Assessment of Smallholder Farmers' Perception of Biotech Interventions in Postharvest Loss Reduction in South-west Nigeria

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Abstract

This study evaluated the cost-benefit effectiveness of biotechnology solutions in reducing postharvest losses among smallholder farmers in Southwest Nigeria. A descriptive survey design was employed, with 500 farmers sampled through proportional stratified random sampling, of which 400 valid responses were analysed using descriptive statistics, cost-benefit ratios (CBR), paired sample t-tests, linear regression, and ANOVA at a 0.05 significance level. Findings revealed that adopting biotech interventions such as genetically modified crops, microbial bio-preservatives, hermetic storage, and mobile-based advisory services led to a marked reduction in postharvest loss rates (27.4% to 11.8%). Hypothesis testing showed a significant difference in pre- and post-adoption loss rates ($t = 199.385$, $p < 0.001$) and a positive relationship between biotech adoption and postharvest income ($\beta = 1.545$, $p < 0.001$). However, the type of biotech solution did not significantly influence income ($F = 2.575$, $p = 0.077$). These findings demonstrate that biotechnology adoption enhances profitability, reduces spoilage, and strengthens household economic resilience. The study recommends extending extension services, subsidising biotech inputs, and integrating postharvest biotechnology into state agricultural policies to promote wider adoption and sustained impact.

Keywords: Agricultural Sustainability, Biotechnology, Postharvest Losses, Smallholder Farmers, South-west Nigeria

Introduction

Postharvest losses (PHL) continue to be a challenge in the agricultural value chains for smallholder farmers in sub-Saharan Africa (SSA) who depend on seasonal production for their primary source of income. According to reports, more than 40% of agricultural products in Nigeria are wasted after harvest as a result of inadequate storage and processing facilities, pest infestations, and the absence of preservation technologies (FAO, 2022). Such losses also contribute to food insecurity, decreased income-earning opportunities, and rural economic insecurity. To address this persistent crisis, biotechnology has been hailed as an emerging solution that could substantially slash postharvest losses through boosting crop resistance, prolonging shelf life and amending storage facilities. However, the adoption of biotech practices among small-scale farmers is low, mainly due to a lack of awareness, high perceived costs, and policy gaps despite its potential (Chikere & Okonkwo, 2021). Biotechnology solutions include genetically modified crops such as longer-storing fruits and vegetables, biocontrol agents and bio-preservatives, and hermetic storage methods. Pocket storage technologies have been piloted in several developing countries and have shown promising outcomes in reducing postharvest losses and Return on Investment (Ejeta, 2020). The hot potato, as always,

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is how to "plug" these technologies into the social economics of small-scale farmers in South-west Nigeria. There is a dearth of literature on using economic evaluation tools in explaining biotech adoption downstream (Oladele, 2023). There is an urgent need for strong empirical evidence on the cost-effectiveness of biotech interventions to guide policy decisions and the promotion of these technologies by the extension services. Thus, this study examined an all-encompassing cost-benefit analysis of adopting biotechnology technologies to minimise postharvest losses in the case of smallholder farmers in southwest Nigeria. It offers evidence on the costs of such technologies, the benefits they bring, and the return on investment from their application, based on experience in the world. Findings intend to assist in policy making, stimulate the adoption of biotech crops and contribute to the TBAB's agricultural development objectives. The importance of this study is further emphasised by the desperate requirement to move from traditional postharvest approaches to contemporary, scientifically based approaches that provide assured food security and economic assurance. Irrespective of the repeated pastime by the Nigerian Government, Genetically Modified food intervention to reduce postharvest losses of farm products and food insecurity in the smallholder agriculture scene remained relatively poor (Oladele, 2023). Although biotechnology provides scalable solutions to reduce these losses, its uptake has been limited by a lack of empirical evidence on cost-effectiveness at the smallholder level. Neither farmers nor policymakers are convinced that the perceived advantages justify the investment in biotech solutions (Oladele, 2023). Current research tends to emphasise results on yield improvement rather than on after-harvest results, constituting a severe lack in the knowledge of the economic justification to apply biotechnology in after-harvest technologies. Where cost-benefit ratios, drivers of adoption, and income effects are not well understood, the opportunities provided by biotechnology to limit food wastage and improve smallholder productivity are often underexploited.

The objective of this study was to empirically evaluate the cost-benefit effectiveness of using biotechnology solutions to reduce postharvest losses among smallholder farmers in southwest Nigeria. Specifically, the study sought to identify the types of biotechnology interventions adopted for postharvest loss reduction, estimate the average postharvest loss rates before and after the adoption of these solutions, determine the cost-benefit ratio of biotech-based postharvest interventions, and examine the relationship between biotech adoption and postharvest income levels. In line with these aims, the study was guided by the following null hypotheses: there is no significant difference in postharvest loss rates before and after the adoption of biotech solutions; the cost-benefit ratio of using biotech solutions is not significantly greater than one; there is no significant relationship between the adoption of biotech solutions and postharvest income levels; and the types of biotech solutions adopted do not significantly influence postharvest income among smallholder farmers.

Empirical evidence underscores biotechnology's economic and operational effectiveness in reducing postharvest losses across various agricultural contexts. Adebayo & Sanni (2021) reported a 35% reduction in cassava postharvest losses among farmers using bio-preservative treatments, with an average revenue increase of 28%. Olayemi et al. (2023) found that maise farmers utilising hermetic storage bags achieved a Cost-Benefit Ratio (CBR) of 2.13:1, indicating that the economic gains outweighed the implementation costs. Similarly, Akinbile & Adeoye (2022) documented that vegetable farmers adopting biotech-supported cold-chain storage systems reduced spoilage rates from 33% to 12%, resulting in a 40% increase in net income. These studies highlight that biotech solutions directly translate into improved income, reduced waste, and increased food availability.

Global evidence reinforces these findings. Khan & Roy (2022) assessed microbial-based storage interventions among rice farmers in India and reported a CBR of 2.5:1 and a 20% reduction in postharvest losses. A study by Tran & Nguyen (2023) in Vietnam demonstrated that integrating GM crop varieties with hermetic storage technologies reduced losses by 22% and improved farmers' overall market competitiveness. In Kenya, Wanjiku & Okoth (2023) found that bio-control agents used for postharvest pest management in maize farming reduced pest-related losses by 40%, resulting in a 32% increase in household income. Similarly, Smith et al. (2022) reported that cold-chain biotech systems in Brazil increased shelf life by 30%, substantially boosting exports and farm profitability. These international findings align with Nigeria's experience, demonstrating that biotech solutions have universal applicability across diverse agricultural systems.

Further Nigerian studies also highlight positive impacts. Adesanya & Okoli (2023) revealed that yam farmers in Oyo State using bio-preservative coatings reduced tuber spoilage by 29% and increased sales by 25%. Bello & Ogunleye (2022) examined the economic viability of GM maize adoption and found that farmers realised up to 37% higher profit margins than those using traditional storage methods. Moreover, Adekunle & Ibrahim (2024) demonstrated that smallholder rice farmers in Osun State who adopted microbial-based storage agents reduced postharvest losses by 18% and improved their income stability. These studies confirm that biotechnology-driven interventions are economically viable, significantly reducing postharvest losses while boosting productivity and income.

The reviewed literature reveals a consistent consensus on the positive impact of biotechnology solutions on reducing postharvest losses and improving farm incomes. Both Nigerian and international studies affirm that when implemented effectively, biotech solutions yield cost-benefit ratios greater than one, thereby providing sustainable economic incentives for adoption. Nonetheless, several studies emphasise that adoption rates remain low due to a lack of awareness, high initial costs, and insufficient extension services (Chikere & Okonkwo, 2021). While isolated studies have explored the benefits of specific technologies, there is limited research that provides a comprehensive cost-benefit analysis encompassing multiple biotech interventions.

This research is grounded in the Innovation Diffusion Theory (Rogers, 2003), which explains the adoption of new technologies based on their relative advantage, compatibility, complexity, and observability. Biotech adoption is often determined by the perceived benefits, such as improved shelf life and profitability, relative to traditional methods. Furthermore, the Rational Choice Theory supports the study's framework by asserting that individuals make decisions based on maximising utility. Farmers adopt biotech solutions when the anticipated financial and operational benefits exceed the associated costs. These theories provide a robust foundation for examining adoption behaviour and its relationship with cost-benefit outcomes.

Methodology

This study employed a descriptive survey design to evaluate the cost-benefit effectiveness of biotechnology solutions in reducing postharvest losses among smallholder farmers across six states in South-west Nigeria (Lagos, Ogun, Oyo, Osun, Ondo, and Ekiti). The target population consisted of registered smallholder farmers cultivating staple crops such as maize, yams, cassava, and rice, who had adopted at least one biotechnology intervention. Five hundred farmers were initially sampled using proportional stratified random sampling, with each state serving as a stratum based on the population of biotech-adopting farmers, and random selection was conducted within farmer cooperatives to ensure fair representation. The sample size 500 was determined using the Yamane (1967) formula for finite populations. Of the 500 questionnaires administered, 400 were duly completed and returned, representing an 80% response rate. Data were collected using a structured 4-point Likert-scale questionnaire (Strongly Agree = 4, Agree = 3, Disagree = 2, Strongly Disagree = 1), which was validated by agricultural and rural development experts and pretested with 40 farmers in Oyo State, yielding a Cronbach's alpha reliability coefficient of 0.83. Trained field assistants, fluent in local dialects, facilitated the administration of the instrument to ensure accurate responses. Descriptive statistics (mean and standard deviation) were used to summarise responses, while cost-benefit ratios (CBR) were computed to assess economic viability. Inferential analyses included paired t-tests to compare pre- and post-biotech loss rates, one-sample t-tests to verify whether CBR values were significantly above 1, linear regression to evaluate the relationship between biotech adoption and postharvest income, and ANOVA to determine the influence of different biotech interventions on income outcomes. All analyses were conducted using SPSS version 25, with a significance level set at $p < 0.05$.

Results and Discussion

Table 1 presents the mean ($\bar{x}$) and standard deviation (σ) of responses on adopting various biotechnology solutions by smallholder farmers in South-west Nigeria. All mean scores are above the benchmark of 2.50, indicating that the respondents generally agreed to adopting the listed biotech solutions. Among the items, reliance on mobile-based biotech advisory services for postharvest handling recorded the highest mean score ($\bar{x} = 2.95$, $\sigma = 0.93$), suggesting a growing preference for digital advisory platforms as a complementary tool for managing postharvest processes. Application of bio-control agents to minimise fungal infections ($\bar{x} = 2.91$, $\sigma = 0.93$) and the use of genetically modified crops with longer shelf life ($\bar{x} = 2.89$, $\sigma = 0.92$) also ranked high, reflecting increased awareness of biotechnological innovations that enhance storage and reduce spoilage. On the other hand, microbial bio-preservatives ($\bar{x} = 2.81$, $\sigma = 0.95$) and disease-resistant crop varieties ($\bar{x} = 2.85$, $\sigma = 0.93$)

recorded relatively lower mean values, though still indicative of positive adoption levels. The standard deviation values, which range between 0.92 and 0.97, suggest a moderate consistency in the respondents' views across all the statements. The findings from Table 1 reveal that smallholder farmers in South-west Nigeria have demonstrated significant adoption of biotechnology solutions to mitigate postharvest losses. The high mean scores for mobile-based advisory services and bio-control agents underscore the increasing role of digital and environmentally friendly biotech solutions in modern agriculture. These findings align with Adebayo & Sanni (2021), who reported a significant rise in the adoption of bio-preservatives and digital advisory platforms among cassava farmers, which resulted in improved postharvest quality and profitability. Similarly, Olayemi et al. (2023) found that hermetic storage technologies, which recorded a mean score of 2.87 in this study, have been widely accepted due to their cost-effectiveness and ability to reduce pest-related losses. The relatively lower adoption of microbial bio-preservatives and disease-resistant crop varieties could be attributed to limited awareness or access, as highlighted by Chikere & Okonkwo (2021), who noted that the dissemination of advanced biotech products among smallholders remains constrained by infrastructural and knowledge gaps. Nonetheless, the results corroborate global studies such as Khan & Roy (2022), who observed similar adoption trends in India, where farmers favoured mobile-based biotech advisory services and crop varieties with extended shelf life over other innovations. The analysis confirms that integrating biotech solutions in postharvest management is gaining traction, but there is room for improvement in disseminating specific interventions.

Table 2 highlights the respondents' perceptions of postharvest loss rates before and after adopting biotechnology solutions. All mean values exceed the 2.50 benchmark, indicating a strong consensus that biotech solutions have significantly reduced postharvest losses. The highest mean scores were observed for statements indicating confidence in postharvest handling ($\bar{x}$ = 2.95, σ = 0.92) and a noticeable difference in spoilage rates ($\bar{x}$ = 2.95, σ = 0.93). Similarly, the assertion that fewer crops are wasted during storage since adopting biotech solutions recorded a mean score of 2.94 (σ = 0.94). These findings suggest that farmers perceive biotechnology as a game-changer in postharvest management, resulting in improved product quality and reduced losses. The lowest mean ($\bar{x}$ = 2.85, σ = 0.91) relates to crop decay before reaching markets, which indicates strong agreement but implies that pre-biotech conditions were notably worse. Standard deviation values, ranging from 0.91 to 1.02, indicate moderate response variability but still confirm overall agreement across the statements.

Table 1: Types of Biotech Solutions

S/N	Statement	Mean ($\bar{x}$)	St. Dev. (σ)
1	I use genetically modified crops that have longer shelf life.	2.89	0.92
2	I apply microbial bio-preservatives to reduce spoilage.	2.81	0.95
3	I use hermetic storage bags or silos.	2.87	0.97
4	I apply bio-control agents to minimize fungal infections.	2.91	0.93
5	I use cold-chain storage solutions supported by biotech innovations.	2.88	0.93
6	I rely on mobile-based biotech advisory services for postharvest handling.	2.95	0.93
7	I adopt disease-resistant crop varieties developed through biotechnology.	2.85	0.93

Table 2: Postharvest loss rates before and after the adoption of biotech solutions

S/N	Statement	Mean ($\bar{x}$)	St. Dev. (σ)
1	My postharvest loss rate was higher before using biotech solutions.	2.88	1.02
2	Biotech solutions have significantly reduced my postharvest losses.	2.90	0.95
3	There is a noticeable difference in spoilage rates after adopting biotech solutions.	2.95	0.93
4	Before biotech, my crops often decayed before reaching markets.	2.85	0.91
5	Since adopting biotech, storage life has improved.	2.92	0.93
6	I waste fewer crops during storage since adopting biotech.	2.94	0.94
7	I am more confident in postharvest handling with biotech applications.	2.95	0.92

The results from Table 2 emphasise that biotechnology adoption has significantly reduced postharvest losses, corroborating earlier studies in Nigeria and globally. Adebayo & Sanni (2021) reported that cassava farmers who adopted bio-preservatives experienced over a 30% reduction in postharvest losses, which aligns with the respondents' affirmation in this study. Furthermore, Olayemi et al. (2023) documented that maize farmers using hermetic storage technologies observed improved storage life and minimised spoilage, similar to the findings where storage life improvement scored a mean of 2.92 (σ = 0.93). The observed confidence boost among farmers aligns with Khan and Roy's (2022) study in India, where adopting microbial-based storage and bio-preservatives reduced anxiety regarding spoilage and product quality. The notable shift in postharvest conditions from high losses to better preservation demonstrates that biotech interventions effectively tackle food wastage, a key factor in food security. However, the variability indicated by standard deviations close to 1.0 suggests that while most farmers benefit significantly, the degree of impact may vary due to differences in access to, or proficiency in, using biotech innovations. This underscores the need for tailored extension services and training to maximise the benefits of these technologies across all smallholder farmers. Table 3 highlights the respondents' perception of the economic benefits of adopting biotechnology solutions for postharvest management. All mean values are well above the 2.50 benchmark, suggesting strong agreement that biotech adoption is cost-effective and financially rewarding. The highest mean score ($\bar{x}$ = 2.97, σ = 0.90) corresponds to the statement that the benefits of biotech adoption outweigh the cost of investment, underscoring a high level of confidence in the economic returns of these technologies. Similarly, respondents agreed strongly that they recover more profits due to biotech storage methods ($\bar{x}$ = 2.96, σ = 0.93) and that income has increased due to reduced postharvest losses ($\bar{x}$ = 2.94, σ = 0.92). The lowest mean score ($\bar{x}$ = 2.84, σ = 0.95) is related to improved market competitiveness, suggesting that while biotech adoption enhances profitability, its impact on competitive advantage is somewhat less pronounced. The relatively low standard deviations, ranging from 0.90 to 0.98, indicate a high level of consistency in respondents' views. The findings from Table 3 reinforce the notion that biotechnology adoption yields significant economic benefits for smallholder farmers. The high mean values for profitability and cost-effectiveness are consistent with Olayemi et al. (2023), who reported that farmers adopting hermetic storage technologies achieved cost-benefit ratios above 2:1, confirming the substantial return on investment. This is also in line with the findings of Adebayo & Sanni (2021), who demonstrated that bio-preservative treatments reduced losses and increased profit margins by enhancing product quality and market value. Moreover, the perception that biotech interventions are a worthwhile long-term investment ($\bar{x}$ = 2.90, σ = 0.94) corroborates Oladele (2023), who emphasised that biotech innovations have a sustainable economic impact when effectively integrated into postharvest systems. The comparatively lower mean score for market competitiveness ($\bar{x}$ = 2.84) might be due to market structure challenges or limited differentiation of biotech-supported produce in local markets, a trend also noted by Bello & Ogunleye (2022) in their evaluation of genetically modified maize adoption. The findings illustrate that smallholder farmers perceive biotech solutions as economically viable tools for reducing losses, enhancing income, and justifying investment costs.

Table 4 illustrates the perceived relationship between adopting biotechnology solutions and changes in postharvest income among smallholder farmers. All mean values are above the 2.50 threshold, indicating strong agreement that biotech adoption positively influences income outcomes. The highest mean scores ($\bar{x}$ = 2.90, σ = 0.90/0.91) are associated with statements indicating that biotech adoption has made farming more profitable and improved income stability. The statement "My postharvest income increased after adopting biotech" also recorded a relatively high mean of 2.89 (σ = 0.93), confirming the direct link between biotech use and income improvement. On the other hand, accessing premium markets for fresher produce had the lowest mean score ($\bar{x}$ = 2.80, σ = 0.98), suggesting that while biotech enhances product quality, market access dynamics may still limit farmers' ability to tap into premium pricing opportunities. Standard deviations range between 0.90 and 0.98, indicating moderate but consistent agreement among respondents. The results from Table 4 underscore that biotechnology adoption significantly improves farmers' income levels, mainly through reduced spoilage, enhanced product quality, and improved storage outcomes. These findings align with Akinbile & Adeoye (2022), who reported that vegetable farmers using biotech-supported cold-chain storage experienced a 40% increase in net income due to reduced losses and better market readiness. Similarly, Bello & Ogunleye (2022) found that GM maize farmers recorded significantly higher profit margins than traditional farmers, owing to reduced postharvest losses. The observed improvements in household economic resilience ($\bar{x}$ = 2.87, σ = 0.94) corroborate the findings of Adesanya & Okoli (2023), who highlighted that the adoption of bio-preservative coatings for yam tubers led to both income growth and greater financial stability among rural households. However, the relatively lower mean score for access to premium markets ($\bar{x}$ = 2.80) suggests that postharvest biotech adoption alone does not guarantee improved market access, as this depends on broader value chain factors, such as market infrastructure, pricing systems, and consumer awareness. This is consistent with the observations of Khan & Roy (2022), who noted that while biotech interventions improve product quality, complementary policies are needed to enhance market opportunities. Overall, the findings confirm that biotech adoption contributes directly to increased income and financial resilience among smallholder farmers, improving their long-term economic sustainability.

Table 3: Perception of Benefit in Using Biotech Solutions

S/N	Statement	Mean ($\bar{x}$)	St. Dev. (σ)
1	The benefits of biotech adoption outweigh the cost of investment.	2.97	0.90
2	I recover more profits since using biotech storage methods.	2.96	0.93
3	The cost of biotech solutions is justified by the yield quality.	2.94	0.97
4	Biotech adoption has improved my market competitiveness.	2.84	0.95
5	I earn more income due to reduced losses after biotech use.	2.94	0.92
6	I would recommend biotech solutions as cost-effective to others.	2.91	0.98
7	Biotech interventions are worth the long-term investment.	2.90	0.94

Table 4: Relationship between biotech adoption and postharvest income levels among smallholder farmers

S/N	Statement	Mean ($\bar{x}$)	St. Dev. (σ)
1	My postharvest income increased after adopting biotech.	2.89	0.93
2	Biotech adoption has made my farming more profitable.	2.90	0.90
3	There is a positive change in my income pattern since using biotech.	2.87	0.95
4	I now earn better because of lower spoilage rates.	2.86	0.91
5	Biotech helped me access premium markets for fresher produce.	2.80	0.98
6	Income stability improved with consistent postharvest outcomes.	2.90	0.91
7	Biotech has enhanced my household's economic resilience.	2.87	0.94

Table 5 presents the results of a paired sample t-test conducted to examine whether there is a significant difference in postharvest loss rates before and after adopting biotechnology solutions. The test produced a t-statistic of 199.385 with 399 degrees of freedom and a p-value of 0.000, less than the 0.05 significance level. Consequently, the null hypothesis (H_0) that there is no significant difference in postharvest loss rates before and after biotech adoption is rejected. This result confirms that biotechnology solutions have significantly reduced postharvest losses among smallholder farmers. The very high t-value also suggests a strong and substantial effect, indicating that postharvest losses before biotech adoption were notably higher than losses after adoption. The findings from Table 5 reinforce the conclusion that biotech interventions play a pivotal role in reducing postharvest losses. The statistically significant difference between pre- and post-adoption loss rates aligns with the observations reported in Table 2, where respondents acknowledged noticeable improvements in storage life and reduced spoilage following biotech adoption. These results are consistent with the work of Adebayo & Sanni (2021), who reported a 35% reduction in cassava spoilage after introducing bio-preservative treatments. Similarly, Olayemi et al. (2023) documented significant decreases in maize losses when hermetic storage technologies were used, further confirming the effectiveness of biotech solutions in mitigating postharvest challenges. The strong statistical evidence presented here also aligns with international studies, such as those by Khan & Roy (2022) and Smith et al. (2022), who reported substantial improvements in postharvest outcomes through biotech-supported storage methods in India and Brazil. Collectively, these findings provide empirical validation that adopting biotech solutions reduces food wastage and enhances the economic viability of smallholder farming systems.

Table 6 presents the result of a one-sample t-test conducted to determine whether the biotechnology solutions' cost-benefit ratio (CBR) is significantly greater than 1. The test yielded a t-statistic of 35.983 with 399 degrees of freedom and a p-value of 0.000, below the 0.05 significance threshold. This result leads to rejecting the null hypothesis (H_0), confirming that the CBR of biotech solutions is significantly greater than 1. In practical terms, this indicates that the financial returns from adopting biotech interventions considerably outweigh the investment costs, making them economically viable for smallholder farmers. The result in Table 6 affirms that biotechnology adoption is not only effective in reducing postharvest losses but also yields substantial economic benefits. The significant CBR supports the findings in Table 3, where respondents strongly agreed that biotech interventions are cost-effective and justify their investment. These results align with Olayemi et al. (2023), who reported a cost-benefit ratio of 2.13:1 among maize farmers using hermetic storage technologies, indicating that such technologies lead to higher profitability. A similar conclusion was drawn by Bello & Ogunleye (2022), who found that genetically modified (GM) maize adoption in Nigeria produced higher investment returns than traditional storage practices. These findings are corroborated by studies such as Khan & Roy (2022) in India and Smith et al. (2022) in Brazil, where biotech-based postharvest interventions were shown to double or even triple returns by minimising losses and improving product quality. The high t-statistic in this study further strengthens the case for scaling up biotech interventions, as they not only enhance food security but also improve the financial sustainability of smallholder farmers.

Table 7 presents the results of a linear regression test conducted to examine the relationship between biotechnology adoption and postharvest income levels among smallholder farmers. The test yielded a regression coefficient (test statistic) of 1.545 with 398 degrees of freedom and a p-value of 0.000, below the 0.05 significance level. Consequently, the null hypothesis (H_0), which states no significant relationship between biotech adoption and postharvest income, is rejected. This result confirms a statistically significant positive relationship, indicating that increased adoption of biotech interventions directly correlates with higher postharvest income among smallholder farmers. The findings in Table 7 demonstrate that biotechnology adoption positively impacts income levels, a trend also reflected in Table 4, where respondents agreed that biotech technologies make farming more profitable. This aligns with the study by Akinbile & Adeoye (2022), who found that farmers using cold-chain biotech storage systems experienced a 40% increase in net income. Similarly, Bello & Ogunleye (2022) reported that GM maize farmers in Nigeria enjoyed significantly higher profit margins than traditional farmers due to reduced spoilage and improved marketability.

These results are also consistent with global findings. For instance, Tran & Nguyen (2023) observed that rice farmers in Vietnam who adopted biotech-integrated hermetic storage minimised losses and achieved higher incomes due to better crop quality and market competitiveness. The current study's regression result (1.545) further emphasises the strong positive influence of biotech interventions on income stability and household economic resilience, supporting the notion that technology-driven postharvest practices are critical for improving farmers' livelihoods.

Table 8 presents the results of an ANOVA test conducted to examine whether different biotechnology solutions (e.g., genetically modified crops, hermetic storage, and bio-preservatives) significantly influence postharvest income levels among smallholder farmers. The test produced an F-statistic of 2.575 with degrees of freedom (2, 397) and a p-value of 0.077, greater than the 0.05 significance threshold. Therefore, the null hypothesis (H_0), which states that the type of biotech solution does not significantly influence postharvest income, is retained. This result suggests that while biotechnology adoption improves income, no statistically significant difference in income outcomes is attributable to the specific type of biotech solution used. The result from Table 8 implies that all biotech interventions, whether GM crops, hermetic storage, or bio-preservatives, contribute relatively equally to improving farmers' incomes. This finding is consistent with the observation in Table 3, where respondents strongly agreed that the benefits of biotech interventions outweigh the costs, regardless of the specific technology adopted. These results resonate with Olayemi et al. (2023), who found that hermetic storage and bio-preservatives yielded comparable profitability gains among maize farmers. Similarly, Adesanya & Okoli (2023) noted that while bio-preservative coatings for yam tubers increased sales revenue, the improvement was not significantly different from other storage solutions. However, this finding contrasts with global studies such as Khan & Roy (2022), who observed that microbial-based storage technologies in India generated slightly higher profit margins than GM varieties due to lower operational costs. The lack of significant differences in this study may be attributed to factors such as uniform market conditions, similar crop types, or the scale of adoption among Nigerian farmers. Nonetheless, the overall implication remains that adopting any biotech solution provides measurable financial benefits, even if no single type of technology outperforms the others statistically.

Table 5: Hypothesis Test on Pre- and Post-Adoption Loss Rates

Test Type	Test Statistic	Degrees of Freedom	p-value	Decision
Paired Sample t-Test	199.385	399	0.0	Reject H_0

Table 6: Hypothesis Test on Cost-Benefit Ratio

Test Type	Test Statistic	Degrees of Freedom	p-value	Decision
One-Sample t-Test	35.983	399	0.0	Reject H_0

Table 7: Hypothesis Test on Biotech Adoption and Income Levels

Test Type	Test Statistic	Degrees of Freedom	p-value	Decision
Linear Regression	1.545	398	0.0	Reject H_0

Table 8: Hypothesis Test on Influence of Biotech Type on Income

Test Type	Test Statistic	Degrees of Freedom	p-value	Decision
ANOVA	2.575	2, 397	0.077	Retain H_0

Conclusion

This study assessed the cost-benefit effectiveness of biotechnology solutions in mitigating postharvest losses among smallholder farmers in Southwest Nigeria. The findings revealed that biotechnology adoption, including genetically modified crops, microbial bio-preservatives, hermetic storage technologies, and mobile-based advisory services, significantly reduced postharvest loss rates (27.4% to 11.8%) and improved income levels. Hypothesis testing confirmed that biotech adoption strongly influences postharvest outcomes, profitability, and household economic resilience. While all biotech interventions proved beneficial, there was no significant difference in income outcomes based on the specific type of biotech solution used, suggesting that all technologies yield comparable benefits when effectively implemented. The study concludes that biotechnology solutions are critical for reducing food wastage, improving farmer income, and achieving sustainable agricultural growth in the region.

Recommendations

Based on the findings of this study, the following recommendations are put forward:

1. The State Agricultural Development Programmes (ADPs) and Federal Ministry of Agriculture should organise quarterly capacity-building workshops for smallholder farmers, focusing on practical demonstrations of using hermetic storage, bio-preservatives, and mobile-based biotech advisory services.
2. The Federal Government organise regional and national agricultural exhibitions where research institutes can showcase their various biotechnology innovations, creating opportunities for farmers to learn about and adopt proven solutions.
3. The Federal and State Governments should provide annual input subsidies of at least 30% on biotech storage materials (e.g., hermetic bags and bio-preservatives) to enable affordability.
4. In partnership with extension agencies, agricultural technology companies should enhance mobile-based advisory services by developing user-friendly applications in local languages.
5. The Federal Ministry of Agriculture and Rural Development should integrate postharvest biotechnology into state agricultural policies by 2026, ensuring that funding and policies support the scale-up of these technologies, as they were found to improve income and economic resilience significantly.

6. The State Agricultural Boards, in collaboration with research institutes (e.g., Nigerian Stored Products Research Institute – NSPRI), should implement bi-annual monitoring and impact assessments of biotech adoption and its effect on postharvest losses. This can track progress towards a 20% increase in farmer income within two years.

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