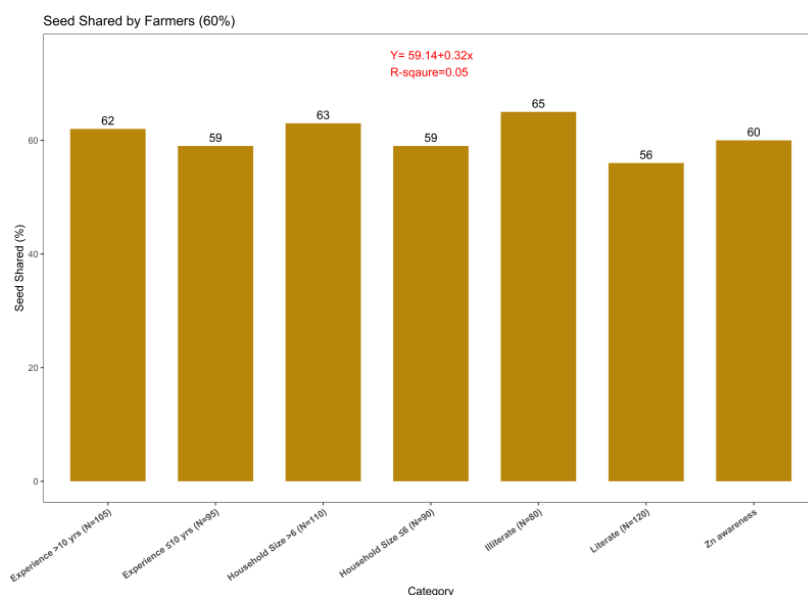


Figure 4. Percentage of zinc-biofortified wheat (Akbar-19) seed shared by smallholder farmers (N = 200) across socio-economic categories and farmer awareness levels.

the harvest from Akbar-19 contributed substantially to household grains availability. For many smallholder households that typically rely on market purchases during lean periods, this level of self-sufficiency represented a meaningful improvement in food security. However, this wheat production remains insufficient to meet annual household consumption needs, and farmers still depend on market purchases for the remaining months. Similar trends have been observed in other smallholder farming systems as well, where the improved crop variety doesn't fully prevent seasonal food gaps (Apanovich & Mazur, 2018). A notable outcome of the intervention is that 78% of participating farmers reported a reduction in wheat purchases from the market, showing reduced household dependence on external grain sources. This reduced market dependency not only improves food security but may also strengthen household economic resilience by lowering expenditure on staple foods. For resource-constrained families in District Khyber, even small reduction in money spends on food items help them to utilize that money for other important needs such as education, healthcare and other farm inputs.

Table 2. Comparative matrix of educational, behavioral and perceived health indicators before and after project intervention (N=200).

Core Project Indicator	Pre-Intervention Baseline (Before Project)	Post-Intervention Status (After Harvest & Consumption)	Educational / Livelihood Shift
SOCIO-EDUCATIONAL AND BEHAVIORAL			
Awareness of Zinc Health Benefits	20% (40 Farmers)	100% (200 Farmers)	+80% (Complete awareness achieved)
Active Cultivation / Adoption Rate	16% (32 Farmers)	100% (200 Farmers)	+84% (Trial participation)
Community Seed Retention Habits	0% / Not practiced (Minimal)	86% (172 Farmers)	+86% (Established local seed saving)
Informal Seed Sharing Networks	0% / Not practiced (Minimal)	60% (120 Farmers)	+60% (Active farmer-to-farmer sharing)
Staple Wheat Sufficiency Buffer	Deficit / High market dependency	4–5 months of grain availability	Significantly improved food security buffer
PERCEIVED HOUSEHOLD HEALTH IMPACTS			
Perceived Improvement in Child Health and Immunity (Self-reported, not clinically verified)	Limited to initial 16% adopters	68% (136 Farmers)	+52% (Broadening of impact: households broadly reported a noticeable reduction in common seasonal illnesses among children)

In terms of perceived health outcomes, 68% of the participating farmers (136 households) reported improvements in household



health, particularly child health. This represents a significant community-wide expansion compared to the pre-intervention phase, where such perceived health advantages were restricted exclusively to the initial 16% of early adopters (32 farmers) who already had access to the zinc biofortified variety. These findings are based entirely on self-reported farmer perceptions and were not verified through clinical assessments. Therefore, this should not be interpreted as objective evidence of improved health outcomes. Rather, this reflects farmers' perceptions regarding the potential benefits of cultivating and consuming zinc-biofortified wheat. Farmers are more likely to continue growing bio-fortified crops in the long term when they observe clear improvements in their family's health as these visible benefits strengthen their motivation to maintain these farming practices.

The findings suggested that the adoption of Akbar-19 wheat contributes to improved household food availability, reduced market dependence and increased nutrition awareness. However, the limited duration of wheat sufficiency indicates that bio-fortified wheat alone cannot fully address year-round food security challenges. Future interventions should therefore, integrate bio-fortified crop promotion with broader strategies such as crop diversification, improved storage systems and strengthened local seed supply chains to enhance both nutritional and livelihood outcomes for smallholder farmers.

3.6. Determinants of Adoption of Zinc-Biofortified Wheat

A binary logistic regression model was used to identify factors influencing the adoption of zinc-biofortified wheat (Akbar-19). The model showed good explanatory power (Nagelkerke $R^2 = 0.42$) with an overall classification accuracy of 78% (Table 3). Extension services emerged as the strongest positive determinant of adoption (OR = 3.49, $p < 0.001$), indicating that farmers receiving extension support were significantly more likely to adopt the variety. Similar findings have been reported by Hossain et al. (2024), who demonstrated that institutional support and extension networks substantially increase the adoption of improved seed technologies among smallholder farmers. Access to certified seed (OR = 2.56, $p = 0.01$), secondary or higher education (OR = 2.39, $p = 0.01$), awareness of zinc health benefits (OR = 1.91, $p = 0.04$), and larger landholding size (OR = 1.52, $p = 0.03$) also positively influenced adoption. In contrast, input cost barriers significantly reduced the likelihood of adoption (OR = 0.48, $p = 0.02$). Similar barriers have been documented by Reddy and Rahut (2025), who identified production costs and limited resource availability as major constraints to technology adoption in South Asian farming systems.

These findings suggest that institutional support, access to quality seed, farmer education, and nutrition awareness play important roles in promoting the adoption of biofortified wheat, while high production costs remain a major constraint. Therefore, strengthening extension services, improving seed availability, and reducing financial barriers could enhance the widespread adoption of zinc-biofortified wheat among smallholder farmers.

Table 3. Binary logistic regression analysis of socio-economic and institutional factors influencing the adoption of zinc-biofortified wheat (Akbar-19) among smallholder farmers.

Predictor Variable	Odds Ratio (Exp β)	p-value	Interpretation
Landholding size	1.52	0.03	Larger farms are more likely to adopt zinc-biofortified wheat.
Education (Secondary or above)	2.39	0.01	Educated farmers adopt the technology more readily.
Extension services (Yes)	3.49	<0.001	Strongest positive predictor of adoption.
Awareness of zinc health benefits (Yes)	1.91	0.04	Awareness significantly increases the likelihood of adoption.
Input cost barrier (Yes)	0.48	0.02	High input costs reduce the likelihood of adoption.
Certified seed availability (Yes)	2.56	0.01	Access to certified seed strongly predicts adoption.

Model fit: Nagelkerke $R^2 = 0.42$; Classification accuracy = 78%; Odds Ratio (OR) $> 1 \rightarrow$ predictor increases odds of adoption; Odds Ratio (OR) $< 1 \rightarrow$ predictor decreases odds of adoption; $p < 0.05 \rightarrow$ strong evidence that the predictor truly influences adoption; $p > 0.05 \rightarrow$ effect is not statistically significant (could be due to chance).

4. Conclusions and Recommendations

This study demonstrated that the introduction of zinc-biofortified wheat (Akbar-19) among smallholder farmers in District Khyber generated benefits beyond varietal adoption alone. The observed yield advantage, high rates of seed retention and farmer-to-farmer seed exchange, and improved awareness of zinc nutrition indicate strong acceptance of the technology within local farming systems. These findings suggest that biofortified wheat can simultaneously contribute to agricultural productivity, household food availability, and the dissemination of nutrition-sensitive agricultural practices in resource-constrained communities. The emergence of informal seed-sharing networks further highlights the potential for community-led scaling and sustained adoption beyond the project period. However, the study was limited to a single production season and relied on self-reported perceptions regarding household health outcomes. Future research should therefore evaluate the long-term agronomic, nutritional, and socioeconomic impacts of zinc-biofortified wheat across multiple locations and seasons, including clinical assessment zinc status in humans.



Author Contributions

Muhammad Khalid: Software, Writing – original draft, Writing – review & editing; Maryam Samad: Conceptualization, Methodology, Investigation, Data curation; Shehzad Elahi: Conceptualization, Investigation, validation, Resources; Shah Fahad: Software, Visualization, Writing – original draft, Writing – review & editing

Funding Information

Not applicable.

Acknowledgement

The authors extend their sincere appreciation to Welthungerhilfe (WHH), Germany, for their financial support in conducting this study.

Declarations

Conflicts of Interest: The authors declare no conflict of interest.

Institutional/Ethical Approval: Not Applicable.

Supplementary Information Availability: Not applicable.

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